ANSI/IEEE Std 344-1987

(Revision of ANSI/IEEE Std 344-1975)

An American National Standard

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

Approved June 11, 1987

IEEE Standards Board

Approved February 2, 1988

American National Standards Institute

The Institute of Electrical and Electronics Engineers, Inc

345 East 47th New York, NY 10017, USA

IEEE Standards documents are developed within the Technical Committees of the IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Board. Members of the committees serve voluntarily and without compensation. They are not necessarily members of the Institute. The standards developed within IEEE represent a consensus of the broad expertise on the subject within the Institute as well as those activities outside of IEEE which have expressed an interest in participating in the development of the standard.

Use of an IEEE Standard is wholly voluntary. The existence of an IEEE Standard does not imply that there are no other ways to produce, test, measure, purchase, market, or provide other goods and services related to the scope of the IEEE Standard. Furthermore, the viewpoint expressed at the time a standard is approved and issued is subject to change brought about through developments in the state of the art and comments received from users of the standard. Every IEEE Standard is subjected to review at least once every five years for revision or reaffirmation. When a document is more than five years old, and has not been reaffirmed, it is reasonable to conclude that its contents, although still of some value, do not wholly reflect the present state of the art. Users are cautioned to check to determine that they have the latest edition of any IEEE Standard.

Comments for revision of IEEE Standards are welcome from any interested party, regardless of membership affiliation with IEEE. Suggestions for changes in documents should be in the form of a proposed change of text, together with appropriate supporting comments.

Interpretations: Occasionally questions may arise regarding the meaning of portions of standards as they relate to specific applications. When the need for interpretations is brought to the attention of IEEE, the Institute will initiate action to prepare appropriate responses. Since IEEE Standards represent a consensus of all concerned interests, it is important to ensure that any interpretation has also received the concurrence of a balance of interests. For this reason IEEE and the members of its technical committees are not able to provide an instant response to interpretation requests except in those cases where the matter has previously received formal consideration.

Comments on standards and requests for interpretations should be addressed to:

Secretary, IEEE Standards Board
345 East 47th Street
New York, NY 10017
USA

--`,,,,`,`,`,,,`,,`,`,,,`-`-`,,`,,`,`,,`---

Copyright The Institute of Electrical and Electronics Engineers, Inc.
Provided by IHS under license with IEEE

Document provided by IHS Licensee=Fluor Corp no FPPPV per administrator /use new u/2110503106, User=AHESPINOZA, 07/22/2004 11:28:52 MDT Questions or comments about this message: please call the Document Policy Group at

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.

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

At the time this recommended practice was approved the members of the working group were as follows:

G. D. Shipway*, *Chair*
K.M. Skreiner*, *Vice Chair*

T. Akos
L. Berkowitz
C. Chen
W. Djordjevic
D. Dura*
E. Fischer
J. Freeman
R. Fronk
R. Gilfoy
R. Grischow
J. Hendricks
A. Javid*
H. Jordan
D. D. Kana*
B. M. Kukreti
W. LaPay *
A. Lee*
C. W. Lin
B. Linderman *
T. MacNair
T. McNamara
T. Morrone*
D. K. Ostrum
D. Rheuble
Z. T. Shi
T. A. Shook
D. Tang*
D. Umble

* Members of the Writing Group

At the time this recommended practice was approved the members of Subcommittee 2 were as follows:

G. K. Henry, *Chair*
R.B. Miller, *Vice Chair*
D. J. Castro, *Secretary*

S. K. Aggarwal
R. A. Brown
N. M. Burstein
M. D Calcamuggio
S. P. Carfagno
W. J. Denkowski
G. T. Dowd
R. M. Eastham
J. B. Gardner
D. R. Green
W. Hadovski
T. P. Harrall
J. T. Keiper
P. L. Kine
J. Klingerman
C. E .Kunkel
T. H. Ling
C. F. Miller
M. Pai
J. S. Pirrong
N. S. Porter
C. F. Seyer
M. W. Sheets
G. Shipway
K. M. Skreiner
G. E. Sliter
E. F. Sprout
A. P. Stakutis
L. D. Test
F. Unmack
R. C. Williams

At the time this recommended practice was approved the members of the Nuclear Power Engineering Committee were as follows:

J. T. Bauer, *(Chairman)*
W.G. Schwartz, *(Vice Chairman)*

R. E. Allen *
F. D. Baxter
G. G. Boyle
D. F. Brosman
S. P. Carfagno
R. C. Carruth
E. F. Dowling
R. E. Dulski
J. M. Gallagher
W. C. Gangloff
L. W. Gaussa
L. C. Gonzalez
L. P. Gradin
B. Grim
T. L. Cleveland
R. E. Hall
L. F. Hanes
G. K. Henry
S. Kasturi
T. S. Killen
A. Laird
D. C. Lamken
B. Nemroff
M. Pai
J. R. Penland
W. K. Peterson
C. A. Petrizzo
W. S. Raughley
B. M. Rice
A. R. Roby
E. F. Sprout
A. J. Spurgin
L. Stanley
D. F. Sullivan
P. Szabados
L. D. Test
J. E. Thomas
T. R Vadaro
F. J. Volpe

* Past Chairman

The following persons were on the balloting committee that approved this recommended practice for submission to the IEEE Standards Board:

F. Catudal
L. Costrell
J. Forster
J. M. Gallagher
R. L. Kathren
P. W. Kauppila
J. E. Kaveckis
J. P. Kennedy
J. P. Markey
J. R. Patterson
W. F. Sailer
P. R. Shoop
P. D. Sigler
H. M. Terwilliger
M. D. Weber
E. C. Wenzinger

When the IEEE Standards Board approved this standard on June 11, 1987, it had the following membership:

Donald C. Fleckenstein, *(Chairman)*
Marco W. Migliaro, *(Vice Chairman)*
Andrew G. Salem*, Secretary*

James H. Beall
Dennis Bodson
Marshall L. Cain
James M. Daly
Stephen R. Dillon
Eugene P. Fogarty
Jay Forster
Kenneth D. Hendrix
Irvin N. Howell
Leslie R. Kerr
Jack Kinn
Irving Kolodny
Joseph L. Koepfinger *
Edward Lohse
John May
Lawrence V. McCall
L. Bruce McClung
Donald T. Michael *
L. John Rankine
John P. Riganati
Gary S. Robinson
Frank L. Rose
Robert E. Rountree
Sava I. Sherr *
William R. Tackaberry
William B. Wilkens
Helen M. Wood

* Member emeritus

CLAUSE PAGE

CLAUSE PAGE

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]

---

[1] ANSI/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.

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

[3] This 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.

---

[4] The 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 the squares (SRSS), except where closely spaced modes apply. Closely spaced modes shall be appropriately considered in the response evaluation. Closely spaced modes are those with frequencies differing by 10% or less of the next lower frequency. In the analysis using three-dimensional (3D) individual earthquake components, the responses (acceleration, displacement, force, moment) due to two horizontal and one vertical component input should be combined at the last step by the square root of the sum of the square method (SRSS). When three-dimensional (3D) statistically indepen-dent time histories are input simultaneously, for a time history analysis, the responses can be combined algebraically at each time increment. To ensure statistical independence, artificially generated time histories should have coherence values of less than 0.5 when computed with at least 12 data samples. Alternatively, an absolute value for the correlation coefficient of less than 0.3 for all time delays may be used (See Appendix E for further explanation).

