3.7.3 Seismic Subsystem Analysis

Seismic analysis methodology for U.S. EPR standard plant structural subsystems is described in this section. The plant structural subsystems include heating, ventilation, and air conditioning (HVAC) duct, cable tray, conduit, and tubing distribution systems; equipment and component supports; platforms and support frame structures; buried piping, and conduits; yard structures; and atmospheric tanks. Structural subsystems include structural items that are not directly impacted by seismic forces imparted through the soil, but are directly impacted by seismic forces as they are transmitted through the building structure.

With the exception of Seismic Category I to non-Seismic Category I interface criteria in Section 3.7.3.8, seismic analysis for piping subsystems is addressed in Sections 3.9.2 and 3.12. Seismic and dynamic qualification methods for mechanical equipment are addressed in Section 3.10. Section 3.11 addresses seismic qualification of electrical equipment. Design criteria for distributed subsystem supports for piping, HVAC ducts, cable trays, and conduits are contained in Appendix 3A. Appendix 3C addresses seismic and dynamic analysis of supports for the reactor coolant system.

As addressed in Section 3.7, the design of the U.S. EPR does not consider explicit design analysis for the operating basis earthquake (OBE). The requirement for seismic fatigue through a cyclic load basis of one safe shutdown earthquake (SSE) and five OBEs is met for the U.S. EPR by consideration of full and fractional SSE events.

Seismic Category I subsystems are designed to withstand the effects of an SSE and maintain the capability to perform their safety functions. This design is accomplished by performing seismic analyses for Seismic Category I subsystems using methods in accordance with 10 CFR 50, GDC 2 and 10 CFR 50, Appendix S, per SRP 3.7.3 (Reference 6). These methods, as described in the following sections, include the response spectrum method, time history method or, where applicable, the equivalent static load method.

3.7.3.1 Seismic Analysis Methods

3.7.3.1.1 Response Spectrum Method

The effects of the ground motion during an SSE event are transmitted through structures to the subsystem at support and equipment anchorage locations. In the response spectrum method of analysis, values are determined for each mode of the subsystem from the in-structure response spectra (ISRS). The ISRS represent the maximum acceleration response of an idealized single-degree-of-freedom damped oscillator as a function of natural frequency to the vibratory input motion of the structure.

The ISRS are developed as described and are applied to the subsystem at locations of structural attachment, such as support or equipment locations (see Section 3.7.2.5). The response spectra analysis is performed using either enveloped uniform response spectra or independent support motion (ISM) using multiple spectra input.

ISRS for each of the three directional components of earthquake motions are applied separately to the subsystem. Modal responses are determined by accelerating each mode with the spectral acceleration corresponding to the frequency of that mode. The modal and co-directional responses are then combined by the methods described in Sections 3.7.3.7 and 3.7.3.6, respectively.

Peak Broadening Method

ISRS are generated from the seismic structural analysis using the methods provided in Section 3.7.2 and following guidance from RG 1.122. ISRS are peak broadened by a minimum of ±15 percent to account for uncertainties in the structural response, as described in Section 3.7.2.5.

Peak Shifting Method

Peak shifting as described in ASCE 4-98 (Reference 4) and ASME BPV Code, Section III, Division 1, Appendix N (Reference 12) may be used in place of peak broadening to obtain a more realistic design. However, the peak shifting method described by these codes is applicable only to piping systems. Similar to broadening, peak shifting considers a minimum of ±15 percent uncertainty in the peak structural frequencies. However, spectral shifting refines the analysis by considering only one mode of the distribution subsystem to respond at the peak acceleration.

In the peak shifting method, the structural frequencies of the distribution subsystem within the maximum peak acceleration, broadened spectral frequency range are determined. If no distribution subsystem natural frequencies exist within this frequency range, successively lower acceleration peaks are broadened until the first range containing at least one natural frequency of the subsystem is found.

Considering that the peak structural frequency may lie at any one frequency within the broadened range, N+3 separate response spectra analyses are then performed, where N is the number of subsystem modes within the broadened frequency range. The first analysis uses the unbroadened response spectrum. The second and third analyses use the unbroadened spectrum modified by shifting the frequencies associated with each spectral value by $-\Delta f_j$ and $+\Delta f_j$, where Δf_j is the amount of peak shifting required to account for the uncertainties of the structural response. The remaining N analyses also use the unbroadened spectrum modified by shifting the frequencies associated with each spectral value by a factor of:

$$1 + \frac{(f_e)_n - f_j}{f_j}$$

Where:

$(f_e)_n$= Subsystem natural frequency occurring within the broadened range, for n = 1 to N,

f_j = frequency at which the peak acceleration occurs (for the peak under consideration).

For each response spectra analysis performed in the peak shifting method, the modal results are combined separately to obtain responses of interest by the methods described in Section 3.7.3.7. The peak shifting method is preformed for each orthogonal direction of earthquake input motion resulting in three sets of analysis results. Each set of analysis results includes thereby N+3 responses. The governing response for each direction of earthquake input motion is obtained by enveloping the N+3 separate analysis results in each set. The co-directional responses are then determined using the combination methods described in Section 3.7.3.6.

Multiply-Supported Systems

Section 3.7.3.9 describes the uniform support motion (USM) and ISM for subsystems supported at multiple locations within one or more buildings.

