9.14.2
NUCLEAR PUMP SEISMIC QUALIFICATIONS

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Nuclear electric generating stations and their components shall be designed to resist the dynamic forces that could result from an earthquake at the site. This subsection covers the seismic qualification requirements for pumps classified according to function and importance based on safe operation and public safety.

SEISMIC CLASSIFICATION OF PUMPS

Pumps that must withstand a safe shutdown earthquake (SSE) and remain functional during and after such an event are designated seismic Category I. Pumps that are not required to remain functional during SSE are designated nonseismic Category I and may be classified as follows:

- Nonseismic Category I pumps are located so their failure or structural deformation might keep a seismic Category I piece of equipment or system from performing its intended function. The analysis methods and seismic input used on nonseismic Category I pumps to show that gross failure or excessive deformations will not occur are identical to those used for seismic Category I equipment.
- Nonseismic Category I pumps are located so their failure or structural deformation cannot affect any seismic Category I system or component. Seismic-related requirements for these pumps, if any, are established using a less stringent seismic environment with the aim of minimizing possible replacement expenses following a credible event.

DEFINITIONS

Critical Damping This is the minimum damping for which a vibrating system has no vibratory motion. For analysis purposes, damping is expressed as a percentage of critical damping. The amplification of input motion, or magnitude of response, is inversely proportional to the damping ratio of the vibrating system. Figure 1 shows responses obtained for damping ratios which vary from 0.5 to 10% of critical damping.

Damping Damping is the dissipation of energy in a vibrating system. Damping is a function of many factors, including material characteristics, stress levels, and geometric configurations and takes place as a result of the transformation of input energy in the form of seismic motion to heat, sound waves, or other energy forms. For analysis purposes, damping is assumed to be viscious; that is, the damping force is proportional to velocity and acts in the opposite direction.

Degrees of Freedom The degrees of freedom are the coordinate(s) necessary to adequately describe the behavior of a structure or component. A node, or nodal point, may have as many as six degrees of freedom, consisting of three translations and three rotations (such as Δ_x, Δ_y, Δ_z, θ_x,θ_y,θ_z, as shown in Figure 2). This complex representation in

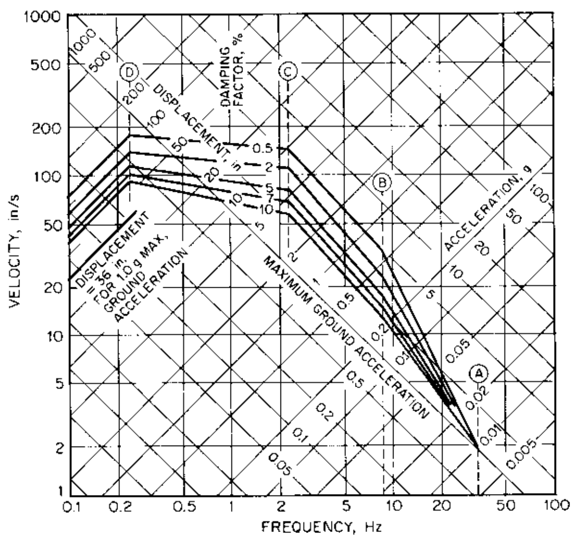

FIGURE 1 Horizontal design response spectra scaled to 1g ground acceleration (1 in = 2.54 cm; g = 32.17 ft/s^2 = 9.807 m/s^2)