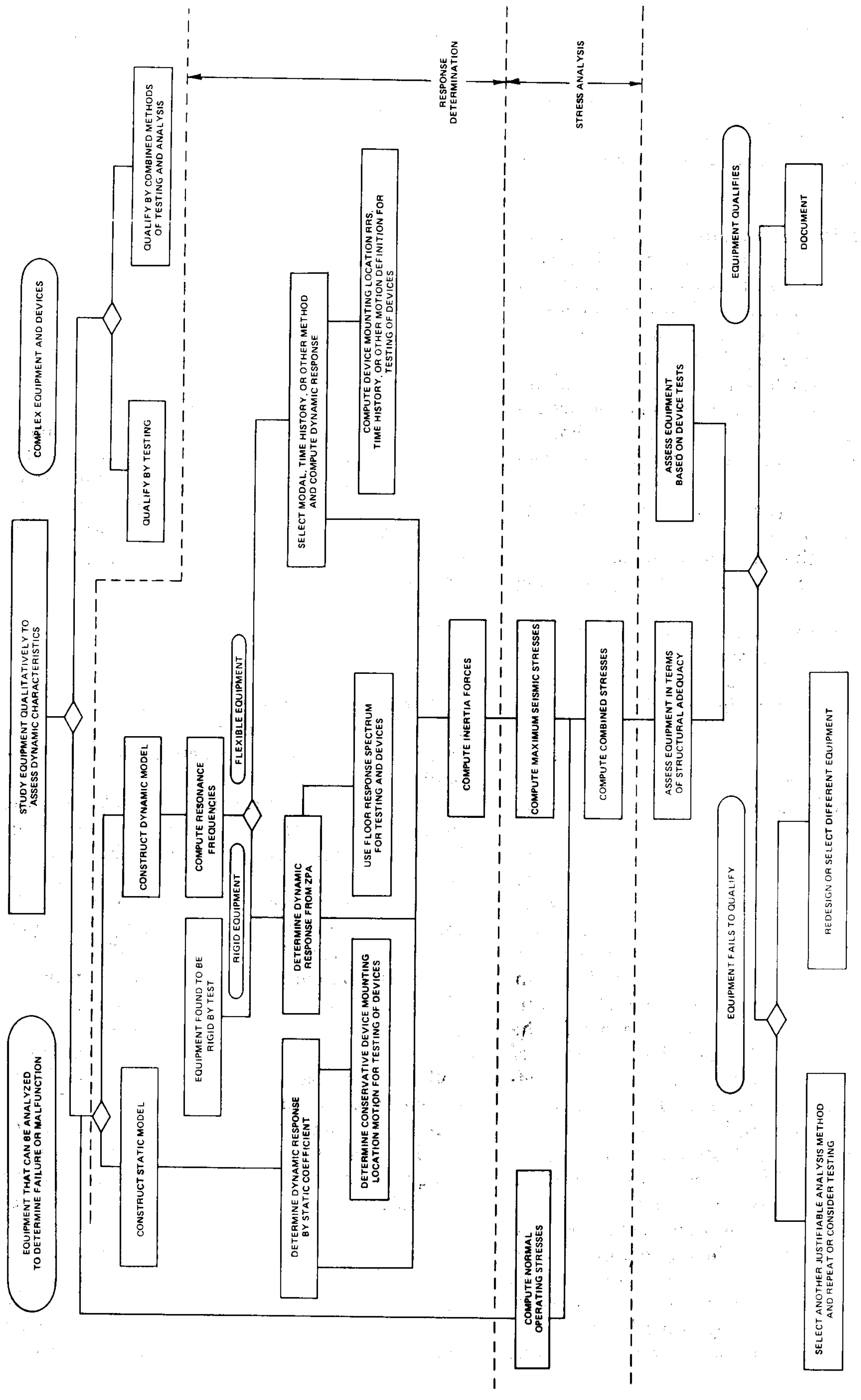

Figure 1—Seismic Analysis Flowchart

6.3 Static Coefficient Analysis

This is an alternate method of analysis that allows a simpler technique in return for added conservatism. A determination of natural frequencies is not required. The acceleration response of the equipment is assumed to be the maximum peak of the RRS at a conservative and justifiable value of damping. A static coefficient of 1.5 has been established from experience to take into account the effects of multifrequency excitation and multimode response for linear frame-type structures, such as members physically similar to beams and columns, which can be represented by a simple model. A lower static coefficient may be used when it can be shown to yield conservative results. In a static coefficient analysis, the seismic forces on each component of the equipment are obtained by multiplying the values of the mass times the maximum peak of the RRS times the static coefficient. The resulting force should be distributed over the component in a manner proportional to its mass distribution. The stress at any point in the equipment can then be determined by combining the stress at that point due to the earthquake loading in each direction using the SRSS method.

6.4 Nonlinear Equipment Response

Non-linearities may exist in addition to those associated with damping. These effects may be of a geometric nature, such as the closing of gaps, working of connections and rattling of components, or of a material source such as localized yielding. These effects may result in changing stiffness with increasing load. As frequency is also a function of stiffness, the frequencies may also change under increasing load. If a system exhibits significant nonlinearity, such behavior must be recognized and accounted for in any subsequent analysis so as to accurately predict the system response. If the nonlinearities cannot be adequately modeled, testing is required.

Nonlinearity may also occur as a result of local vibrations of equipment structure. One example has been the high-frequency rattling of electrical cabinet doors that are not solidly secured in place. When such a condition exists and the operability of the mounted devices is deemed sensitive to this type of equipment nonlinear behavior, the analytic procedure must account for the behavior and must be properly validated.

6.5 Other Dynamic Loads

The analytical methodology described in 6.3 and 6.4 for seismic loading is equally applicable to other dynamic loadings such as hydrodynamic. For further guidance on hydrodynamic loads see 7.1.6.1.

6.6 OBE and SSE Analysis

An analysis should be performed using one of the previously described methods, with an assumed number of OBE events (the number shall be not less than one and shall be justified for each site or five OBE shall be used). Each OBE should contain a fatigue-inducing potential that is similar to the earthquake response motion at the mounting of the equipment. For floor level excitation, this should be approximated by demonstrating that each excitation waveform will produce a response that includes the equivalent of at least ten maximum peakstress cycles. For ground level excitation, the number of equivalent peak-stress cycles may be different (see Appendix D). The number of OBE and the fatigue-inducing potential per OBE is important only for low-cycle fatigue-sensitive equipment. The analysis should determine that the structural integrity of the equipment is maintained in combination with other applicable loads during the OBE. The analysis must show that OBE events followed by an SSE will not result in failure of the equipment to perform its safety function. this may be particularly difficult to show for complex electrical equipment, in which case the use of the test procedures in Section 7. should be considered.

6.7 Documentation of Analysis

The demonstration of qualification shall be documented and shall include the requirements of the equipment application or specifications, the results of the qualification, and the justification that the methods used are capable of demonstrating that the equipment can perform its safety function (see Section 10).

7. Testing

7.1 Introduction

Procedures are presented in this section that can be used to seismically qualify equipment by test. Seismic tests should be performed by subjecting equipment to vibratory motion that conservatively simulates that postulated at the equipment mounting during an earthquake. The details of the test procedures given herein constitute the more common methods currently in use but do not preclude other justifiable methods. It is outside the scope of this recommended practice to give the theoretical basis for the test procedures. These may be found in the literature on dynamics. One practical problem that arises when attempting to establish the tests to be used to qualify equipment is the choice of the earthquake environment. Many factors must be considered (see Section 3.). These involve the location of the equipment, the nature of the equipment, the nature of expected earthquakes, and others. An additional consideration is whether the equipment is to be used in only one application, or many. When equipment is used in only one application, the seismic motion can be specified and the qualification test can be chosen to meet the specification (proof-testing). When the equipment is used in many applications, the test should be designed to qualify the equipment for future undefined applications (generic testing). Prooftesting and generic testing are discussed further in 7.2. Fragility testing, conducted to determine the limit of the equipment's capabilities, is discussed in 7.3. Another factor to be considered is the multidirectional nature of earthquakes. Equipment should be tested to conservatively account for these multidirectional effects. These are discussed in greater detail in 7.6.6.