3.7.3.1.2 Time History Method

Seismic analyses may be performed using time history analysis methods in lieu of response spectrum analysis. The modal superposition method of time history analysis is used for seismic analysis of U.S. EPR subsystems. This method is based on decoupling of the differential equations of motion, considering a linear elastic system. The total response of the system is determined by integrating the decoupled equations for each mode and combining the results of the modes at each time step using algebraic addition.

Mode shapes and frequencies are determined in the response spectrum analysis method. The cutoff frequency for determining modal properties is selected to account for the principal vibration modes of the subsystem based on mass and stiffness properties, modal participation factors, and the frequency content of the input forcing function. The missing mass effects of high frequency modes are included based on the same principles described in Section 3.7.3.7.

The time step is set to be no larger than one-tenth of the shortest period of importance (e.g., the reciprocal of the cutoff frequency). In solution convergence, the general rule is that a time step must be small enough that use of one-half its duration does not

change the response by more than ten percent, as defined by ASCE 4-98 (Reference 4), Section 3.2.2.1(c). Other factors that are considered in the selection of an acceptable time step are the fundamental frequency of the subsystem being analyzed and the input time history.

To account for uncertainties in the structural analysis, one of two methods may be used following the guidance of ASCE-4-98 (Reference 4). Similar to peak shifting in the response spectrum method of analysis, three separate input time histories from the structure dynamic analysis may be analyzed with modified time steps. In this approach, the frequency content of the input data is varied by minimum ±15 percent to account for uncertainties in the analysis of the supporting structure. Variation in the frequency content is done by using the same time history data with at least three different time steps, the initial time step Δt and $\Delta t(1\pm0.15)$. Additional variations of the time step shall be determined based on consideration of the subsystem frequencies and the frequency content of the excitation data.

When time history analysis is performed using this method, a separate analysis is performed for each set of time histories for each of the analysis cases addressed in Section 3.7.2.4.1. The results (e.g., support loads) from the individual analysis cases are then combined to create an enveloping design.

Alternatively, a more conservative approach using a generated synthetic time history may be used as a subsystem forcing function. Time histories are developed to match the enveloped response spectra in accordance with SRP 3.7.1, SAC-1B. This method is not used for U.S. EPR design of subsystems supported at multiple points and having different ISRS. This approach conservatively accounts for uncertainties in the structure frequencies if the response spectra computed from the synthetic time history envelop the broadened ISRS. When this method is used, the additional variation of frequency content is not required because the effects of uncertainties in the supporting structure are included in the broadened ISRS.

Damping values and procedures are addressed in Section 3.7.3.5.

The total response of the subsystems due to excitation in three directions is calculated by methods described in Section 3.7.3.6.

3.7.3.1.3 Inelastic Analysis Methods

Inelastic analysis is not used to qualify seismic subsystems for the U.S. EPR standard plant.

3.7.3.1.4 Equivalent Static Load Method

An alternate method of analyzing the effects of the SSE on a subsystem is to use an equivalent static load method. This simplified analysis considers the mass of

subsystem components as lumped masses at their center of gravity locations. The seismic response forces from these masses are then statically determined by multiplying the contributing mass by an appropriate seismic acceleration coefficient. The seismic acceleration coefficient is determined from response spectrum based on the system natural frequency. When the equivalent static load method is used, justification is provided that the use of a simplified model is realistic and the results are conservative. Additionally, relative motion between all points of support, where determined to be significant, are considered in the analysis. Maximum relative support displacements may be determined using conventional static analysis methods and then imposed in the most unfavorable combination. Every support is considered active in the analysis.

In general, many subsystems, and especially distribution subsystems, are multiple degree-of-freedom systems and have a number of significant modal frequencies in the amplified region of the response spectrum curve below the zero period acceleration (ZPA). For these systems, the peak response system may be conservatively used. When the subsystem frequency is not determined analytically, or is determined to be equal to or less than the peak frequency of the appropriate ISRS, the seismic acceleration coefficient is taken as the peak acceleration of the ISRS.

Alternatively, the frequency determination method may be used when the subsystem frequency is greater than the peak frequency of the appropriate ISRS. In the frequency determination method, the subsystem frequency is greater than the peak frequency and the corresponding seismic acceleration is less than the ISRS peak acceleration. For ISRS with multiple peaks, the seismic acceleration coefficient shall not be less than the accelerations corresponding to subsequent ISRS peaks at frequencies higher than the subsystem frequency, as all subsequent modes will have higher frequencies and lower seismic acceleration coefficients.

The seismic acceleration coefficient, from both the peak response method and the frequency determination method is multiplied by a multi-mode factor of 1.5 to account for multi-modal participation. Single-degree-of-freedom (SDOF) systems with a known fundamental frequency or rigid systems with fundamental frequency beyond the cutoff frequency may use a factor of 1.0 with the highest spectral acceleration at that frequency or any subsequent higher frequency (as may be the case for multiple peak input spectra).

This analysis is performed for the three directions of seismic input motion. The results of these three analyses are combined as described in Section 3.7.3.6.

3.7.3.2 Determination of Number of Earthquake Cycles

Criteria are established for the evaluation of distribution subsystems and for mechanical and electrical equipment for the effects of seismic-induced fatigue when

fatigue is expected to have a significant effect on the design. Because the U.S. EPR design does not consider OBE load cases, the effects of seismic-induced fatigue are evaluated in accordance with SECY 93-087 (Reference 5) and SRP 3.7.3 of NUREG-0800 (Reference 6).