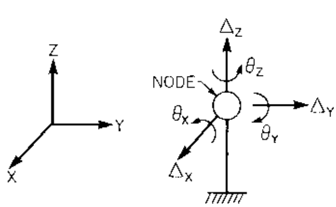

FIGURE 2 Nodal degrees of freedom

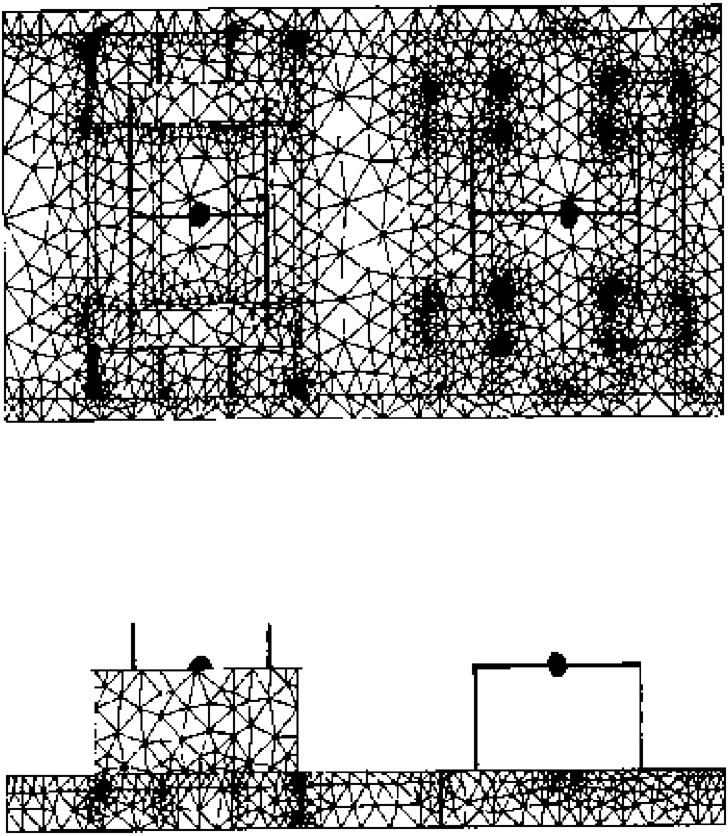

FIGURE 3 Typical FEM mesh of Horizontal Pump/Motor Assembly Pump and motor are modeled as lumped-mass elements whereas bedplate is modeled with shell elements.

terms of degrees of freedom is used when performing static analysis to obtain forces, stresses, or displacements.

Finite Element Method The finite element method of analysis involves the idealization of a structure or component, such as a pump, as an assemblage of elements of finite size. This mathematical model can be a lumped-mass model, a shell element model, a three-dimensional solid model, or a combination of all three. Figures 3 and 4 contain typical shell element models of horizontal and vertical pumps respectively.

Floor Acceleration This is the acceleration at a structural floor or any acceleration applicable at the equipment mounting location.

Ground Acceleration Ground acceleration is the acceleration of the ground associated with earthquake motion.

Modal Analysis Modal analysis is a type of dynamic analysis in which the response of a vibrating system is obtained as a combination of responses of the system's mode shapes. (Specific requirements on the combination of modal responses is contained in U.S. Nuclear

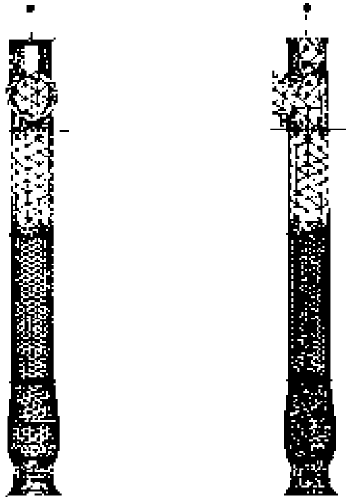

FIGURE 4 Typical FEM mesh of Vertical Circulating Water Pump. The pump is modeled with shell elements while the motor is modeled with lumped-mass elements.

Regulatory Commission Guide 1.92.) Modal analysis may be used in conjunction with a response spectrum or time history analysis.

Natural Frequency The natural frequency is the frequency at which a body vibrates due to its own physical characteristics and to the elastic restoring forces developed when it is displaced in a given direction and then released while restrained or supported at specific points.

Operating Basis Earthquake (BE) An operating basis earthquake is an earthquake that could reasonably be expected to affect a plant site during the operating life of the plant. The systems and components necessary for continued operation of a nuclear plant without undue risk to public health and safety are designed to remain functional when subjected to the vibratory ground motion produced by an operating basis earthquake.

Required Response Spectrum (RRS) The RRS is the response spectrum for which the equipment (pump assembly) has to be dynamically qualified.

Response Spectrum The response spectrum is the plot of the maximum response (acceleration, velocity, displacement) of a series of damped single-degree-of-freedom (SDF) oscillators versus the natural frequencies (or, sometimes, periods) of the oscillators when subjected to the vibratory motion input (time history) at their supports. Figure 5 represents a plot of response spectra obtained for 0, 2, 5, and 10% of critical damping with an earthquake time history as input. The plot is on tripartite log paper, and only a limited number of SDF oscillators are shown (usually, more than 70 are needed to correctly define a spectrum).