Another practical problem arises in attempting to describe tests for devices (relays, motors, sensors, etc) and for complex assemblies such as control panels. In the first case, it is reasonable to assume that the device can be subjected to seismic tests while simulating the operating condition and monitoring its performance during the test; however, in the case of complex equipment, such as control panels, this may not be true. Such panels usually contain many devices that are part of several systems extending over many other panels located in various parts of the power generating station. To test such panels while in an operating condition may be impractical and in such cases the following alternate approach is recommended. Apply the appropriate vibration input (RRS) to the panel with the actual devices installed but inoperative, or with the device's dynamic properties simulated. The dynamic response at the device;s locations is measured and is used as input criteria to qualify the devices separately in an operating condition (see 7.4 and 7.5, NOTE). The purpose of installing the non-operating devices is to ensure that the panel exhibits the dynamic characteristics it will have when in use.

It is noted that an equipment that has been shaker-table tested should, in general, not be installed in a plant, unless it can be demonstrated that the accumulated stress cycles already experienced by the equipment will not degrade its ability to perform its safety function.

Regardless of whether devices or assemblies are to be proof tested, fragility tested, or generically tested, there are certain common considerations. These are listed in 7.1.1 through 7.1.5.

7.1.1 Mounting

The equipment to be tested shall be mounted on the vibration table in a manner that simulates the intended service mounting. The mounting method shall be the same as the recommended for actual service, and shall use the recommended bolt size, type torque, configuration and weld pattern and type, etc. The effect of electrical connections, conduit, sensing lines, and any other interfaces shall be considered and included in the setup unless otherwise justified. The orientation of the equipment during the test shall be documented and shall be the only one for which the equipment is considered qualified unless adequate justification can be made to extend the qualification to an untested orientation. The method of mounting the equipment to the shake table shall be documented and a description of any interposing fixtures and connections shall be provided. Interposing fixtures, when used, shall be such that their use will not filter out or change any frequencies from the input motion. The effect of such fixtures and connections must be evaluated and addressed in the report when they are only used during qualification and not for in-service mounting.

7.1.2 Monitoring

Functional and vibrational response parameters must be considered for monitoring Class 1E equipment during vibration testing.

Sufficient monitoring instrumentation shall be used to evaluate the functionality of the equipment before, during, and following its vibration-test exposure. Details of executing this requirement must be obtained from documents that pertain to the specific equipment. It should be noted that compliance with this requirement often takes a significant effort in test planning and implementation.

Sufficient vibration response monitoring instrumentation shall be used to allow determination of the applied vibration levels. It is recommended that vibration response monitoring instrumentation also be used to determine the response of the equipment along all three orthogonal input axes simultaneously at those points within the structure that reflects the equipment response associated with its structural integrity and its functionality. This data may be useful for structural design analysis, functionality failure analysis, for future design changes or device change-out, determining instructure response spectra, and other applications. The location of the vibration sensors and the functional monitoring system(s) shall be documented.

7.1.3 Refurbishment

Any refurbishment performed on equipment during a test program may be classified into maintenance or repair according to its degree. Examples of maintenance activities include calibration of relays and retorquing of hardware. Examples of repairs include welding or rewelding of portions of an equipment, replacing damaged components, such as sheared bolts, and retightening loose electrical terminals.

7.1.3.1 Maintenance

When maintenance is required, the severity of the problem shall be determined and documented in detail in the test report. Maintenance may be performed and testing continued. When maintenance is performed during OBE testing, it becomes part of the post earthquake field maintenance checks and procedures for the equipment.

7.1.3.2 Repairs

When repairs are necessary during the OBE test, retest is required unless justified otherwise. When repairs are necessary during or after the SSE test, the general requirement is to retest unless justified otherwise. When the condition requiring repair during the SSE tests does not interfere with the performance of the safety function, during or after the test, then the SSE can be shown to be not cumulative due to testing in other axes, and does not unacceptably affect equipment performance in subsequent qualification tests, such as LOCA, then continuation without retest may be justifiable. When repairs constitute a design change, the equipment must be retested, unless justified otherwise. When repairs are made, the details shall be included in the test report.

7.1.4 Exploratory Tests

Exploratory vibration tests are generally not part of the seismic qualification requirements, but may be run on equipment to aid in the determination of the best test method for qualification or to determine the dynamic characteristics of the equipment. These low input level vibration tests are normally described as resonance searches. They are generally performed at input levels well below the required seismic qualification vibration level. These tests can be performed in several ways. The most common method is the resonance search that is performed as a slowly swept sinusoidal vibration test with the input uniaxial. The equipment responses may be measured biaxially or triaxially to determine resonances and cross coupling. A second method involves impacting the equipment in a controlled manner at critical points on the structure, capturing the impact and response data and computing the transfer function between impact and response locations. The output is the transfer function and associated phase information. A third method involves the use of a broadband random input signal and simultaneous measurement of response at locations of interest.

The transfer function and associated phase relationship between excitation and response locations are computed.

7.1.4.1 Resonance Search by Base Excitation

This method offers the advantage that it can be performed on the same type of vibration equipment used for the qualification vibration test. The resonance search is generally performed just prior to the qualification seismic vibration test as the information gathered may be useful in performing it. Resonances are determined by instrumenting the structure with accelerometers at the input location and at those locations where the structural response is desired. Generally, a slowly swept low-level sinusoidal vibration should be employed. The sweep rate should be two octaves per minute, or less, to ensure resonance buildup. A 0.2 g peak input is the conventional input level but it may be adjusted lower to avoid equipment damage, or higher to take nonlinearities into consideration. It is recommended that the resonance search be carried beyond 33 Hz, for example, to 50 Hz, or to the RRS cutoff frequency, whichever is higher, to obtain data on equipment dynamic characteristics that may be valuable to justify qualification for other dynamic loads.

The user is cautioned that if the equipment is not mounted on its service foundation for the resonance search, the mass and stiffness of the mounting used may have a significant effect on the accuracy of the results. When large equipment is tested on a table, coupled table / equipment modes may exist, which should not be interpreted as equipment modes.

Structural resonances are normally detected by observing amplifications of the input motion in the test item. Phase relationships between the sinusoidal input signal and the structural response at the point of measurement may also be helpful in defining resonances. A higher degree of confidence in establishing resonance is obtained by combining amplification and phase data. Similar results may be obtained by base excitation with low-level broadband random motion. In this case transfer functions and phase data are obtained by Fast Fourier Transform (FFT) analysis of excitation and response time histories. Caution must be exercised to ensure that the number of data samples acquired and the resolution bandwidth correspond to the transfer function accuracy desired. An FFT analyzer is usually required for this technique.

7.1.4.2 Resonance Search by Impedance Methods

Resonance search by impedance methods may be accomplished by exciting the structure with a small portable shaker or by impact testing. The induced vibration under such conditions is usually of small amplitude in nature. Caution should be exercised in applying the test results for large amplitude earthquake response conditions. See 8.2 for further discussion.