Seismic-induced fatigue of piping systems is described in the AREVA NP Topical Report ANP-10264NP-A (Reference 1). The consideration of low-level seismic effects (i.e., fatigue) is required by IEEE Std 344-2004[1] (Reference 7) to qualify electrical and mechanical equipment with the equivalent of five OBE events followed by one SSE event (with 10 maximum stress cycles per event). This consideration includes the seismic qualification process based on the approach provided in Reference 5 and outlined in SRP 3.10.III.3.C of Reference 6. To meet this requirement, earthquake cycles included in the fatigue analysis are composed of five one-half SSE events followed by one full SSE event. A number of fractional peak cycles equivalent to the maximum peak cycles for five one-half SSE events may be used in accordance with Appendix D of Reference 7 when followed by one full SSE event. This approach results in consideration of fractional peak cycles.

The effects of seismic-induced fatigue on distributed subsystems other than piping and electrical and mechanical equipment are evaluated, and when determined as appropriate the effects are evaluated using the same guidance from Reference 5 and SRP 3.7.3 of Reference 6 for piping systems. To meet this requirement, earthquake cycles included in the fatigue analysis are composed of two SSE events, with 10 maximum stress-cycles each, for a total of 20 full cycles. This is considered equivalent to the cyclic load basis of one SSE and five OBEs. Alternatively, the methods of Appendix D of Reference 7 may be used to determine a number of fractional vibratory cycles equivalent to 20 full SSE cycles. When this method is used, the amplitude of the vibration is taken as one-third of the amplitude of the SSE resulting in 300 fractional SSE cycles to be considered.

3.7.3.3 Procedures Used for Analytical Modeling

For dynamic analysis, the subsystem is idealized as a three dimensional framework using specialized finite element analysis programs. The analysis model consists of a sequence of nodes connected by beam elements with stiffness properties representing the subsystem components. Nodes are typically modeled at points required to define the subsystem geometry as well as lumped mass locations, support locations, and locations of structural or load discontinuities. Subsystem supports are idealized as springs with appropriate stiffness values.

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1. Section 3.11 provides the justification for the use of the latest version of the IEEE standards referenced in this section that have not been endorsed by existing Regulatory Guides. AREVA NP maintains the option to use current NRC-endorsed versions of the IEEE standards.

In the dynamic mathematical model, the distributed mass of the subsystem is represented either as a consistent (i.e., distributed) mass or as lumped masses placed at each node. For the latter case, in order to adequately determine the dynamic response of the system, elements may be subdivided and additional mass points added. The minimum number of degrees-of-freedom in the model is equal to twice the number of modes with frequencies below the ZPA frequency.

For equipment, components, and subsystems other than piping, the seismic analysis also requires the development of a model representative of the dynamic properties of the particular system. For simple systems, a single-mass model may be sufficient with the mass lumped at the center of mass of the system. Otherwise, a multiple-mass model is developed by concentrating the mass of the system at a sufficient number of locations including locations where mass concentration or a drastic change in stiffness or orientation occurs, and by connecting the lumped masses with beam elements or spring elements. In lieu of a lumped multiple-mass model, a finite element model may also be used for the seismic analysis of the system. Dynamic properties of the supporting structural elements such as floor slab, roof slab, walls, miscellaneous steel platforms, and framing on which the system is attached, are included in the analysis model of the system unless:

- Such structural element may be demonstrated to be dynamically rigid.
- The particular floor slab, roof slab, or wall is dynamically flexible but an amplified ISRS that accounts for both the mass of the system and the flexibility of the floor slab, roof slab, or wall is available.

When developing the dynamic model of such structural elements (i.e., floor slab, roof slab, wall, miscellaneous steel platform, or framing) supporting the system, masses equal to 25 percent of the floor live load or 75 percent of the roof snow load, whichever is applicable, and miscellaneous dead loads of at least 50 psf, are included.

In most cases, the subsystems, equipment, and components are analyzed (or tested) as a decoupled system from the primary structure. For the decoupling of the subsystem and the supporting system, the following criteria are used:

- If $R_m < 0.01$, decoupling can be done for any R_f. Mass of the subsystem is considered in the supporting system model through uniformly distributed load.
- If $0.01 \leq R_m \leq 0.1$, decoupling can be done if $R_f \leq 0.8$ or $R_f \geq 1.25$. When $R_f \geq 1.25$, mass of the subsystem is included in the supporting system model. When $R_f \leq 0.8$, mass of the subsystem is not included in the supporting system model.
- If $R_m > 0.1$ or if $0.01 \leq R_m \leq 0.1$ and $0.8 < R_f < 1.25$, an approximate model of the subsystem should be included in the primary system model.

Where:

R_m and R_f are defined as:

R_m = Ratio of total mass of the supported subsystem to total mass of the supporting system.

R_f = Ratio of fundamental frequency of the supported subsystem to dominant frequency of the support motion.

Seismic input for the subsystem and component design are the peak-broadened ISRS envelopes described in Section 3.7.2.5 or the floor acceleration time histories described in Section 3.7.2.4. Where amplified ISRS for the flexible slabs or walls are not available, they are generated and enveloped according to the methodology described in Section 3.7.2.5.

When subsystems and components are attached to flexible floors or walls, an alternative approach to using the decoupling criteria is to include the effect of system-subsystem interaction (see Reference 9). This method is based on a dynamic substructuring concept in which the dynamic interaction between the subsystem and the supporting structural system is characterized by using the subsystem support impedance function and the input motion at the support location without the presence of the subsystem. Using this method, ISRS considering system-subsystem interaction can be established rigorously in terms of damping values and tributary masses of the subsystems.