In order to facilitate the understanding of how to use the Figure 5 plots, the 0% of critical damping response spectrum is presented in Figure 6. Assuming a SDF oscillator having a frequency of 2 cycles/s (Hz), the maximum displacement of the mass point when subjected to the earthquake record is 7 in (17.8 cm), the maximum velocity is 50 in/s (1.27 m/s), and the maximum acceleration is $2g$, where g = gravitational acceleration = 32.2 ft/s^2 (9.807 m/s^2). A line is drawn perpendicular to the frequency axis, and from the intersection of this line with the spectrum curve, a line parallel to the acceleration lines will

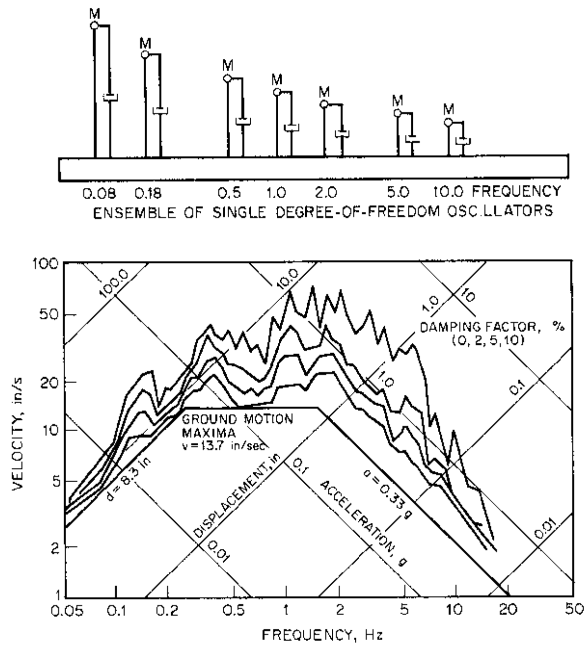

FIGURE 5 Response spectra plots for various dampings (1 in/s = 0.0254 m/s; 1 in = 2.54 cm; 1g = 32.17 ft/s^2 = 9.807 m/s^2)

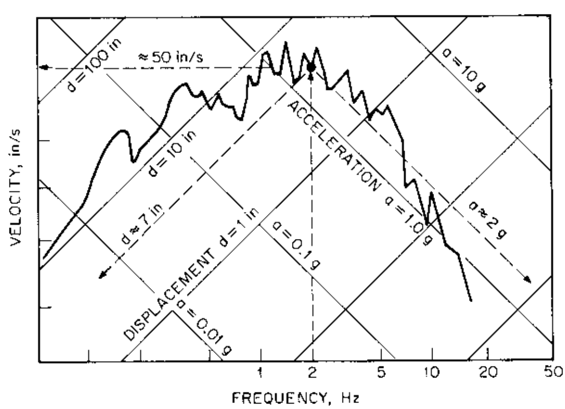

FIGURE 6 Response displacement, velocity, and acceleration versus frequency (1 in/s = 0.0254 m/s; 1 in = 2.54 cm; 1g = 32.17 ft/s^2 = 9.807 m/s^2)

provide the acceleration a $\approx 2g$, a line parallel to the displacement lines will provide the displacement $d \approx 7$ in (17.8 cm), and a line perpendicular to the velocity axis will provide the velocity $v \approx 50$ in/s (1.27 m/s).

In general, response spectra are presented as plots of acceleration versus frequency. Given a time history of acceleration, such as the one presented in Figure 7, the response spectrum is obtained as described previously. The response acceleration at frequencies above

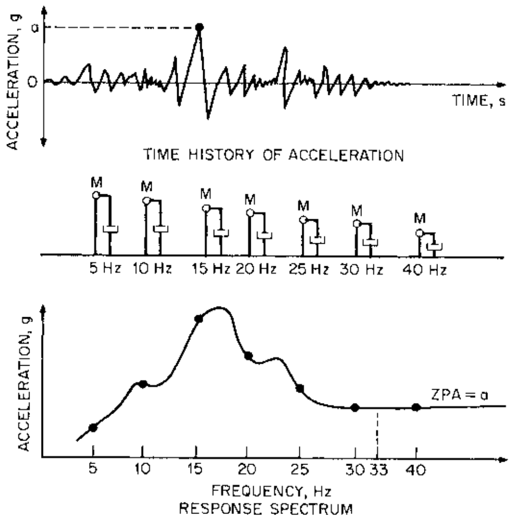

FIGURE 7 Development of acceleration response spectrum (1g = 32.17 ft/s² = 9.807 m/s²)

33 Hz (also called zero period acceleration) is equal to the peak acceleration of the time history record regardless of the damping ratio used (the value a is specified in Figure 7).

