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IEEE Recommended Practice for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations

Sponsor
**Nuclear Power Engineering Committee of the
of the
IEEE Power Engineering Society**

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Foreword

(This Foreword is not a part of IEEE Std 344-1987, IEEE Recommended Practice for Seismic Qualification Of Class 1E Equipment for Nuclear Power Generating Stations.)

This revision of ANSI/IEEE Std 344-1975 was developed to expand and amplify guidance for developing programs to seismically qualify Class 1E equipment for nuclear power generating stations. Specific areas of amplification included are based on actual data published in the open literature.

The Class 1E equipment to be qualified by procedures or standards based upon this revised recommended practice can be of many forms; therefore, this recommended practice presents the guidelines for many acceptable seismic qualification methods with the intent of permitting the user to make a judicious selection from the options offered. This revised recommended practice attempts to define more fully the procedures by which Class 1E equipment can be seismically qualified. It presents the methods that are known by the working group to be practices acceptable by the nuclear power generation industry, its equipment suppliers, and the industrial test and analysis facilities utilized by the industry. The addition of new test or analysis methods in this recommended practice reflects an effort to recommend state-of-the-art techniques at the time of publication. An appendix has been included to further clarify, amplify, and elaborate upon these qualification methods. The deletion of a previously recommended test or analysis method from this recommended practice is not to be interpreted as an invalidation of the method.

The methods and definitions presented in this revision are not intended to limit other seismic qualification techniques. Exceptions to these recommended practices may be made at any time where it can be shown that the substituted procedure verifies that the equipment can perform its safety function with justifiable methodology. The basis for a technical justification may be, but is not limited to, partial analysis, tests on similar equipment, experience data, or a combination thereof.

A rapidly developing area is the use of experience data. Section 9. has been added to reflect this development and to provide interim guidance for the use of experience data for seismic qualification of equipment. A continuing effort will be coordinated between the writers of this recommended practice, the Seismic Qualification Utilities Group (SQUG), and the Senior Seismic Review and Advisory Panel (SSRAP) to follow the development of the use of experience data. This effort is expected to yield further information on the generic ruggedness of equipment, a refinement of qualification practice based on experience data, and to a subsequent revision of this recommended practice.

Adherence to this recommended practice to obtain equipment seismic qualification alone will not suffice for assurance of public health and safety since it is the integrated performance of structures, fluid systems, instrumentation systems, electrical systems, and man/machine interface systems of a nuclear power generating station that establishes totally safe operating conditions.

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IEEE Recommended Practice for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations

1. Scope and References

1.1 Scope

Recommended practices for establishing procedures that will yield data, which verify that the Class 1E equipment can meet its performance requirements during and following one safe shutdown earthquake (SSE) preceded by a number of operating basis earthquakes (OBE), are provided in this document. This recommended practice may be used to establish tests or analyses that will yield data to substantiate performance claims or to evaluate and verify performance of representative devices and assemblies as part of an overall qualification effort.

1.2 References

This recommended practice shall be used in conjunction with the following publications:

[1] ANSI/IEEE Std 100-1984, IEEE Standard Dictionary of Electrical and Electronics Terms.¹

[2] ANSI/IEEE Std 323-1983, IEEE Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations.

[3] ANSI/IEEE Std 382-1985, IEEE Standard for Qualification of Actuators for Power Operated Valve Assemblies with Safety-Related Functions for Nuclear Power Plants.

[4] MIL-S 901C-1963, Requirements for Shock Test H. I. (High Impact) Shipboard Machinery, Equipment, and Systems.²

[5] 10 FR, Energy. Chapter I, Nuclear Regulatory Commission.³

¹ANSI/IEEE publications are available from IEEE Service Center, 445 Hoes Lane, PO Box 1331, Piscataway, NJ 08855-1331, or from the Sales Department, American National Standards Institute, 1430 Broadway, New York, NY 10018.

