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(Revision of
IEEE Std 344-1987)

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

IEEE Power Engineering Society

Sponsored by the
Nuclear Power Engineering Committee



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8 June 2005

Print: SH95327

PDF: S344327



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

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**Nuclear Power Engineering Committee
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IEEE Power Engineering Society**

Approved 8 December 2004

IEEE-SA Standards Board

Abstract: Recommended practices are provided for establishing procedures that will yield data to demonstrate that the Class 1E equipment can meet its performance requirements during and/or following one safe shutdown earthquake event preceded by a number of operating basis earthquake events. This recommended practice may be used to establish tests, analyses, or experienced-based evaluations that will yield data to demonstrate Class 1E equipment performance claims or to evaluate and verify performance of devices and assemblies as part of an overall qualification effort. Common methods currently in use for seismic qualification by test are presented. Two approaches to seismic analysis are described, one based on dynamic analysis and the other on static coefficient analysis. Two approaches to experienced-based seismic evaluation are described, one based on earthquake experience and the other based on test experience.

Keywords: Class 1E, earthquake, earthquake experience, equipment qualification, inclusion rules, nuclear, operating basis earthquake, prohibited features, qualification methods, required response spectrum, response spectra, safe shutdown earthquake, safety function, seismic, seismic analysis, test response spectrum, test experience, type testing

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Print: ISBN 0-7381-4678-1 SH95327
PDF: ISBN 0-7381-4679-X SS95327

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Introduction

This introduction is not part of IEEE Std 344-2004, IEEE Recommended Practice for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations.

This revision of IEEE Std 344-1987 was developed to expand and clarify guidance for developing programs to seismically qualify Class 1E equipment for nuclear power generating stations. Specific areas of amplification included are based on experience gained since 1987.

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 that are acceptable to the nuclear power generation industry, its equipment suppliers, and the industrial test and analysis facilities utilized by the industry. The clarification and update of methods in this recommended practice reflect an effort to recommend state-of-the-art techniques at the time of publication.

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. Engineering judgment may be used in conjunction with these methods. Exceptions to these guidelines, which are founded on a broad base of actual test, analysis, and earthquake experience, supplemented by engineering judgment, may be used to meet the intent of this standard, provided the methods are justified.

The Foreword of the 1987 revision of this standard noted that experience-based methods for seismic qualification of equipment were under development, and Clause 9 of the 1987 revision contained interim guidance for the use of experience data for this purpose. Since then, development of the experience-based approach has been furthered by the Seismic Qualification Utility Group (SQUG). The SQUG approach was used at many nuclear power plants to resolve USI A-46. It has also been adopted, in part, and used by other governmental and industrial organizations. Accordingly, Clause 10 and relevant parts of Clause 11 of this revision of the standard have been rewritten to incorporate the results of this development. Use of the experience-based approach in this recommended practice is acceptable for use in nuclear plants if it is consistent with the plant's licensing/regulatory design basis.

Issues related to use of median-centered in-structure response spectra for the earthquake experience-based method, operating basis earthquake (OBE) requirements associated with the test experience method, and generation of a test-experience spectrum were considered at length by the working group in the preparation of this document.

Further guidance for qualification of replacement components and devices within an existing, previously qualified larger equipment assembly by the earthquake experience-based method is deferred to the next revision of the standard. Special consideration could be added to determine how to extend earthquake experience data to replacement of components and devices in a previously qualified equipment assembly so that there is sufficient detail and traceability in the areas of equipment performance (physical configuration, operational, and dynamic), installation, excitation, and demonstration of safety function.

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.

This standard was prepared by Subcommittee 2 Working Group 2.5 (Seismic) of the Nuclear Power Engineering Committee of the IEEE Power Engineering Society.