In general, three-dimensional models are used for seismic analysis. In structures, six degrees-of-freedom exist for mass points (i.e., three translational and three rotational). In most structures, some of the dynamic degrees-of-freedom can be neglected or can be uncoupled from each other so that separate analyses can be performed for different types of motions.

Concentrated weights are also modeled as lumped masses. Torsional effects of eccentric masses are included in the analysis. For rigid components (i.e., those with natural frequencies greater than the ZPA cutoff frequency), the lumped mass is modeled at the center of gravity of the component with a rigid link to the subsystem centerline. Flexible components (i.e., those with natural frequencies less than the ZPA cutoff frequency) are included in the model using beam elements and lumped mass locations to represent the dynamic response of the component.

3.7.3.4 Basis for Selection of Frequencies

The modes having frequencies above the ZPA are included in the modal analysis to establish that the principal response of the subsystem is computed. The residual rigid response due to the missing mass effect is calculated as described in Section 3.7.3.7. It is considered sufficient to include enough modes to confirm that inclusion of the

remaining modes does not result in more than a 10 percent increase in total responses of interest.

For the analysis and design of subsystems for the U.S. EPR, seismic effects due to coupling with the building are accounted for either by the use of ISRS from the uncoupled building analysis as input to the subsystem, or by a coupled analysis of the building and equipment. Certain components are designed to be rigid to minimize their seismic response by establishing that their first fundamental natural frequency exceeds 40 Hz. For some situations in which resonance with the supporting structure is well defined, the design avoids a resonance situation by establishing that the fundamental frequencies of the subsystem are outside a band defined by one-half and twice the fundamental frequencies of the supporting structure.

3.7.3.5 Analysis Procedure for Damping

Damping values used in seismic analyses of subsystems are presented in Section 3.7.1.3 and are dependent on the seismic analysis method used. Damping values for the SSE used for different types of analysis are provided in Table 3.7.1-1. For subsystems that are composed of different material types, composite modal damping using either the weighted stiffness method or the weighted mass method is used as described below. Composite modal damping is also used when subsystems and non-simple module steel frames are used in a single coupled model. The minimum damping value may conservatively be used for these systems.

For subsystems that consist of substructures with different damping properties, the composite global damping matrix, [C], may be obtained by appropriate superposition of damping matrices for individual substructures as:

$$[C] = \sum_{i=1}^{NS} [C]_i$$

Where:

$[C]_i =$ Damping matrix for the ith substructure in the global coordinate system.

$NS =$ Number of substructures being assembled.

The damping matrix for each substructure modeled by proportional damping coefficients is then calculated as:

$$[C]_i = \alpha_i [M]_i + \beta_i [K]_i$$

Where:

α_i and β_i = proportional damping coefficients for the ith part of the substructure

$[M]_i$ = mass matrix for i^{th} part of the structure in the global coordinate system

$[K]_i$ = stiffness matrix for the ith part of the structure in the global coordinate system.

The proportional damping coefficients for the ith part of the substructure, α_i and β_i, should be evaluated using the damping ratio value for that part of the substructure and the ω_{max} and ω_{min} system frequencies selected to define the range of frequencies that contribute to the response of the ith part. For subsystems of which the composite damping matrix has been calculated, as previously described, the modal damping values are obtained from the following equation:

$$\lambda_j = \frac{\{\phi_j\}^T [C] \{\phi_j\}}{2\omega_j}$$

Where:

λ_j = damping ratio of the jth mode

$\{\phi_j\}$ = j^{th} mode shape, where $\{\phi_j\}^T [M] \{\phi\} = 1$

ω_j = circular frequency of the jth mode (rad/s)

$[M]$ = mass matrix.

For subsystems that consist of major substructures or components with different damping characteristics, composite modal damping values are determined using either the stiffness-weighted or mass-weighted approaches of Reference 4. Composite modal damping values are limited to less than 20 percent of critical, unless additional justification is provided to support the use of higher values. The following methods are used with either response spectrum or time history methods of analysis.

The two approaches for determining composite modal damping values are stiffness weighted damping and mass-weighted damping.

Stiffness-Weighted Damping

$$\lambda_j = \frac{\{\varnothing\}^T \left[\sum_{i=1}^{N} [\lambda K]_i \right] \{\varnothing\}}{\omega_j^{\,2}}$$

Where:

λ_j = damping ratio of the *j*th mode

$\{\phi_j\}$ = *j*th mode shape, where $\{\phi_j\}^T [M] \{\phi_j\} = 1$

ω_j = circular frequency of *j*th mode (rad/s)

$[M]$ = mass matrix

$[\lambda K]_i$ = stiffness matrix for the *i*th element or subsystem in the global coordinate system, scaled by the modal damping ratio of the *i*th element.

Mass-Weighted Damping

$$\lambda_j = \{\phi_j\}^T \left[\sum_{i=1}^{N} [\lambda M]_i \right] \{\phi\}$$

Where:

$[\lambda M]_i$ =mass matrix for the *i*th element or subsystem in the global coordinate system, scaled by the modal damping ratio of the *i*th element.

At degrees-of-freedom that are common to more than one substructure, masses are divided between the substructures in proportion to the tributary masses from each substructure.