²MIL publications are available from the Director, US Navy Publications and Printing Service, Eastern Division, 700 Robbins Avenue, Philadelphia, PA 19111.

³This publication is available from Superintendent of Documents, US Government Printing Office, Washington, DC 20402.

2. Definitions

The definitions in this section establish the meanings of words in the context of their use in this recommended practice. See ANSI/IEEE Std 100-1984 [1]⁴ for further definitions.

broadband response spectrum: A response spectrum that describes motion in which amplified response occurs over a wide (broad) range of frequencies.

coherence function: The coherence function defines a comparative relationship between two time histories. It provides a statistical estimate of how much two motions are related, as a function of frequency. The numerical range is from zero for unrelated, to 1.0 for related motions.

correlation coefficient function: The correlation coefficient function defines a comparative relationship between two time histories. It provides a statistical estimate of how much two motions are related, as a function of time delay. The numerical range is from zero for unrelated, to + 1.0 for related motions.

cutoff frequency: The frequency in the response spectrum where the zero period acceleration asymptote begins. This is the frequency beyond which the single-degree-of-freedom oscillators exhibit no amplification of motion, and indicate the upper limit of the frequency content of the waveform being analyzed.

damping: An energy dissipation mechanism that reduces the amplification and broadens the vibratory response in the region of resonance. Damping is usually expressed as a percentage of critical damping. Critical damping is defined as the least amount of viscous damping that causes a single-degree-of-freedom system to return to its original position without oscillation after initial disturbance.

flexible equipment: Equipment, structures, and components whose lowest resonant frequency is less than the cutoff frequency on the response spectrum

floor acceleration: The acceleration of a particular building floor (or equipment mounting) resulting from the motion of a given earthquake. The maximum floor acceleration is the zero period acceleration (ZPA) of the floor response spectrum.

Fourier spectrum: A complex valued function that provides amplitude and phase information as a function of frequency for a time domain waveform.

ground acceleration: The acceleration of the ground resulting from the motion of a given earthquake. The maximum ground acceleration is the zero period acceleration (ZPA) of the ground response spectrum.

narrowband response spectrum: A response spectrum that describes the motion in which amplified response occurs over a limited (narrow) range of frequencies.

natural frequency: The frequency(s) at which a body vibrates due to its own physical characteristics (mass and stiffness) when the body is distorted in a specific direction and then released.

operating basis earthquake (OBE): An earthquake that could reasonably be expected to occur at the plant site during the operating life of the plant considering the regional and local geology and seismology and specific characteristics of local subsurface material. It is that earthquake that produces the vibratory ground motion for which those features of the nuclear power plant, necessary for continued operation without undue risk to the health and safety of the public, are designed to remain functional.

power spectral density (PSD): The mean squared amplitude per unit frequency of a waveform. PSD is expressed in g^2/Hz versus frequency for acceleration waveforms.

qualified life: The period of time, prior to the start of a design basis event (DBE), for which the equipment was demonstrated to meet the design requirements for the specified service conditions.

required response spectrum (RRS): The response spectrum issued by the user or his agent as part of his specifications for qualification or artificially created to cover future applications. The RRS constitutes a requirement to be met.

⁴The numbers in brackets correspond to those of the references in 1.2.

resonant frequency: A frequency at which a response peak occurs in a system subjected to forced vibration. This frequency is accompanied by a phase shift of response relative to the excitation.

response spectrum: A plot of the maximum response, as a function of oscillator frequency, of an array of single-degree-of-freedom (SDOF) damped oscillators subjected to the same base excitation.

rigid equipment: Equipment, structures, and components whose lowest resonant frequency is greater than the cutoff frequency on the response spectrum.

safe shutdown earthquake (SSE): An earthquake that is based upon an evaluation of the maximum earthquake potential considering the regional and local geology and seismology and specific characteristics of local subsurface material. It is that 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 ensure

- 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
- 3) The capability to prevent or mitigate the consequences of accidents that could result in potential off-site exposures comparable to the guideline exposures of 10 FR, Ch 1, Section 100 [4]

sine beats: A continuous sinusoid of one frequency, amplitude modulated by a sinusoid of a lower frequency.

stationarity: A condition that exists when a waveform is stationary and when its amplitude distribution, frequency content, and other descriptive parameters are statistically constant with time.

test response spectrum (TRS): The response spectrum that is developed from the actual time history of the motion of the shake table.