7.1.4.3 Application of Resonance Search Data

All resonances should be recorded for possible use as

1) Design information
2) Necessary data for certain test methods
3) Data for use in potential qualification efforts

When it can be shown that the equipment is not resonant at any frequency within the amplified frequency range of the RRS, it may be considered rigid and analyzed or tested accordingly. On the other hand, when resonances exist, or when the configuration of the equipment is such that critical resonant frequencies cannot be ascertained due to either the complexity of the equipment or the inaccessability of critical parts, the equipment should be tested according to one of the various methods of 7.6 or another justifiable method.

It must be noted that, because of nonlinearities, resonance responses at high levels may differ in frequency and damping from those at low levels, and further, that resonance response may not be excited at all at low levels. Therefore, a low-level exploratory test may not be conclusive as an indication of either equipment dynamic response or lack of resonances. When nonlinearities are suspected, it may be necessary to perform the exploratory test at more than one input level.

7.1.5 Vibrational Aging

Seismic qualification tests on equipment designed to show adequacy of performance during and following a SSE must be preceded by tests that produce the equivalent fatigue effect of the number of OBE specified for each site and the equivalent fatigue effects of specified in-plant vibration resulting from normal and transient plant operating conditions. It is suggested that the equivalent conditions consistent with the service life of the facility be simulated if possible; however, as a minimum, the equivalent fatigue effects consistent with the qualified life of the equipment must be achieved.

The purpose of the vibrational aging is to show that the lower levels of normal and transient vibration, associated with plant operation and the lower intensity earthquake that has a higher probability of occurrence, will neither adversely affect an equipment's performance of its safety function nor cause any condition to exist that, if undetected, would cause failure of such performance during a subsequent SSE. These tests may also provide part of the aging requirement of ANSI/IEEE Std 323-1983 [2]. Vibration-aging tests shall be performed preceding the OBE and SSE tests.

7.1.5.1 Aging from Nonseismic Vibration Conditions

Portions of the seismic tests may be used to provide part of the aging requirement of ANSI/IEEE Std 323-1983 [2] for the specified nonseismic related vibration due to normal and transient plant operating conditions and inplant vibration. It shall be demonstrated that the equivalent amplitude response cycles achieved in the seismic tests, excluding those required for the seismic low-cycle fatigue requirement, exceed the amplitude response cycles required for the nonseismic vibration loads (See 7.6.5 and Appendix D for discussion on equivalent cycles). Credit may be taken for any test preceding the SSE. However, special care must be taken in establishing equivalency when the nonseismic vibration loads, such as a safety relief valve (SRV) load, contain significant frequency content greater than 33 Hz, or when the applied nonseismic forcing function is substantially different from that achieved during the base excited motions simulated in the tests discussed in subsequent sections. In the latter case, the nonseismic loading could result in excitation of equipment vibration modes not excited by base motions.

The amplitude response cycles may be determined by analysis as discussed in Section 6. or by short tests conducted with the equipment in a simulated nonseismic vibration condition.

7.1.5.2 Seismic Aging (OBE)

Seismic qualification tests on equipment must include OBE tests, preceding the SSE, that produce a number of equivalent maximum peak cycles (at least as given in 7.6.5) for each specified seismic event. The number of OBE shall be justified for each site or shall produce the equivalent effect of five OBE.

7.1.6 Loading

Seismic qualification tests on Class 1E equipment shall be performed with the equipment subjected to normal operating conditions (electric loads, mechanical loads, thermal loads, pressure, etc), and other plant conditions that may adversely effect the safety function. Simulation of these loads is acceptable if it is justified. If not included as part of the test, the absence of the loading effect shall be justified.

7.1.6.1 Hydrodynamic Loads

Some of the equipment in nuclear power plants is subjected to vibratory loads that are categorized as hydrodynamic loads. These include the loads associated with SRV discharge and the loss-of-coolant accident (LOCA). Hydrodynamic loads effect the aging requirement (see 7.1.5) and the seismic testing requirement.

Since the structural integrity and operability of the components must be evaluated under the simultaneous effects of the seismic and other vibratory loads, a combined spectrum is required for the RRS, that is, OBE or SSE combined with vibratory loads. The RRS for testing may be obtained by an appropriate combination of the individual spectra such as SRSS or absolute sum.

7.2 Proof and Generic Testing

Proof testing is used to qualify equipment for a particular requirement. A proof test requires equipment to be subjected to one of the tests described in 7.6. The equipment must be subjected to the particular response spectrum, time history, or other parameters defined for the mounting location of the equipment. No attempt need be made to explore the failure thresholds of the equipment. Therefore, the proof test requires the preparation of a detailed specification. The specification is usually written by the ultimate user as an application requirement. The equipment is tested to the specified performance requirement and not to its ultimate capability. Generic testing may be considered a special case of proof testing. The specification is usually written to encompass most, or all, of the known requirements. The objective is to show qualification for a wide variety of applications during one test. The resultant generic RRS typically encompasses a wide frequency bandwidth with relatively high acceleration levels. The user is cautioned that the enveloping of a variety of requirements can produce a very severe test motion.

7.3 Fragility Testing

Fragility testing is used to determine the ultimate capability of equipment. Such information may later be used to prove adequacy for a given requirement or application.

Fragility testing should be performed in a manner that yields equipment capability data that can be related to, and compared with any of the various requirements from various installations and agencies.

For some requirements, an equipment's capability can be best defined by a demonstration of its response to sine beat (or transient) type excitation. For other requirements, it may be defined by a demonstration of its response to continuous sine excitation. Still other equipment capability may be defined by a demonstration of its response to multifrequency wave-forms. A measurement of the equipment's fragility level for a particular motion excitation constitutes a demonstration of its ultimate capability to perform its required safety function when subjected to that motion.

Variations in the seismic environment have been shown to influence the fragility level of an equipment or system. One such variation is the directional nature of the excitation. In addition, the environment may possess the characteristics of a shock, a transient, or a steady-state vibration. The tests outlined in 7.6 may be performed to establish fragility data using the guidelines of that section to ensure proper application (See Appendix C for additional guidance on fragility testing).

7.4 Device Testing

Devices shall be tested simulating operating conditions to either the levels dictated by expected service requirements or their ultimate capability. The devices shall be mounted on the shake table in a manner that dynamically simulates the recommended mounting. When a device is intended to be mounted on a panel, the panel should be included in the test mounting, or the response at the device mounting location should have been monitored during the assembly testing (see 7.5), in which case the device may then be mounted directly to the shake table for the simulation of in-service excitation.

Some types of equipment, such as cabinets with bolted doors or panels, produce impacts, rattling, chatter, or banging. These impacts are transmitted throughout the equipment and result in increased acceleration levels at frequencies much higher than the original frequencies input to the shake table. A low-frequency input thereby produces high-frequency response that may adversely affect devices mounted in the equipment and must be considered in their .qualification. When this is the case assembly testing is preferred, or the device mounting location RRS obtained in the assembly test must include the effect of impacts in the time history by analyzing the motion to sufficiently high frequencies. Devices may then be tested using the methods described in 7.6, or any other justifiable methods. When such impacts are present additional provisions should be included to demonstrate that the time history for device testing is conservative in terms of duration, amplitude, and frequency content. Methods of demonstrating adequate frequency content include plotting a TRS or a PSD to higher frequencies.