3.7.3.6 Three Components of Earthquake Motion

Following the modal combination of results, the responses of the subsystem due to each of the three orthogonal earthquake motion inputs are combined. The collinear responses due to each of the input components of motion are combined using the SRSS method of RG 1.92.

Response Spectrum Method

The seismic loads from all three components of the earthquake are combined using the SRSS method as follows:

$$R = \pm\sqrt{\sum_i R_I^{\,2}}$$

Where:

R = any response of interest

R_I = 1, 2 and 3 is the response component for each of the two horizontal components and one vertical component of earthquake motion, respectively.

Time History Method

In a linear time history analysis, the analysis may be performed separately for each of the three components of earthquake motion, or one analysis may be performed by applying all three components simultaneously if the three components of earthquake motion are statistically independent in accordance with Section 3.7.1.2. When linear time history analyses are performed separately for each component, the combined response for all three components may be obtained using the SRSS rule to combine the maximum responses from each earthquake component, as illustrated above.

When the seismic analysis is performed using simultaneous application of the time history input, the responses may be obtained individually for each of the three independent components and combined algebraically at each time step to obtain the combined response time history:

$$R(t) = \sum R_i(t)$$

Equivalent Static Load Method

The seismic loads from the three components of the earthquake motion are combined using the SRSS method.

3.7.3.7 Combination of Modal Responses

The inertial response of a distribution subsystem in a seismic response spectrum analysis is considered in two parts: low frequency mode and high frequency mode. The modal analysis calculates the peak response of the distribution subsystem for natural frequencies of the system below a defined cutoff frequency. The low frequency (or non-rigid) modes consist of every mode with seismic excitation

frequencies up to the frequency at which spectral accelerations return to the ZPA. For seismic analysis of the U.S. EPR standard plant, this frequency, the ZPA cutoff frequency, is about 40 Hz, as shown in Figure 3.7.1-1. Higher ZPA cutoff frequencies may be required for other dynamic load cases.

At modal frequencies above the ZPA cutoff frequency, distribution subsystem members are considered rigid. The acceleration associated with these rigid modes is usually small. However, in certain situations the response to high frequency modes can significantly affect support loads, particularly axial restraints on long distribution system runs. To account for these effects, a missing mass correction is applied.

3.7.3.7.1 Low Frequency (Non-Rigid) Modes

RG 1.92, Revision 2, provides guidance on combining the individual modal results of a response spectrum analysis for structure supported at a single point and for multiply supported structures analyzed using the USM method. Guidance for modal combinations for the ISM method including the missing mass effects is provided in NUREG-1061, Volume 4. (Reference 8).

The combination method used considers the effects of closely spaced modes. Modes are defined as being closely spaced if their frequencies differ from each other by 10 percent or less of the lower frequency.

For subsystems analyzed using the USM method and with no closely spaced modes, the SRSS method is applied to obtain the representative maximum response of each element, as shown in the following equation:

$$R = \left[\sum_{k=1}^{N} R_k^2 \right]^{\frac{1}{2}}$$

Where:

R = the representative maximum response due to earthquake motion in one direction. (This calculation is performed in each of the earthquake directions.)

R_k = the peak response due to the kth mode

N = the number of low frequency modes.

If modes with closely spaced frequencies exist, the SRSS method is not applicable, and one of the two methods presented in C.1.1.2 and C.1.1.3 of RG1.92, Revision 2 should be used instead.

The more conservative methods of the combining modal responses as described in RG 1.92, Revision 1 remain acceptable; however, when using the Revision 1 methods, the residual response provisions of Revision 2 for treatment of the missing mass modes (as discussed in C.1.4.1 and C.1.5.1 of RG 1.92, Revision 2) shall be implemented.

3.7.3.7.2 High Frequency (Rigid) Modes

Modes with frequencies greater than the ZPA cutoff frequency are considered as high frequency, or rigid range, modes. For flexible subsystems, the high frequency response may not be significant since a significant portion of the system mass is excited at frequencies below the ZPA. For subsystems, portions of subsystems that are more rigidly restrained or have lumped masses near rigid restraints, a significant portion of the system mass may not be accounted for in the low frequency modal analysis. This mass which is not excited at the lower frequencies is termed the missing-mass of the system. While high frequency modes usually involve small displacement amplitudes and small stresses, they can have a significant impact on support loads.

The response from high frequency modes must be included in the response of the subsystem. Guidance for including the missing mass effects is provided in SRP Section 3.7.3 of Reference 6, RG 1.92 for subsystems supported at a single point and for multiply supported subsystems analyzed by USM. Guidance for subsystems analyzed by ISM is provided in Reference 8, Volume 4.

The peak modal responses of the system at frequencies above the ZPA are considered to be in phase. For subsystems supported at a single point and for multiply support subsystems analyzed by either USM or ISM methods of analysis, the responses of high frequency modes are combined by algebraic summation.

The U.S. EPR design calculates the response of the high frequency modes by including a missing mass correction.

The total inertia forces in a subsystem under simple excitation in a steady-state condition with unit acceleration applied in a specified direction is mathematically represented by the following expression.

$$\{F_1\} = [M]\{r\}\ddot{u}g$$

Where:

$\{F_1\}$ = total inertia forces in the specified direction

$[M]$ = mass matrix

$\{r\}$ = mass point displacement vector produced by a statically applied unit ground displacement.