NOTE — When qualifying equipment by utilizing response spectra, the TRS is to be compared to the RRS using the methods described in 7.6.2 and 7.6.3 of this recommended practice.

transfer function: A complex frequency response function that defines the dynamic characteristics of a constant parameter linear system. For an ideal system, the transfer function is the ratio of the Fourier transform of the output to that of a given input.

zero period acceleration (ZPA): The acceleration level of the high frequency, nonamplified portion of the response spectrum. This acceleration corresponds to the maximum peak acceleration of the time history used to derive the spectrum.

3. General Discussion of Earthquake Environment and Equipment Response

This section provides background information on earthquake behavior and on the performance of equipment during simulated seismic events. Numerical values in this section are typical and illustrative and should not be considered as standards.

3.1 Earthquake Environment

Earthquakes produce three-dimensional random ground motions that are characterized by simultaneous but statistically independent horizontal and vertical components. The strong motion portion of the earthquake may last from 10 s to 15 s, although the complete event may be considerably longer. The ground motion is typically broadband random, and produces potentially damaging effects over a frequency range of 1 Hz–33 Hz.

3.2 Equipment on Foundations

The vibratory nature of the ground motion (both horizontal and vertical) can be amplified or attenuated in foundation-mounted equipment. For any given ground motion, the alteration depends on the system's natural frequencies of

vibration (soil, foundation, and equipment) and the damping mechanisms. The typical broadband response spectra that describe the ground motion indicate that multiple-frequency excitation predominates.

3.3 Equipment on Structures

The ground motion (horizontal and vertical) may be filtered by intervening building structures to produce amplified or attenuated narrowband motions within the structure. The dynamic response of equipment on structures may be further amplified or attenuated to an acceleration level many times more or less than that of the maximum ground acceleration, depending upon the equipment damping and natural frequencies. The narrowband response spectra that typically describe a building floor motion indicate that single-frequency excitation of equipment subcomponents can predominate. Similar filtering of in-structure motion may occur in flexible piping systems. For components mounted away from supports, the resultant motion may be predominantly single frequency in nature and centered near or at the resonant frequency of the piping system. This resonance condition may produce the most critical seismic load on components mounted on the line.

3.4 Simulating the Earthquake

The goal of seismic simulation is to reproduce the postulated earthquake environment in a realistic manner. The form of the simulated seismic motion used for the qualification of equipment by analysis or testing can be described by one of the following functions:

- 1) Response spectrum
- 2) Time history
- 3) PSD

This function may be generated for the foundation, floor of the building, or substructure upon which the equipment is to be mounted. It is supplied by the user or his agent to the manufacturer as a part of the specifications for that equipment (see Section 9.) or generated by the manufacturer for generic applications.

Because of the directional nature of seismic motion, and the filtered output motion of building and equipment structures, the directional components of the motion and their application to the equipment should be specified or accounted for in some other appropriate manner.

3.4.1 Response Spectrum

The response spectrum provides information on the maximum response of single-degree-of-freedom oscillators as a function of oscillator frequency and damping when subjected to an input motion. The frequency content and the peak value zero period acceleration (ZPA) of the input motion is indicated.