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

1. Overview

This recommended practice is divided into 11 clauses. Clause 1 provides the scope of this recommended practice. Clause 2 lists normative references to other standards that are useful in applying this recommended practice. Clause 3 provides definitions that are either not found in other standards or have been modified for use with this recommended practice. Clause 4 provides background information on earthquake behavior and on the performance of equipment during simulated seismic events. Clause 5 defines the most commonly used methods for seismic qualification of equipment contained in this recommended practice. Clause 6 provides guidance on the measurement and application of damping in the seismic qualification of equipment. Clause 7 provides procedures for two approaches most commonly used to seismically qualify equipment by analysis. Clause 8 provides procedures for the commonly used methods for seismic qualification of equipment by test. Clause 9 provides guidelines for seismic qualification of equipment that cannot be practically qualified by analysis or testing alone. Clause 10 provides guidelines for two approaches to seismically qualify equipment using experience data for a reference equipment class. Clause 11 provides documentation guidelines for the seismic qualification of equipment.

This recommended practice also contains six annexes. Annex A explains how to measure the zero period acceleration (ZPA) from seismic test data. Annex B explains frequency content and stationarity of the input waveform. Annex C provides guidance on fragility testing. Annex D explains the use of test duration and response cycles in ensuring adequate equipment response relative to low-cycle fatigue capability. Annex E provides guidance in establishing statistically independent simulated simultaneous multiaxis motions for seismic testing and analysis. Annex F provides bibliographic references.

1.1 Scope

This document describes recommended practices for establishing seismic qualification procedures that will yield quantitative data to demonstrate that the Class 1E equipment can meet its performance requirements during and/or following one safe shutdown earthquake (SSE) event preceded by a number of operating basis earthquake (OBE) events. The test, analysis, or experienced-based evaluation methods described herein may be used to yield data to demonstrate Class 1E equipment performance claims or to evaluate and verify performance of devices and assemblies as part of an overall qualification effort.

1.2 Purpose

The purpose of this document is to provide recommended practices and documentation requirements for seismic qualification of Class 1E equipment to verify the equipment's ability to perform its safety function during and/or after the specified seismic motions.

2. Normative references

This recommended practice shall be used in conjunction with the following publications. When the following standards are superseded by an approved revision, the revision shall apply.

IEEE Std 323TM-2003, IEEE Standard for Qualifying Class 1E Equipment for Nuclear Power Generating Stations.^{1,2}

IEEE Std 382TM-1996, IEEE Standard for Qualification of Actuators for Power-Operated Valve Assemblies with Safety-Related Functions for Nuclear Power Plants.

MIL-S-901C-1963, Requirements for Shock Tests, H. I. (High Impact); Shipboard Machinery, Equipment and Systems.³

10 CFR, Energy—Chapter 1, Nuclear Regulatory Commission.⁴

3. Definitions

For the purpose of this recommended practice, the following terms and conditions apply. IEEE 100, *The Authoritative Dictionary of IEEE Standards Terms*, Seventh Edition [B1],⁵ should be referenced for terms not defined in this clause.

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

3.2 coherence function: 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.

3.3 correlation coefficient function: 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.

3.4 critical seismic characteristics: Those design, material, and performance characteristics of an equipment item that provide assurance that the item will perform its required function under seismic loads.

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⁵The numbers in brackets correspond to those of the bibliography in Annex F.

3.5 cutoff frequency: The frequency in the response spectrum where the ZPA asymptote begins. This is the frequency beyond which the single-degree-of-freedom (SDOF) oscillators exhibit no amplification of motion and indicate the upper limit of the frequency content of the waveform being analyzed.

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

3.7 earthquake experience spectrum (EES): The response spectrum that defines the seismic capacity of a reference equipment class based on earthquake experience data.

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

3.9 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 ZPA of the floor response spectrum.

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

3.11 ground acceleration: The acceleration of the ground resulting from the motion of a given earthquake. The maximum ground acceleration is the ZPA of the ground response spectrum.

3.12 inclusion rules: The rules that define the bounds of equipment included in a reference equipment class based on an acceptable range of equipment physical characteristics, dynamic characteristics, and functions for which seismic ruggedness has been demonstrated by experience data.

NOTE—See 10.2.3.1 and 10.3.3.1.⁶

3.13 independent items: Components and equipment that (a) have different physical characteristics or (b) experienced different seismic motion characteristics, e.g., different earthquakes, different sites, different buildings, or different orientations/locations in the same building.