$\ddot{u}g$ = ground acceleration

The sum of the inertia forces for each mode included in the modal analysis is calculated as:

$$\{F_s\} = \sum_{n=1}^{N} \{F_n\} = \sum_{n=1}^{N} [M]\left[\{\phi_n\}\{\phi_n\}^T [M]\{r\}\right]\ddot{u}g$$

Where:

$\{F_s\}$ = total inertia force seen by the system in the low frequency modal analysis

$\{F_n\}$ = inertia force of mode n

$\{\phi_n\}$ = mode shape

N = number of modes calculated in the modal analysis.

Therefore, the missing forces considering unit ground acceleration in a specified direction are calculated as:

$$\{F_m\} = \{F_t\} - \{F_s\} = [M]\{r\}\ddot{u}g - \sum_{n=1}^{N} [M]\{\phi_n\}\{\phi_n\}^T [M]\{r\}\ddot{u}g$$

or:

$$\{F_m\} = [M]\{r\}\ddot{u}g\left[1 - \sum_{n=1}^{N} [M]\{\phi_n\}\{\phi_n\}^T\right]$$

The missing inertia forces are calculated independently for all input components of earthquake motion (i.e., in each direction for each support group). The mode displacements, member end action, and support force corresponding to each missing force vector are determined.

For subsystems supported at a single point or for multiple supported systems analyzed by the USM method, these results are treated as an additional modal result in the response spectra analysis. This missing mass mode is considered to have a modal frequency and acceleration defined at the cut-off frequency used in the modal analysis. These modal results are combined with the low frequency modal results using the methods described in Section 3.7.3.7.1.

For multiply supported systems analyzed using ISM, the rigid range (missing mass) results will be combined with the low frequency modal results by SRSS, per Reference 8, Volume 4. All of the provisions of Reference 8 for the ISM method of

analysis will be followed. For ISM, the responses in the rigid range are considered in phase and combined by algebraic summation and the total rigid response will then be combined with the modal results by SRSS.

3.7.3.8 Interaction of Non-Seismic Category I Subsystems

The U.S. EPR uses state-of-the-art computer modeling tools for design and location of structures, subsystems, equipment, and piping. These same tools are used to minimize interactions of Seismic Category I and non-Seismic Category I components, making it possible to protect Seismic Category I subsystems from adverse interactions with non-Seismic Category I subsystem components. If any part of Seismic Category I subsystem lies within the impact zone of a non-Seismic Category I subsystem component, one of the following methods is used to prevent the Seismic Category I subsystem from losing functionality as a result of impact from the non-Seismic Category I component during the SSE event.

1. The two components are isolated from one another so that interaction does not occur.

2. The Seismic Category I subsystem is analyzed to confirm that its safety function is not lost as a result of impact from a non-Seismic Category I component during the SSE event. An impact analysis assumes the non-Seismic Category I component falls from a static state and impacts the Seismic Category I component concurrent with SSE loading. Impact loads are determined in accordance with SRP 3.5.3.II.2 and locally added to the analyzed stress of the Seismic Category I subsystem for load combinations that include seismic. Code allowables for the Seismic Category I subsystem with the additional impact load shall not be exceeded. This method shall not be used for vibratory sensitive Seismic Category I subsystems. Isolation or application of a restraint system shall be used for vibratory sensitive Seismic Category I subsystems.

3. A restraint system is used to verify that no interaction occurs between the Seismic Category I subsystem and the non-Seismic Category I subsystem. The restraint system is designed to Seismic Category I standards and qualifications and is classified as Seismic Category II. Examples of restraint systems are barriers, lanyards, or shields.

For non-Seismic Category I subsystems attached to Seismic Category I subsystems, the dynamic effects of the non-Seismic Category I subsystem are accounted for in the modeling of the Seismic Category I subsystem. The attached non-Seismic Category I subsystem is classified as Seismic Category II and is designed to not cause failure of the Seismic Category I subsystem during a seismic event. Section 3.7.3.3 describes decoupling criteria used to determine if the flexibility of the non-Seismic Category I subsystem is included in the subsystem model.

Seismic Category I subsystem design requirements extend to the first seismic restraint beyond the system boundary with non-Seismic Category I subsystems. In addition, the following requirements must be met:

- If the first seismic restraint beyond the Seismic Category I subsystem boundary is an anchor restraining the Category I subsystem in the six degrees of freedom, the analysis model includes the Category I system and any extended portion of the system which is Category II up to the anchor defining the analysis boundary. The subsystem components within the analysis boundary will be designed to Seismic Category I requirements. Loads from the non-Seismic Category I subsystem will be developed as described in Section 5.5 of Reference 1.

- If the first seismic restraint cannot be an anchor, the non-Seismic Category I subsystem and supports beyond this location that affect the Seismic Category I subsystem dynamic analysis are classified Seismic Category II, included in the model, and designed to the same requirements as Seismic Category I components. Loads from the non-Seismic Category I subsystem will be developed as described in Section 5.5 of Reference 1.

Boundary conditions of the model at the Seismic Category I to non-Seismic Category I interface are described in Section 5.5 of Reference 1.

3.7.3.8.1 Isolation of Seismic Category I and Non-Seismic Category I Subsystems

Isolation of Seismic Category I and non-Seismic Category I subsystems is provided by geographical separation. Isolation eliminates the interaction effects that must be considered for a Seismic Category I subsystem and minimizes the overall number of impact analyses performed and restraint systems needed to prevent interaction.