It is important to recognize that the response spectrum does not supply the following information:

- 1) The waveform or time history of the excitation that produced it
- 2) The duration of motion (this must be defined in the qualification specification)
- 3) The response of any particular equipment without accounting for its dynamic characteristics

3.4.2 Time History

A time history displays the earthquake-induced motion (usually in terms of acceleration) as a function of time. The simulated motion is derived from existing or artificially generated earthquake records. For application at any floor, the time history record generated includes the dynamic filtering and amplification effects of the building and other intervening support structures.

3.4.3 Power Spectral Density Function

The mean squared amplitude per unit frequency of the vibratory motion is characterized in terms of the PSD as a function of frequency.

NOTE — Although the response spectrum and the PSD function do not define the exact waveform or duration of the excitation, they are valuable tools. They enable significant frequency-dependent properties of the motion to be seen at a glance from one curve. The PSD provides information regarding the excitation directly without including the effects on an array of single-degree-of-freedom oscillators as is done for the response spectrum. As a result, the PSD allows application of relationships between excitation and response by way of the transfer functions for linear systems.

4. Seismic Qualification Approach

The seismic qualification of equipment should demonstrate an equipment's ability to perform its safety function during and after the time it is subjected to the forces resulting from one SSE. In addition, the equipment must withstand the effects of a number of OBE (see 6.5, and 7.1.5.1) prior to the application of an SSE. The most commonly used methods for seismic qualification are contained in this recommended practice. The methods are grouped into four general categories that

- 1) Predict the equipment's performance by analysis
- 2) Test the equipment under simulated seismic conditions
- 3) Qualify the equipment by a combination of test and analysis
- 4) Qualify the equipment through the use of experience data

Each of the preceding methods, or other justifiable methods, may be adequate to verify the ability of the equipment to meet the seismic qualification requirements. The choice should be based on the practicality of the method for the type, size, shape, and complexity of the equipment configuration, whether the safety function can be assessed in terms of operability or structural integrity alone, and the reliability of the conclusions.

Equipment being qualified must demonstrate that it can perform its safety function during and after an earthquake. The required safety function depends not only on the equipment itself but also on the system and plant in which it is to function. The safety function during the earthquake may be the same, but is often different from the safety function required after the earthquake. For example, an electrical device may be required to have no spurious operations during the earthquake or to perform an active function both during and after the earthquake, or it may be required to survive during the earthquake and perform an active function after the earthquake, or any combinations of these. Another device may only be required to maintain structural integrity during and after the earthquake. Throughout this recommended practice, it is assumed that the requirements given here are understood and that the definition of the safety function is provided as part of the equipment qualification specification.

When the safety function of equipment requires a demonstration of operability during the earthquake, it shall be demonstrated during the strong motion portion of the qualification simulation.

The seismic testing, when part of an overall qualification program, should be performed in its proper sequence as indicated in ANSI/IEEE Std 323-1983 [2] and care should be taken to identify and account for significant aging mechanisms as discussed therein. Within these guidelines, it must be demonstrated that the equipment is capable of performing its safety function throughout its qualified life including its functional operability during and after an SSE at the end of that qualified life.

5. Damping

5.1 Introduction

Damping is the generic name ascribed to the numerous energy dissipation mechanisms in a system. In practice, damping depends on many parameters, such as the structural system, mode of vibration, strain, normal force, velocity, materials, joint, and slippage. In linear vibration theory, the simplifying assumption is made that damping is purely viscous, or proportional to the relative velocity of moving parts. Therefore, when a value of damping is associated with a practical system, it is usually assumed to be equivalent to viscous or linear. This is a convenient simplification relating real-world hardware behavior, which may be nonlinear to some degree, with theoretical concepts that normally utilize linear methods of analysis.

For equipment composed of an assembly of components, there is usually no single value of damping. Damping is associated with every part of the equipment ranging from bolted or welded construction to uniform material. The value of damping may vary from place to place, depending on numerous factors. Therefore, when a value of damping is ascribed to equipment, it is common to give a range of typical values. Since each mode of vibration of a structure can, and most often does, have a different value of damping, a useful practice in analysis is to associate a value of damping to each mode of vibration of the equipment that is in the frequency range of interest.