7.5 Assembly Testing

It is preferred that large complex assemblies be tested simulating operating conditions and be monitored for proper functional performance; however, in cases such as control panels containing parts of many systems it is not always practical to simulate all conditions simultaneously. It is acceptable, therefore, to test such equipment in an inoperative mode with the actual or simulated devices installed including nonsafety related devices. The test should determine the vibration response at the device location by either direct measurement at full excitation or by determination of the transfer function from the assembly mounting points to the device mounting points. The resulting vibration response of the device at its location in the assembly shall be less than the vibration to which the device is qualified. In either case, the test methods described in 7.6 or other justifiable methods may be used. The assembly shall be examined following the test and the integrity of any untested Class 1E parts (for example, wiring, etc) verified.

NOTE — It should be recognized that when testing assemblies with dummy devices installed, the TRS from the device location may be excessive due to overtest of the assembly since it is not practical to closely envelop all RRS with the table motion.

7.6 Test Methods

7.6.1 Introduction

Present test methods generally fall into three major categories. They are proof or generic testing (7.2) and fragility testing (7.3). The types of motion available to best simulate the postuseismic environment fall into two categories; single frequency and multiple frequency. The method chosen will depend upon the nature of the expected vibra-tion environment and also somewhat on the nature of the equipment. The various technical requirements appropriate to each test method may provide extra benefits for specific applications.

In general, the proof or generic test seismic simulation waveforms, or both, should

1) Produce a TRS that closely envelops the RRS using single or multiple-frequency input as required to provide a conservative (but not overly so) test-table motion
2) Have a peak acceleration equal to or greater than the RRS ZPA
3) Not include frequency content above the RRS ZPA asymptote
4) Have a duration in accordance with the requirements of 7.6.5

Consideration must also be given to the choice of single-axis or multiple-axis testing as described in 7.6.6 and margins as noted in Section 4.

7.6.1.1 Artificially Broadened Response Spectra

For a floor-level motion, the RRS may be dominated by a single structural resonance. For this case, the RRS is usually broadened to cover the uncertainty in the building structural frequency. This has the effect of making the RRS artificially conservative since the response peak can occur only at a specific frequency and not throughout the entire broadened band. An acceptable testing procedure in this case is as follows:

When the center frequency in the broadened area is f_c, testing may be conducted at this frequency and in addition at the frequencies $fc \pm \Delta f_c, f_c \pm 2\Delta f_c, \ldots, f_c \pm n\Delta f_c$, where Δf_c corresponds to a 1/6 to 1/3 octave interval to envelop the entire broadened area. The TRS generated during each individual test must have the same shape and width as the original narrowband response spectrum (similar to Fig 4). The specification should state clearly the existence of this case to avoid confusion with an RRS that results from genuine broader frequency motion requirements.

7.6.1.2 Test Response Spectrum Analysis

Test response spectra (TRS) must be computed using either justifiable analytical techniques or response spectrum analysis equipment and should be developed over the frequency range of interest. It is recommended that the TRS be computed with 1/6 octave or narrower bandwidth resolution. Any filtering of the acceleration signal performed within the frequency range of analysis must be defined.

7.6.1.3 Damping Selection

The RRS are usually specified at several levels of damping. When available, the RRS with a damping of 5% is the recommended choice for use in testing. The application of damping for testing is described in 5.3.2.

7.6.2 Single-Frequency Test

When the seismic ground motion has been filtered due to one predominant structural mode, the resulting floor motion may consist of one predominant frequency. In this case, a short duration steady-state vibration can be a conservative input excitation to the equipment. Further, single-frequency testing may be used to determine (or verify) the resonant frequencies and damping of equipment. If it can be shown that the equipment has no resonances, or only one resonance, or resonances are widely spaced and do not interact, or if otherwise justified, single-frequency test may be used to fully test the equipment.

The TRS from single-frequency testing suits from each individual frequency and may not be generated as the composite of several nonsimultaneous single-frequency tests unless otherwise justified.

7.6.2.1 Derivation of Test Input Motion

For any waveform employed, the shake-table motion should produce a TRS acceleration at the test frequency, at least equal to that given by the RRS. The peak input acceleration must be at least equal to the ZPA of the RRS except at low frequencies where the RRS goes below and stays below the ZPA for which the value of the RRS must be met. See 7.6.6 for guidance on the number of axes required for testing. For flexible equipment with more than one predominant frequency, and when the RRS has the characteristics of a multiple-frequency broad-band response spectrum, the conditions in 7.6.2 may be difficult to fulfill. Specifically, it may not be practical to attempt a demonstration where modes do not interact to reduce the seismic fragility of equipment. When this is the case, single-frequency tests may be applied according to 7.6.2.1.2 based on the expected behavior or fragility of equipment under vibratory conditions used to determine its seismic qualification.

7.6.2.1.1

When the performance of equipment can be assessed by structural integrity alone, in terms of stress and strain such as in structures and static electrical or passive devices, then the maximum response in equipment governs without regard to the precise vibratory nature or frequency content of the excitation. The motion of the shake table should produce a TRS at the test frequency of 1.5 times that given by the specified RRS peak unless justified to be less. This conservatively allows for combined multimode response. The choice of the preceding factor depends on the shape of the RRS with the largest value (1.5) applicable to a broadband RRS. As a consequence, the TRS need not completely envelop the RRS. Alternatively, when all the resonances of the equipment can be definitely established by an actual test, it will be sufficient for the single-frequency TRS to envelop the RRS only at the equipment resonances with one single-frequency input.

7.6.2.1.2

When the performance of equipment must be assessed by the combination of structural integrity and operability, as for example in electro-mechanical devices, such as relays or instruments, then the precise vibratory nature and frequency content of the excitation will produce equipment responses that determine its fragility. Justification must be provided so that the 1.5 factor (see 7.6.2.1.1) is sufficient to allow for combined multimodal response and to produce a vibratory motion to adequately simulate the effects that the intended multifrequency motion would have on equipment performance. The choice of the factor depends on the nature of the equipment and the shape of the RRS with the largest value, which may require a factor greater than 1.5, applicable to broadband RRS. Consequently, the TRS need not completely envelop the RRS provided proper justification is given. In addition, testing must be performed at all equipment resonances and at frequencies spaced no farther apart than 1/2 octave intervals up to the cutoff frequency unless otherwise justified. Alternatively, when all the resonances of the equipment can be definitely established by an actual test, it will be sufficient for the single-frequency TRS to envelop the RRS only at the equipment resonances with one single-frequency input.

7.6.2.2 Continuous-Sine Test

A test at any frequency should consist of the application of a continuous sinusoidal motion at the frequency and amplitude of interest and with a total duration and low-cycle fatigue potential at any frequency at least as given in 7.6.5. The test frequencies of interest are those at the resonances of the equipment being tested and others as given in 7.6.2.1. The maximum acceleration corresponds to that for which the equipment is to be qualified and should at least produce the maximum response acceleration given in 7.6.2.1.

7.6.2.3

Sine-Beat Test. A test at any frequency should consist of the application of a series of at least five sine beats with a sufficient pause between each so that no significant superposition of equipment response motion results. The sine beats consist of sinusoids at the frequency and amplitude of interest, as shown in Fig 2. Each sine beat should consist of a number of cycles of motion (usually 5 or 10) to produce a TRS acceleration in accordance with the criteria given in 7.6.2.1. The test frequencies of interest are those at the resonances of the equipment being tested and others as given in 7.6.2.1. The total test duration and the low-cycle fatigue potential at any frequency should be at least as given in 7.6.5.

For a given beat-peak amplitude, the degree of test conservatism will increase as the number of cycles per beat increases until the conservatism approaches that of the sinusoidal waveform in 7.6.2.2.