Several routing considerations are used to isolate Seismic Category I and non-Seismic Category I subsystems. When possible, non-Seismic Category I SSC are not routed in rooms containing safety-related SSC. If a non-Seismic Category I SSC can not be completely separated from Seismic Category I SSC, then the non-Seismic Category I SSC must be restrained or an analysis must be performed to verify that the functionality of the Seismic Category I SSC is maintained if impacted by the non-Seismic Category I component during a seismic event.

3.7.3.8.2 Interaction Evaluation

Unrestrained, non-Seismic Category I SSC may be located in the vicinity of safety-related SSC provided an impact evaluation is performed and it is determined that functionality of the safety-related SSC is not lost as a result of impact. In this evaluation, the non-Seismic Category I components are assumed to fall or overturn as a result of a seismic event. Any safety-related subsystem or component which may be impacted by the non-Seismic Category I component is identified as an interaction target and is evaluated to establish that there is no loss of ability to perform its safety-related function.

The following assumptions and guidelines are used to evaluate non-Seismic Category I and Seismic Category I interactions, resulting from an SSE seismic event:

- The non-Seismic Category I subsystem or component (source) is assumed to fail instantaneously at every connection allowing each section to fall or overturn independently.

- The fall trajectory of the source is evaluated for potential impacts. Impact is assumed for non-Seismic Category I subsystem or components within an impact evaluation zone around the safety-related system or component. If the falling or overturning source is outside of the impact zone, no interaction occurs. Otherwise, the falling source could potentially impact the target.

  The impact zone is defined by the volume extending in such a way that it is wholly or partially within a 15-degree angle from the vertical extending from each side of the Seismic Category I subsystem or component. The impact evaluation zone does not need to extend beyond Seismic Category I structures (e.g., walls or slabs).

- The parameters of the target are evaluated to determine if it has significant structural integrity to withstand impact without loss of ability to perform its safety-related function.

- The energy of the source impacting the target is evaluated to determine if the energy level is low enough not to cause adverse impact on the target.

  Unrestrained, non-Seismic Category I SSC located in the vicinity of safety-related SSC is acceptable if an analysis demonstrates that the weight and configuration of the non-Seismic Category I SSC, relative to the target, and the trajectory of the falling non-seismic SSC interaction do not cause unacceptable damage to the safety-related SSC. Otherwise, the non-Seismic Category I SSC present a hazard, and are relocated or restrained.

3.7.3.9 Multiply-Supported Equipment and Components with Distinct Inputs

The criteria presented are primarily applicable to distribution subsystems that span between multiple locations within a structure or between locations in different structures and, as a result, experience non-uniform support motion. Two conventional methods are presented: the uniform support motion (USM) method and the independent support motion (ISM) method. For both methods: relative displacements at the support points are considered and determined by conventional static analyses, or conservatively approximated from floor response spectra. When displacements are determined from floor response spectra, the maximum displacement is predicted by the following relationship:

$$S_d = \frac{S_a g}{\omega^2}$$

Where:

S_d = maximum displacement at each support.

S_a = spectral acceleration in "g's" at the ZPA cutoff frequency.

ω = fundamental frequency of the building (rad/sec).

The support displacements are imposed on the subsystems in the most unfavorable combination. The responses due to support displacements are combined with inertial responses as described in Sections 3.7.3.9.1 or 3.7.3.9.2.

3.7.3.9.1 Uniform Support Motion Method

Distribution subsystems supported at multiple elevations within one or more buildings may be analyzed using the USM method. This analysis method applies a single spectrum, called a uniform response spectrum, at each support location. This spectrum envelops the individual response spectra for other locations. The enveloping response spectrum is developed and applied for each of the three orthogonal directions of input motion. The modal and directional responses are then combined as described in Sections 3.7.3.7 and 3.7.3.6, respectively. The responses due to relative displacements at the support points are combined with the inertial responses by the absolute sum method.

3.7.3.9.2 Independent Support Motion Method

Distribution subsystems supported at multiple locations within one or more buildings with different seismic input response maybe analyzed using the ISM method. In this method of analysis, supports may be divided into support groups. A single ISRS is applied to all supports of each group, but different ISRS are applied to different groups. Typically, a support group is made up of supports attached to the same structure, floor, or portion of a floor. For distribution subsystems analyzed using the ISM method, criteria presented in NUREG-1061 (Reference 8) are followed.

In lieu of performing a response spectrum analysis with USM or ISM inputs, time histories of support motions may be utilized as input excitations. The responses due to relative displacements at the support points are combined with the inertial responses by the SRSS method.

3.7.3.10 Use of Equivalent Vertical Static Factors

Equivalent vertical static factors are not used in the design of subsystems for the U.S. EPR design. Seismic loads are calculated assuming that the vertical seismic motion occurs simultaneously with the two horizontal motions.

3.7.3.11 Torsional Effects of Eccentric Masses

Torsional effects due to the effect of eccentric masses connected to a subsystem are included in that subsystem analysis. For rigid components (i.e., those with natural frequencies greater than the ZPA cutoff frequency of 40 Hz), the lumped mass is modeled at the center of gravity of the component with a rigid link to the subsystem member centerline. For flexible components having a frequency less than the ZPA, the subsystem model is expanded to include an appropriate model of the component.