3.14 median-centered in-structure response spectrum: In-structure response spectrum developed using realistic damping and best estimate modeling parameters to obtain the most probable structural amplification that could realistically occur for the level of the specified earthquake ground motion.

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

3.16 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.

3.17 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.

⁶Notes in text, tables, and figures are given for information only, and do not contain requirements needed to implement the standard.

3.18 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.

3.19 prohibited features: Design details, materials, construction features, or installation characteristics that have resulted in seismic induced failure or malfunction of the equipment to maintain its structural integrity and perform its specified function at earthquake or test excitations up to and including the defined seismic capacity level.

3.20 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.

3.21 reference equipment: The equipment used to establish a reference equipment class.

3.22 reference equipment class: A group of equipment sharing common attributes as defined by a set of inclusion rules and prohibited features.

3.23 reference site: A site containing equipment or items used to establish a reference equipment class.

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

3.25 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.

3.26 response spectrum: A plot of the maximum response, as a function of oscillator frequency, of an array of SDOF damped oscillators subjected to the same base excitation.

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

3.28 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 the following:

- a) Integrity of the reactor coolant pressure boundary
- b) Capability to shut down the reactor and maintain it in a safe shutdown condition
- c) Capability to prevent or mitigate the consequences of accidents that could result in potential off-site exposures comparable to the guideline exposures of 10 CFR—Chapter 1, Part 100⁷

3.29 seismic capacity: The highest seismic level for which required adequacy has been verified.

3.30 seismic ruggedness: The ability to resist the damaging effects of an earthquake imparted by robust design and manufacture.

3.31 seismic vulnerability: A physical and/or electrical characteristic that renders an equipment item susceptible to structural damage or malfunction from the effects of an earthquake.

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

⁷Information on references can be found in Clause 2.

3.33 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.

3.34 structure diameter: The diameter of a circle having the equivalent area of the facility's foundation.

3.35 test experience spectra (TES): The test-based response spectra that define the seismic capacity of a reference equipment class.

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

3.37 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.

3.38 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.

4. General discussion of earthquake environment and equipment response

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

4.1 Earthquake environment

Earthquakes produce three-dimensional (3D) 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 to 33 Hz.

4.2 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.

4.3 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.

4.4 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:

- a) Response spectrum
- b) Time history
- c) Power spectral density (PSD)

The simulated seismic motion 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 the user's agent as a part of the specifications for that equipment (see Clause 11) or generated by others 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.

4.4.1 Response spectrum

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

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

- a) The waveform or time history of the excitation that produced it
- b) The duration of motion (this must be defined in the qualification specification)
- c) The dynamic response of any particular equipment

4.4.2 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.

4.4.3 PSD 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 SDOF 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.

4.5 Support structure and interactions

Seismic qualification of equipment requires consideration of installation features, such as (a) the seismic adequacy of the supporting structure (support assembly, structure, anchorage, floors, walls, or foundation), and (b) the potential for adverse seismic interactions (such as falling of overhead components, proximity impacts, differential displacements, spray, flood, or fire).

5. Seismic qualification approach

The seismic qualification of equipment should demonstrate an equipment's ability to perform its safety function during and/or 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 OBEs [see 7.6, 8.1.5.2, item b) in 10.2.3.1, and 10.3] 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

- a) Predict the equipment's performance by analysis.
- b) Test the equipment under simulated seismic conditions.
- c) Qualify the equipment by a combination of test and analysis.
- d) 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/or 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/or 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/or 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. It is the responsibility of the user to verify that the qualification approach selected complies with the requirements.

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 IEEE Std 323-2003 and care should be taken to identify and account for significant aging mechanisms with test margins 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/or after an SSE at the end of that qualified life.

Earthquake experience data will result in seismic capacities that are significantly less than those obtained from seismic testing. This is because earthquake ground motions, which form the basis for establishing capacities in 10.2, are significantly less than the seismic accelerations typically obtained during shake-table testing.

6. Damping

6.1 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.

6.2 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 SDOF assumptions.

Damping 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 is 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 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.

6.2.1 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*.

6.2.2 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*.