NOTES:

1 — As used in this recommended practice, the amplitudes of the sinusoids represent acceleration and the modulated frequency represents the frequency of the applied seismic stimulus.

2 — Beats are usually considered to be the result of the summation of two sinusoids of slightly different frequencies with the frequencies within the beats as the average of the two, and the beat frequency as half the difference between the two. However, as used herein, the sine beats may be amplitude-modulated sinusoids with pauses between the beats.

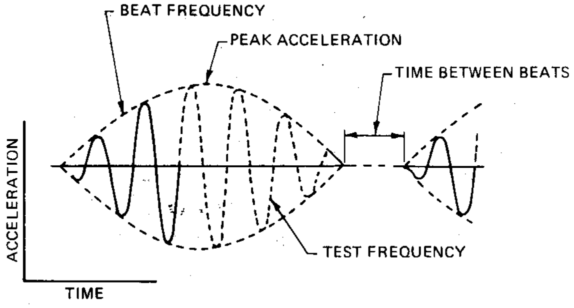

Figure 2—Sine Beat

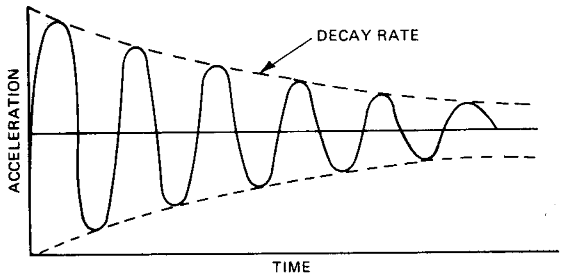

Figure 3—Decaying Sine

7.6.2.4 Decaying-Sine Test

A test at any frequency should consist of the application of at least five decaying sinusoids at the frequency and amplitude of interest with a sufficient pause between the sinusoids so that no significant superposition of equipment response motion results. The total test duration and low-cycle fatigue potential at any frequency should be at least as given in 7.6.5. The decaying sinusoids consist of a single frequency of exponentially decaying amplitude as shown in Fig 3. The test frequencies of interest are those at the resonances of the equipment being tested and others as given in 7.6.2.1. The peak acceleration of the sinusoid corresponds to that for which the equipment is to be qualified and should at least produce the maximum response acceleration given in 7.6.2.1. For a given peak amplitude, the degree of conservatism will increase as the decay rate decreases until the conservatism approaches that of the sinusoidal waveform in 7.6.2.2.

7.6.2.5 Sine-Sweep Test

In this test, a sinusoidal input with continuously varying frequency is applied to the equipment. The frequency band should cover the range for which the equipment is to be qualified, including the equipment resonances and other frequencies as given in 7.6.2.1. This closely approaches the conservatism of the continuous-sine test in terms of producing maximum response. The percentage of steady-state resonance response obtained depends on the sweep rate and the equipment damping. For sweep rates of two octaves per minute, or less, and for typical equipment damping, this percentage exceeds 90. Maximum response is obtained separately at every frequency in the test range. Consequently, this test produces the most thorough search for all resonant frequencies and it is customarily used for this purpose as an exploratory test, with a low input level such as 0.2 g.

To qualify an equipment, the total sine-sweep test duration and equivalent maximum peak cycles at any frequency should be at least as given in 7.6.5. The maximum acceleration corresponds to that for which the equipment is to be qualified and should at least produce the maximum response acceleration given in 7.6.2.1. The TRS may not be a composite of the entire frequency sweep. It must be the response spectrum centered around any single frequency.

7.6.3 Multiple-Frequency Tests

Seismic ground motion is recognized to contain multiple-frequency energy content up to approximately 33 Hz. When this relatively broadband ground motion has not been strongly filtered by the building or the soil, or both, the resulting floor motion that affects the equipment tends to retain the original broadband characteristics. Furthermore, even if strong filtering is present but is caused by two or more distinct building modes, the floor motion will still comprise a complex wave with dominant frequencies at each of the building or soil natural frequencies, or both. In these cases, multiple-frequency testing is applicable for qualification. Specific shake-table excitation includes random or complex time histories, depending on the frequency distribution necessary to simulate the required floor motion. The intent is to produce a table motion that reasonably approximates that which is postulated to occur at the mounting of the equipment for the particular earthquake.

Multiple-frequency testing is intended to provide a broadband test motion that is particularly appropriate for producing a simultaneous response from all modes of a multidegree-of-freedom system whose malfunction may be caused by modal interaction. Multiple-frequency testing provides a closer simulation of a typical seismic motion without introducing a higher degree of conservatism.

There are a number of available waveforms that may be used as test motions to simulate the particular seismic excitation at the mounting of the equipment. Several types of multiple-frequency tests employing these different waveforms are given in 7.6.3.2 through 7.6.3.4. Some test types will be better than others for simulating a specific type of equipment excitation condition, and the degree of conservatism will vary from one type of test to another. The choice of test type will depend on the extent to which the ground motion is filtered by the dynamic characteristics of the building, or soil,or both, to produce the excitation to the equipment at the particular floor level of the building. Other waveforms, or types of multiple-frequency tests, not specifically discussed in this section, may also be employed provided they can be shown to possess similar characteristics for exciting the equipment being tested. Generally, the criteria described in 7.6.3.1 for the derivation of the test input motion are used to justify the adequacy of the test.

7.6.3.1 Derivation of Test Input Motion

For any waveform employed, the motion of the shake table must be adjusted so that

1) The TRS envelops the RRS over the frequency range for which the particular test is designed.
2) For comparison of the TRS and the RRS, the TRS is computed with a damping value equal to or greater than that of the RRS, using the appropriate damping values in 5.3.2 and 7.6.1.2.
3) The shake-table maximum peak acceleration is at least equal to the ZPA of the RRS (See Appendix A for suggestions on the measurement of ZPA).
4) The total test duration and low-cycle fatigue potential are as those in 7.6.5.
5) The time history indicates frequency content at least as broad as that defined by the amplified region of the RRS.
6) The time history indicates waveform stationarity, that is, the statistical parameters (for example, frequency content and amplitude probability distribution) do not vary significantly throughout the test.

To account for the above factors, it is necessary to show that the frequency content of the test waveform is at least as broad as the frequency content of the amplified region of the RRS (except perhaps at the low-frequency end, see 7.6.3.1(10) and 7.6.3.1(13)). There are several techniques for showing this, for example, show that

7) The enveloping of the RRS by the TRS is obtained with similar spectrum shapes so that similar amplifications at significant spectrum peaks in the amplified regions of the spectra result.
8) The frequency content of the Fourier transform of the test waveform is compatible with the amplified portion of the RRS
9) The frequency content of the test waveform PSD is compatible with the amplified portion of the RRS.

It is also intended that stationarity exists over the strong motion portion of the test wave-form. This can be demonstrated by showing that the frequency/amplitude content of the waveform is statistically constant with time (See Appendix B for further explanation of frequency content and stationarity). The RRS occasionally require high acceleration levels at the lowest frequencies that require very high test-table displacement capability. The general requirement for enveloping the RRS by the TRS can be modified under the following criteria.

10) In those cases where it can be shown by a resonance search that no resonance response phenomena exist below 5 Hz, it is required to envelop the RRS only down to 3.5 Hz. Excitation must continue to be maintained in the 1 Hz to 3.5 Hz range to the capability of the test facility.
11) When resonance phenomena exist below 5 Hz, it is required to envelop the RRS only down to 70% of the lowest frequency of resonance.
12) When the absence of resonance response phenomena or malfunction below 5 Hz cannot be justified, the general requirement applies and the low-frequency enveloping should be satisfied down to 1 Hz.
13) Under any circumstances, failure to envelop the RRS at, or above, 3.5 Hz must be justified.