3.7.3.12 Buried Seismic Category I Piping and Conduits

Seismic Category I buried pipe and electrical conduit bank are used in the U.S. EPR design. Examples of such utilities include pipe encased in concrete box, electrical conduit bank, pipe encased in another pipe, and pipes buried in the soil. In some cases, these structural components are anchored to adjacent buildings. Some of these underground utilities are classified as safety-related since seismic and other loads could adversely affect their function. Based on observations of past earthquakes, seismic-induced damage to buried utilities is largely due to wave propagation or permanent ground deformation resulting from fault movement, landslide, and liquefaction-induced lateral spread. Other forms of damage include seismic-induced settlement due to soil compaction and rearrangement. For the case of utilities anchored to an adjacent building, strain development in the utility due to settlement of the building requires evaluation.

Methods for seismic analysis and design of safety-related pipe buried in soil are presented in Section 3.10 of Reference 1.

The seismic design of buried utilities other than piping buried in soil, is in accordance with ASCE Report, "Seismic Response of Buried Pipes and Structural Components" (Reference 3). Axial and bending strain in buried utilities due to propagation of compression, shear, and surface waves is considered. It is assumed that there is no relative motion between the utility and soil so that wave-induced strain in the surrounding soil is equally transmitted to the utility. Based on the axial and bending strains developed in the buried utility, the corresponding axial load and bending stress can be computed.

Concrete components of buried utilities are designed to satisfy requirements of ACI 349 (Reference 10). Tensile strains, ε_t, in pipes made of carbon steel and stainless steel shall be limited to one percent and two percent of the pipe diameter, respectively. To eliminate compressive wrinkling of the pipe, the allowable axial strain is computed. These strain limits apply to both encased pipes and pipes surrounded by soil. For the case of pipes anchored to a building with potential for ground settlement, total allowable strain limit, ε_a, is limited to four percent of the pipe diameter in addition to satisfying the axial strain limit.

Section 3.8.4.1.8 describes requirements placed on the COL applicants to provide a description of Seismic Category I buried conduit and duct banks.

3.7.3.13 Methods for Seismic Analysis of Category I Concrete Dams

There are no Seismic Category I concrete dams in the U.S. EPR design. A COL applicant that references the U. S. EPR design certification will provide a description of methods used for seismic analysis of site-specific Category I concrete dams, if applicable.

3.7.3.14 Methods for Seismic Analysis of Aboveground Tanks

Dynamic pressure on fluid containers in the in-containment refueling water storage tank (IRWST), spent fuel pool, and other fluid reservoirs due to the SSE are considered in accordance with ASCE 4-98 (Reference 4). Section 3.7.1.2 presents damping values for seismic analysis of aboveground tanks. Damping values for concrete aboveground tanks are seven percent of critical for impulsive modes and 0.5 percent for sloshing mode. These damping values are taken from Table 3.7.1-1.

Seismic analyses of concrete above-ground tanks consider impulsive and convective forces of the water, as well as the flexibility of the tank walls and floor, and ceiling of the tank. For the spent fuel pool, cask loading pit, cask washdown pit, and fuel transfer canal, the impulsive loads are calculated by considering a portion of the water mass responding with the concrete walls (see Section 3.7.2.3). Impulsive forces are calculated by conventional methods for tanks determined to be rigid. For non-rigid tanks, the effect of tank flexibility on spectral acceleration is included when determining the hydrodynamic pressure on the tank wall for the impulsive mode.

Convective forces resulting from the sloshing of water are calculated based on the natural frequency of the sloshing water. The natural frequency is used with the 0.5 percent damping curve to determine the spectral acceleration. Guidance from USAEC TID-7024 is used to calculate the forces which are applied as pressures and used in the design of the tank structure.

The IRWST is analyzed using finite element methods by including it in the 3D FEM model of the internal structures described in Section 3.7.2 and detailed in Section 3.8.3.

3.7.3.15 References

1. ANP-10264NP-A, Revision 0, "U.S. EPR Piping Analysis and Support Design Topical Report," AREVA NP Inc., November 2008.

2. Deleted.

3. ASCE "Seismic Response of Buried Pipe and Structural Components," ASCE Committee on Seismic Analysis of Nuclear Structures and Material, American Society of Civil Engineers, 1983.

4. ASCE Standard 4-98, "Seismic Analysis of Safety-Related Nuclear Structures and Commentary," American Society of Civil Engineers, September 1986.

5. SECY-93-087, "Policy, Technical, and Licensing Issues Pertaining to Evolutionary and Advanced Light-Water (ALWR) Designs," U.S. Nuclear Regulatory Commission, July 1993.

6. NUREG-0800, "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants," U.S. Nuclear Regulatory Commission, March 2007.

7. IEEE 344-2004, "Recommended Practices for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations," Institute of Electrical and Electronics Engineers, 2004.

8. NUREG-1061, "Report of the U.S. Nuclear Regulatory Commission Piping Review Committee," U.S. Nuclear Regulatory Commission, (Vol. 1) August 1984, (Vol. 2) April 1985, (Vol. 3) November 1984, (Vol. 4) December 1984, (Vol. 5) April 1985.

9. W.S. Tseng, "Equipment Response Spectra Including Equipment–Structure Interaction Effects," 1989 Pressure Vessel and Piping Conference, ASME PVP, Volume 155.

10. ACI 349-01/349R-01, Appendix C, "Code Requirements for Nuclear Safety Related Concrete Structures and Commentary," American Concrete Institute, January 2001.

11. USAEC TID-7024, "Nuclear Reactors and Earthquakes," U.S. Atomic Energy Commission, August 1963.

12. ASME Boiler and Pressure Vessel Code, Section III, "Rules for Construction of Nuclear Facility Components," American Society of Mechanical Engineers, 2004.

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