5.2 Measurement of Damping

Linear vibration theory indicates that there are numerous methods for measuring damping. Considerable care must be exercised in making the correlation between an idealized model and a practical system. For example, it is rarely possible to locate precise points in equipment that have exact correspondence with the lumped mass elements in a model. Some methods of calculating modal damping, such as the Q method, rely purely on single-degree-of-freedom assumptions.

Damping is calculated directly from the maximum response at the resonance peak measured at any point in the equipment and the magnitude of the sine sweep input excitation. These methods are not generally acceptable since the response of points in equipment is usually determined by the mode shape vector and the participation factor for each vibration mode. The following methods for evaluating the damping are commonly used but other justifiable methods may be used. They assume that a single mode of vibration can be excited in the equipment and that motion transducers are mounted at positions other than at a point of zero motion. In all cases, care should be exercised to determine whether damping nonlinearity with response amplitude is significant.

5.2.1 Damping by Measuring the Decay Rate

The equivalent viscous damping can be calculated by recording the decay rate of the particular vibration mode. This procedure is often referred to as the logarithmic decrement method.

5.2.2 Damping by Measuring the Half-Power Bandwidth

The equipment should be excited with a slowly swept sinusoidal vibration. The response of any desired location in the equipment is measured and plotted as a function of frequency. From these response plots, the damping associated with each mode can be calculated by measurements of the width of the respective resonance peak at the half-power point. This procedure is often referred to as the half-power bandwidth method.

5.2.3 Damping by Curve Fitting Methods

The equipment is excited by swept sine, random, or transient excitation, and a response transfer function is developed. The modal damping is obtained by fitting a mathematical model to the actual frequency response data (transfer function). This curve fitting will smooth out any noise or small experimental errors.

5.3 The Application of Damping

Ranges of damping, measured as described in 5.2, are valuable data for the equipment designer. Damping is used differently in analysis and testing in equipment qualification as described in 5.3.1 and 5.3.2.

5.3.1 The Application of Damping in Analysis

In analysis, a mathematical model is made of the equipment so as to predict the response to the seismic motion. The value of damping used in this model should correspond to the actual energy dissipation in the equipment to enable the response to be accurately predicted. An alternative approach is to use a conservative value of linear damping to obtain a conservative estimate of response. In any case, there is a need to know the ranges of damping for the specific equipment and the nature of nonlinearities and their effect on the response. Appropriate values of damping may be obtained from tests or other justifiable sources.

It is reasonable to state that actual damping is nonlinear by nature. In most equipment, it is a function of response amplitude owing to such factors as internal friction within material, or at connections between components, or Coulomb-type sliding friction. For analytical purposes, these energy dissipation damping mechanisms may often be treated in terms of linear damping approximations if proper consideration is given to the fact that these approximations vary, sometimes significantly, with increasing response. As an example, the use of low-impedance testing to determine damping must be exercised with caution since at strong motion shaking, indicative of significant earthquakes, the aforementioned factors may cause the real damping to be quite different and higher than that measured at low levels.

Generally, most treatment of structural systems assumes viscous damping, however, certain cabinets or housings may exhibit nonviscous damping. The treatment of such a problem is analytically complex and should be performed using appropriate techniques.

5.3.2 The Application of Damping in Testing

In testing, the equipment may be qualified by subjecting it to a simulated seismic motion as defined by the RRS. The response spectrum defines the seismic motion by way of the peak response of an array of single-degree-of-freedom damped oscillators. Since the oscillators are hypothetical, any practical value of damping, for example, 5% may be employed in the RRS for testing, and it need not correspond to the actual equipment damping (Note the distinction from the use of the RRS in analysis where the value of damping must be related to the actual equipment). The application of the RRS and the TRS in selecting acceptable test motions is given in 7.6.1. The following relationships exist for the values of damping in the response spectra.