In the performance of a test program, the TRS may, on occasion, not fully envelop the RRS. The general requirement for a retest may be exempted if the following criteria are met:

14) A point of the TRS may fall below the RRS by 10%, or less, provided the adjacent 1/6 octave points are at least equal to the RRS and the adjacent 1/3 octave points are at least 10% above.
15) A maximum of 5 of the 1/6 octave analysis points may be below the RRS, as in 7.6.3.1(14), provided they are at least one octave apart.

7.6.3.2 Time-History Test

A test may be performed by applying to the equipment a specified time history that has been synthesized to simulate the seismic input. It must be demonstrated that the actual motion of the shake table is as severe as, or more severe than, the required motion. This can be accomplished by a direct comparison of the table-motion time history with the specified motion by means of an oscilloscope or oscillograph trace. A comparison can further be made through the use of response spectra of the required motion and the table motion. In the latter method, a response spectrum of the specified motion (RRS) is developed for the appropriate damping given in Section 5. Subsequently, a table motion is developed so that its TRS envelops the RRS according to the general criteria of 7.6.3.1.

It should be recognized that these two comparison methods can have significantly different degrees of sensitivity and hence, differing adequacy for testing different physical effects. For example, when very low frequencies are important, direct comparison of displacement time histories are useful. On the other hand, if intermediate to high frequencies (up to 33 Hz) are important, then comparison of accelerations or a computation of response spectra is more useful.

7.6.3.3 Random-Motion Test

A test may be performed by applying to the equipment a random excitation, the amplitude of which is adjusted either manually or automatically in multiple-frequency bands. The exact bandwidth of individual bands employed is left to the discretion of the test engineer. Typically, 1/3 octave bands are considered for analog synthesis equipment. Digital synthesis equipment may require narrower bands or intervals. However, the use of wider bands may be adequate in some cases where unfiltered ground-level motion is intended. On the other hand, use of very narrow (that is, 1/6 octave) bands may be necessary when filtering by building resonances is intended in the input motion. In any event, the process involves use of an aggregate of multiple narrowband signals that is input to the shake table with each band adjusted until the TRS envelops the RRS according to the criteria given in 7.6.3.1. For an analog signal synthesis system, the multiple-band frequency source may be either a random noise generator and multiple-channel filter combination, or multiple signals taped on individual channels of an analog tape recorder. A third practical signal synthesis system is a digital computer program that has the capability of computing the inverse of the shaker system transfer function and applying it to the desired table-motion time history. For all types of signal sources, a gradual buildup, hold, and decay of the signals provide a realistic simulation of an actual seismic event.

7.6.3.4 Complex-Motion Tests

In many cases, the required motion may represent significant filtering of ground motion by one or more sharp building or soil resonances, or both. The corresponding RRS may include medium-to-low level amplification over a broad frequency range, with highly amplified narrow-bands associated with each building resonance. For these cases, the use of a random motion test (even with narrow individual bandwidth resolution) may require an unreasonably high maximum peak value of the input so as to meet the higher amplification associated with the building resonances. It is permissible to synthesize a complex signal that comprises the summation of several different types of individual narrowband components superimposed on lower level broadband random motion. This approach affords a better chance of producing a table motion whose TRS will envelop the RRS, according to the criteria of 7.6.3.1, without introducing excessive ZPA levels. Several typical methods of synthesizing complex signals are described in 7.6.3.4.1 through 7.6.3.4.5. For each of these test methods the criteria of 7.6.3.1 must be met. Success in the use of any one of these methods will depend on the type of synthesis equipment available, the exact shape of the RRS, and the experience of the test engineer. The methods described below have been utilized sufficiently to warrant special mention. However, further combinations of these and other signal components may be used as necessary to produce the required table motion.

7.6.3.4.1 Random Motion with Sine Dwells

To meet an RRS that includes a moderately high peak random excitation may require an unreasonably high peak value of the input. In this case, a broadband random motion is first synthesized similar to the description given in 7.6.3.3. The levels of individual frequency bands are adjusted until as much of the RRS, or the lower level broadband portion of the RRS, is enveloped by the TRS using a peak input acceleration that is at least equal to, but not substantially greater than, the required ZPA. Then a sine dwell is added at each frequency corresponding to a sharp peak of the RRS until this TRS envelops the RRS according to the criteria given in 7.6.3.1. The duration of the sine dwell is made equal to the total test duration. When more than one sine dwell frequency is required, all must be initiated simultaneously and continue for the duration of the test run. (For the case of artifically broadened spectra, 7.6.1.1 may apply. In this case a series of tests, each with a different sine-dwell frequency, may be performed to cover the broadened area.) This technique generally affords the maximum amount of amplification possible for a given narrowband RRS.

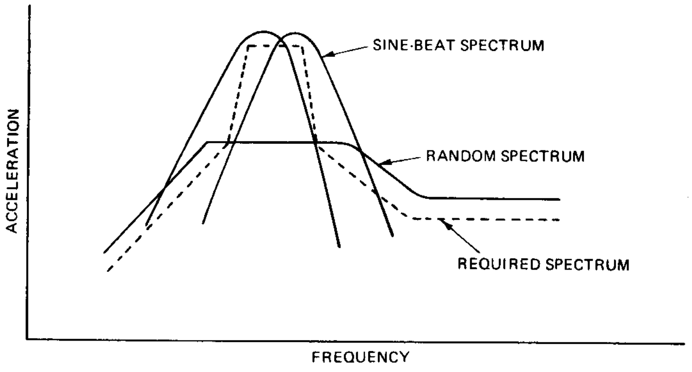

Figure 4—Random Spectrum With Superimposed Sine Beats

7.6.3.4.2 Random Motion with Sine Beats

This motion is similar to that of 7.6.3.4.1 except that sine beats are used in place of sine dwells. The same criteria of motion synthesis, test duration, and simultaneous initiation of sine beats are applicable in this type of test (For the case of artifically broadened spectra, 7.6.1.1 may apply, in which case a series of tests, each with a different sine-beat frequency may be performed to cover the broadened area. See Fig 4). Multiple applications of sine beats, spaced throughout the duration of the test, are applied for each required frequency. The number of cycles per beat becomes an additional parameter that can be adjusted for best results to meet the enveloping criteria of 7.6.3.1. The optimum number of cycles per beat may be determined from Fig 5, which gives resonance amplifications of sine beats for different cycles per beat and damping values.

7.6.3.4.3 Combination of Multiple Sinusoids

This motion consists of the summation of multiple sine waves (sinusoids) with distinct frequencies that include the resonant frequencies of the equipment up to the cutoff frequency. The frequencies of the sinusoids should be spaced typically at 1/3 octave or at narrower intervals to meet the enveloping criteria of 7.6.3.1. All sinusoids must be initiated simultaneously and continue for the duration of the test run. Each frequency must have individual amplitude and phase controls. When many distinct frequency sinusoids are combined, the result approaches broadband random motion. This method can be readily used in digital synthesis of required table motion.