Response Spectrum Analysis The response spectrum analysis is a modal dynamic analysis that uses response spectra as vibratory input at the pump attachment points.

Safe Shutdown Earthquake (SSE) An SSE is an earthquake that produces the maximum vibratory ground motion for which certain structures, systems, and components are designed to remain functional. These structures, systems, and components are those necessary to assure (1) the integrity of the reactor coolant pressure boundary, (2) the capability to shut down the reactor and maintain it in a safe shutdown condition, or (3) the capability to prevent or mitigate the consequences of accidents that could result in potential offsite exposures to radioactive material. Various safety classes are assigned to structures, systems, and components as a function of which of these three categories they belong to.

Single-Degree-Of-Freedom Oscillator (SDF) The SDF is a vibrating system consisting of a single node point where the mass is concentrated and supported by a beam and spring element. If the single dynamic degree of freedom is along the axis of the beam, the frequency of the oscillator is

$$f = \frac{1}{2\pi}\sqrt{\frac{K}{M}}$$

where f = frequency, cycles/s or Hz
$K = EA/L$ = spring stiffness, lb/in (N/mm)
E = Young's modulus of elasticity of support beam, lb/in² (Pa)
A = cross-sectional area of support beam, in² (mm²)
L = length of support beam in (mm)
M = mass lb · s²/in (N · s²/mm)

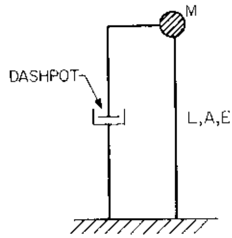

FIGURE 8 Single-degree-of-freedom oscillator

With this idealization, the frequency of the SDF oscillator may be varied by changing the length of the beam element and maintaining *E, A,* and *M* constant (Figure 8). A horizontal degree of freedom would be used in conjunction with beam bending and shearing.

Damping effects are simulated by a dashpot, which can be assigned different damping ratios. Although there is little effect on the frequency of the SDF oscillator when the dashpot is assigned damping ratios below 10 or 15% of critical damping, there is a significant effect when higher values are used. Thus, if the dashpot is assigned 100% of critical damping, the oscillator will behave as a rigid body, duplicating, without amplification, the support input motion.

Test Response Spectrum (TRS) The TRS is a response spectrum that is either theoretically constructed or derived using spectrum analysis based on the actual motion of the shake table (during dynamic testing).

Time History Analysis The time history analysis is an analysis performed in the time domain using time history vibratory input. A direct integration or modal analysis may be performed.

Time History of Acceleration The time history of acceleration is a variation of acceleration as a function of time during the postulated duration of the seismic event.

Zero Period Acceleration (ZPA) The ZPA is a response acceleration at frequencies above 33 Hz.

Although these definitions will facilitate the understanding of the seismic considerations discussed herein, the reader is encouraged to review the works listed at the end of this subsection for a more complete list of terms and definitions used in the process of dynamic qualifications.

SEISMIC QUALIFICATION REQUIREMENTS

The seismic qualification of seismic Category I pumps is performed to demonstrate the ability of the equipment to perform its intended function during and after the time it is subjected to an SSE, which could occur before or after several OBEs. The value of the SSE or OBE response spectra shall be supplied by the equipment buyer (nuclear facility). The simultaneous effects of the seismic accelerations in the two orthogonal horizontal directions and the vertical direction have to be considered.

The seismic qualification can be achieved by

- Analytical methods (static or dynamic analysis)
- Testing the equipment under simulated seismic conditions
- Using a combination of tests and analysis

The information that is provided in the IEEE 344 standard on these qualification methods is applicable to pump assemblies. The information presented hereafter either emphasizes some of the IEEE 344 requirements or is pertinent to pumps and pump assemblies in particular.

Qualification by Analysis The initial step in qualifying a pump assembly by analytical methods is to determine the rigidity of the assembly. If the assembly has its lowest natural frequencies greater than the ZPA frequency, typically 33 Hz, the assembly is considered rigid. On the other hand, if one of its natural frequencies falls below the ZPA, the assembly is considered flexible. Therefore, prior to conducting the qualification analysis, the natural frequency of the pump assembly must be determined by either a modal analysis or an equipment "bump" test. The FEM models as shown in Figures 3 and 4 can be used for the modal analysis.