- 1) In comparing the RRS and the TRS, it is preferred that the damping in the two be the same.
- 2) In some cases, for example, when past test data are used for a new RRS, the damping in the two cases may be different and the following circumstances apply.
 - a) When the damping for the TRS is greater than that for the RRS and the criteria in 7.6.1 are satisfied, then the qualification is acceptable since under this circumstance it is conservative.
 - b) When the damping in the TRS is less than that in the RRS a conclusive statement is not possible without further evaluation. One possibility is to re-analyze the test motions to produce a TRS for an acceptable damping value and apply the criteria given in either (1) or (2)(a)

6. Analysis

NOTE — The analysis method is not recommended for complex equipment that cannot be modeled to adequately predict its response. Analysis without testing may be acceptable only if structural integrity alone can ensure the design-intended function.

6.1 Introduction

Procedures are presented in this section that can be used to seismically qualify equipment by analysis for a number of OBE followed by an SSE. Two approaches to seismic analysis are described. One approach is based on dynamic analysis, the other on static coefficient analysis. The methods described are most commonly used but others may be used if they are justifiable. Figure 1 is a flow chart of the recommended analytical process. The general procedure is

- 1) Review the equipment to assess the dynamic characteristics
- 2) Determine the response using one or more of several methods described in the following sections
- 3) Determine the stresses and displacements that result from the response
- 4) Compare the calculated responses with those that ensure compliance with design requirements

The review stage should take into account the complexity of the equipment and the adequacy of analytical techniques to properly predict the equipment's safety functions while under seismic excitation. The review should determine which method will most accurately represent the equipment's performance under seismic conditions. The response determination phase of the analysis can take several paths, the first of which is determined by the choice between the dynamic analysis method (see 6.2) or static coefficient method (see 6.3). In general, the choice is based on the perceived margin of strength of the equipment since the static coefficient method, while easier and more economical to perform, is generally more conservative.

Dynamic analysis or tests may indicate that the equipment is either rigid or flexible. Rigid equipment may be analyzed using static analysis and the seismic acceleration associated with the mounting location. Flexible equipment, on the other hand, is analyzed using its dynamic response computed from a response spectrum time history, or other analysis methods.

The mathematical models used for analysis can be based on calculated structural parameters, or on those established by test, or by a combination of these. Where complex mathematical models are based solely on calculated structural parameters, the use of verification testing is recommended (see Section 8.). The damping used in the analysis should have a reference basis, that is, it should be specified in the safety analysis report, or specification, or established by testing. When a damping value has not been defined, one can be established by any means when it is justified in the qualification report.

An evaluation of the effects of the calculated stresses and strains on mechanical strength, and, where possible, function, may be performed using the calculated dynamic response. To check for any interference maximum displacements should be computed for the component as installed. The seismic stress must be added to the equipment operating stresses to determine if the strength of the equipment is adequate.

6.2 Dynamic Analysis

The equipment and any secondary structural supports must be modeled to adequately represent their mass distribution and stiffness characteristics. This model may be used to perform a modal (eigenvalue) analysis to determine when the equipment is rigid or flexible.

The equipment is considered rigid when the model has no resonances in the frequency range below the cutoff frequency of the RRS and may be analyzed statically. The seismic forces on each equipment component are obtained by multiplying the distributed mass by the appropriate maximum floor acceleration (ZPA).

For flexible equipment, the model can be analyzed using a response spectrum analysis or a time history analysis. Using response spectrum analysis allows the response of interest, be it deflection, stress, or acceleration, to be determined by combining each modal response considering all significant modes. Sufficient modes (modal mass) should be included to ensure an adequate representation of the equipment dynamic response and constraint forces at supports. An acceptable criterion for sufficiency is that the inclusion of additional modes does not result in more than a 10% increase in response. The response is determined by combining each modal response by the square root of the sum of