After the rigidity of the pump assembly has been determined, the type of qualification analysis can be selected. The allowable types of analysis are

- **Static analysis** If it can be shown that the equipment is rigid, a static seismic analysis may be performed to determine the stresses and deformations due to the dynamic seismic loads. The dynamic forces shall be determined by multiplying the mass of the assembly times the maximum floor acceleration (ZPA from the response spectra). These forces are then applied through the center of gravity of the assembly. The resulting stresses from each acceleration force are combined by taking the square root of the sum of the squares (SRSS) to yield the total dynamic stress. The dynamic deflections shall be calculated in the same manner.
- **Simplified dynamic analysis** If it has been determined that the equipment is flexible and the customer specification permits, a simplified dynamic analysis may be completed applying the same method as the static analysis but using different values for the dynamic floor accelerations. The applicable floor acceleration shall be obtained by multiplying the acceleration values corresponding to the fundamental natural frequency from the appropriate response spectra curve by 1.5. If the fundamental natural frequency is not known, the maximum peak value of the response spectras shall be multiplied by 1.5. The 1.5 factor will conservatively account for possible participation of higher modes.
- **Detailed dynamic analysis** When justification for a static analysis cannot be provided, a detailed dynamic analysis is required, unless a conservative factor is used to account for the participation of higher modes (simplified dynamic analysis). A mathematical model of the equipment is required to determine the dynamic behavior of the equipment. This mathematical model may be a lumped-mass model, a shell model (see Figure 4), a solid element model, or a combination such as shown in Figure 3. The model should include, when applicable, the hydrodynamic mass that represents the contained water or the effects of submergence on vertical pumps. This model is then analyzed using either response spectra modal analysis or time-history (modal or step-by-step) analysis. The various modal contributions shall be combined by taking the SRSS of the individual modal stress and deformations.

These dynamic analyses are performed with computer programs in the public domain. Such programs include ANSYS, MSC/NASTRAN, ALGOR, and COSMOS/M, which incorporate acceptable methods of combining modal responses, or with a multitude of other finite element programs that are either commercially available or developed specifically for the analysis. Further information regarding specific items related to dynamic analysis, such as damping ratios, combination of modal responses, and modeling techniques may be obtained from the works listed at the end of this subsection. Although recent advancements in computer technology and software have made this type of analysis more readily available, when performing detailed dynamic analyses, a thorough understanding, obtained from experience, is imperative.

After these seismic stresses and deformations have been obtained, they must be combined with the other equipment stresses and deformations, resulting from all of the applicable loads, in order to determine the acceptability of the equipment.

Qualification by Testing The equipment is tested by using the applicable seismic information (floor response spectrum or time history). The input test motion should have a TRS that closely envelopes the RRS, and the test should simulate the occurrence of five OBEs followed by one SSE.

Both the pump and the motor are tested under conditions that simulate as closely as possible actual operating conditions and operability. The operability of the pump, which is tested without the piping system attached and in the absence of any fluid, is established by the absence of undue large deflections during testing (which implies low stress levels) and by performance at the end of the test.

The input motion used must have a maximum acceleration equal to or greater than the ZPA and cannot include frequencies above the frequency associated with the ZPA. The input motion is applied to one vertical and one horizontal axis (resultant) simultaneously unless it can be proved that coupling effects are negligible. In general, multiaxis testing using independent random inputs is required.

Unless it has complete symmetry about its vertical axis, the equipment is rotated 90° and retested.

The mounting and support details used during testing should simulate the service mounting as closely as possible and should be designed so the mounting will not cause dynamic coupling to the test assembly or alter the input motion.

Combination of Test and Analysis If the motor assembly is tested separately and the pump is qualified by analysis, RRS at the motor assembly attachment points are developed from the pump assembly seismic analysis and used in the motor assembly testing. If both the pump assembly and the motor have to be tested but it is not feasible to test them together, dummy weights are used to replace the assembly part not included in the test and RRS at the location are established and used in testing the missing part.

DESIGN AND FUNCTIONAL REQUIREMENTS

The preceding sections provided the procedures for determining the seismic response of pumping equipment. However, in order to determine the acceptability of these results, they have to be combined with the pump's normal operational loads and compared to predetermined stress limitations. In accordance with the ASME code, the customer's design specification shall advise the applicable load combinations and allowable stress values.

Typically, the pump load combinations can be divided into four levels or service limits. Table 1 lists these service limits in ascending order dependent upon the magnitude of component deformation resulting from operation at the prescribed condition. In addition, Table 2 lists the ASME code allowable stress limits for each of these conditions. If no allowable stress limits are specified in the customer's design specification, no allowable stress increases should be used for the increasing load combinations, including those for OBE and SSE operation.

In addition to the specific requirements for stress levels or functionality of pressure containing components, the following items should be addressed as part of any seismic qualification of pump-motor assemblies:

- Secondary stress loading caused by differential movement of connected components should be determined.
- Displacements and deflections should be measured during testing or calculated, if qualified by analysis, in order to assure they are not excessive.
- Loads to be used in the design of the pump-motor assembly foundation and anchorage should be established.
- Seismic loads must be added to other normal shaft loads in order to verify stress levels, bearing loads, running clearances and possibly coupling misalignment.
- For electric motors, deflections or component dislocations should be closely monitored in order to assure that

TABLE 1 Typical load combinations and stress limits

Plant Condition	Design/ Normal	Upset	Emergency	Faulted
Concurrent Loads	PD + SL	PD + SL + SOT	PD + SL + SOT + OBE	PD + SL + SOT + SSE
Design/Stress Limits	Level A	Level B	Level C	Level D

Where:
PD = Design pressure and temperature
SL = Sustained loads including dead weight and applied nozzle loads
SOT = System operating transients for upset, emergency, and faulted conditions per customer specifications
OBE = Operating basis earthquake
SSE = Safe shutdown earthquake
Level A = Those loadings that the pump may be subjected to in the performance of its specified function
Level B = Those loadings that the pump must withstand without damage requiring repair
Level C = Those loadings that may result in large deformations that necessitate the removal of the pump from service for inspection or repair
Level D = Those loadings that result in gross general deformations with some consequent loss of dimensional stability and damage requiring repair, which may require removal of the unit from service

TABLE 2 Stress limits

Service limits	Stress limits (maximum normal stress)
Design and Level A	$\sigma_m \leq 1.0S$
	$(\sigma_m \text{ or } \sigma_L) + \sigma_b \leq 1.5S$
Level B	$\sigma_m \leq 1.1S$
	$(z\sigma_m \text{ or } \sigma_L) + \sigma_b \leq 1.65S$
Level C	$\sigma_m \leq 1.5S$
	$(\sigma_m \text{ or } \sigma_L) + \sigma_b \leq 1.8S$
Level D	$\sigma_m \leq 2.0S$
	$(\sigma_m \text{ or } \sigma_L) + \sigma_b \leq 2.4S$

σ_m = General membrane stress; equal to average stress across solid section under consideration; excludes discontinuities and concentrations and is produced only by pressure and other mechanical loads
σ_L = Local membrane stress; same as σ_m except that σ_L includes effect of discontinuities
σ_b = Bending stress; equal to linearly varying portion of stress across solid section under consideration; excludes discontinuities and concentrations and is produced only by mechanical loads
S = Allowable stress, given in Tables I-7.0 and I-8.0 of the ASME code; corresponds to highest metal temperature of section during condition under consideration

SOURCE: ASME Boiler and Pressure Vessel Code, Section III, Nuclear Power Plant Components, Division I, Subsection NC, 1992, New York.

- The rotor will not grind into the stator.
- The fan blades will not damage the winding insulation.
- There is no loss of lubricant and no slipped winding or winding temperature detector.

DOCUMENTATION

Refer to IEEE 344 for a list of documents that might be required for dynamic qualification of the pump-motor assembly (by test or analysis) and for general guidance in preparing the pump assembly purchase specification.

FURTHER READING

U.S. Nuclear Regulatory Commission guides (available from NRC, Washington, D.C.).

Regulatory Guide 1.100, "Seismic Qualification of Electrical Equipment for Nuclear Power Plants."

Regulatory Guide 1.61, "Damping Values for Seismic Design of Nuclear Power Plants."

Regulatory Guide 1.70, "Standard Format and Content of Safety Analysis Reports of Nuclear Power Plants."

Regulatory Guide 1.89, "Qualification of Class 1E Equipment for Nuclear Power Plants."

Regulatory Guide 1.92, "Combining Modal Responses and Spatial Components in Seismic Response Analysis."

Industry Standards (Available from the Institute of Electrical and Electronics Engineers, New York.)

IEEE 323, "Qualifying Class 1E Equipment for Nuclear Power Generating Stations."

IEEE 344, "IEEE Recommended Practices for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations."

Other Another source that may be helpful comes from the American Society of Civil Engineers.

American Society of Civil Engineers. "Structural Analysis and Design of Nuclear Plant Facilities." Manuals and Reports on Engineering Practices, No. 58, New York, 1980.