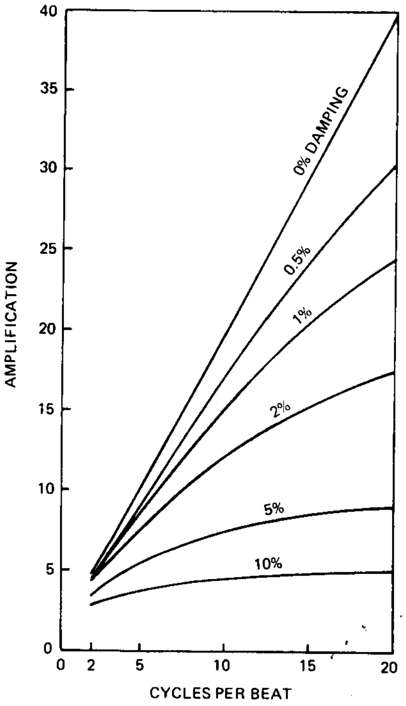

Figure 5—Resonant Amplification Versus Cycles Per Beat

7.6.3.4.4 Combination of Multiple Sine Beats

This motion is similar to that of 7.6.3.4.3 except that a series of sine beats at each distinct frequency is used in place of the sinusoids. The same criteria of 7.6.3.4.3 for the test frequencies, octave spacing, simultaneous initiation of the sine beats, and continuously repeated and test duration are applicable in this type of test. As in 7.6.3.4.2, the number of cycles per beat can be adjusted for best results to meet the enveloping criteria of 7.6.3.1. As with the combination of multiple sinusoids, if many distinct frequency sine beats are combined, the result approaches broadband random motion.

7.6.3.4.5 Combination of Decaying Sinusoids

A complex wave comprising the aggregate of multiple decaying sinusoids can sometimes be used to produce a medium band-with TRS with a reasonably low ZPA. The frequencies of the component signals should be spaced typically at 1/3 octave or narrower intervals to meet the enveloping criteria of 7.6.3.1. The decaying sinusoids should have individual decay rate controls over the damping range from 0.5% to 10%. Each frequency must have individual amplitude and phase controls. All frequencies must be initiated simultaneously and continuously reinitiated for the duration of the test run. It is desirable to vary the decay rate and the amplitude of each frequency to optimize the fit of the TRS to the RRS. The resulting motion must be justifiable as representative of the strong motion portion oft he SSE.

7.6.4 Other Tests

When there are vibration tests other than those described in 7.6.2 and 7.6.3 that are equally justifiable and that conservatively simulate the expected seismic environment, they may be used instead.

The following factors must be considered to justify the test method employed to qualify equipment:

1) Bandwidth of the RRS compared to that of the TRS and equipment characteristics and responses
2) Duration of the test compared to the defined seismic event
3) Peak acceleration of the test input and the magnification observed (that is, the indicated frequency distribution of the input)
4) Natural modes and vibration frequencies of the equipment
5) Typical equipment damping
6) Fragility levels
7) Low-cycle fatigue potential
8) In any case, the TRS must envelop the RRS according to the criteria of 7.6.3.1

7.6.5 Test Duration and Low-Cycle Fatigue Potential

To properly account for vibration buildup and low-cycle fatigue effects, it is necessary to specify the duration and the fatigue inducing properties of the input test waveform.

The duration of the strong motion portion of each test should at least be equal to the strong motion portion of the original time history used to obtain the RRS, with a minimum of 15 s. For multiple-frequency tests, the stationary part of the test defines the strong motion portion of one multiple-frequency waveform employed. For single-frequency tests, the duration is the sum of the individual durations of all tests at all different single frequencies (exclusive of the pause between beats). Note that the individual test duration at any single frequency should be sufficient to produce a TRS acceleration in accordance with the criteria of 7.6.2.1.

The fatigue-inducing potential of the test waveform should be at least equivalent to the strong motion portion of the earthquake response motion at the mounting of the equipment. This equivalence may be ensured for multiple-frequency testing by showing that the test waveform has a stationarity similar to that of the earthquake response motion, or that the test waveform generates a similar number of equivalent maximum peak-stress cycles when exciting a given structural resonant frequency.

See Appendix D for further discussion of test duration and equivalent number of maximum peak-stress cycles.

7.6.6 Multiaxis Tests

Seismic ground motion occurs simultaneously in all directions in a random fashion. However, for test purposes, single-axis, biaxial, and triaxial tests are allowed. If single-axis or biaxial tests are used to simulate the three-dimensional environment, they should be applied in a conservative manner to account for the absence of input motion in the other orthogonal direction(s). One factor to be considered is the three-dimensional characteristics of the input motion. Other factors are the dynamic characteristics of the equipment, flexible or rigid, and the degree of spatial cross-coupling response. Single and biaxial tests should be applied to produce adequate levels of excitation to equipment where coupling is significant and yet minimize the cross-level of over-testing where the cross-coupling is not significant. To expose potential failure modes, single-axis and biaxial tests must be performed in a number of directions as described in 7.6.6.1 and 7.6.6.2. In terms of total duration and fatigue induced, these tests are intended to be conservative.

7.6.6.1 Single-Axis Tests

Single-axis tests should conservatively reflect the seismic event at the equipment mounting locations and thereby account for the absence of motion in the other orthogonal directions. Single-axis tests are justified when the input motion can be shown to be essentially unidirectional, or when the equipment being tested can be shown to respond independently in each of the three orthogonal axes. The former is the case when a device is normally mounted on a panel that amplifies motion in one direction, when it is restrained to motion in one direction, or its response in one direction does not produce stresses at the same location as a response in any other orthogonal direction. The latter is the case when an equipment has very low cross-coupling among all axes, or when other justification can be given.

For single-axis tests, it is permissible to perform the required OBE followed by the SSE in each axis in sequence, or any other justifiable method whereby adequate OBE aging can be demonstrated.

7.6.6.2 Biaxial Tests

Biaxial tests should conservatively simulate the seismic event at the equipment mounting location. They should account for the absence of motion in one orthogonal direction for independent input motions in the other two orthogonal axes or for the absence of motion in two orthogonal directions if dependent inputs are used. The factors to be considered include the directional nature of the input motion and the cross-coupling of the equipment. Biaxial testing should be performed with simultaneous inputs in a horizontal and vertical axis. The selection of the horizontal axis may include the principal axes or some other direction selected to expose potential failure modes by testing the equipment in its most vulnerable direction.

Independent random inputs are preferred, and when used, the test shall be performed in two steps with the equipment rotated 900 about the vertical axis for the second step. To provide statistically independent simulated motions, the table time histories should have coherence values of less than 0.5 when computed with at least 12 data samples. Alternatively, an absolute value of less than 0.3 correlation coefficient for all time delays may be used (See Appendix E for further explanation). It is permissible to perform the required OBE followed by the SSE in the first step, followed by the same sequence in the second step, or any other justifiable method whereby adequate OBE aging can be demonstrated.

When independent random inputs are not used, four tests should be run

1) With the inputs in phase
2) With one input 180° out of phase
3) With the equipment rotated 90° about the vertical axis and the inputs in phase
4) With the same equipment orientation as (3) but with one input 180° out of phase

It is permissible to perform the required OBE followed by the SSE in (1) followed by the same sequence in (2), (3), and (4), or any other justifiable method whereby adequate OBE aging can be demonstrated.

7.6.6.3 Triaxial Tests

Triaxial tests, when performed, must be done with a simulator capable of independent motions in all three orthogonal directions. To provide statistically independent simulated motions, the table time histories should have coherence values of less than 0.5 when computed with at least 12 data samples. Alternatively, an absolute value of less than 0.3 correlation coefficient for all time delays may be used (See Appendix E for further explanation).

7.6.7 Line-Mounted Equipment

The seismic qualification of pipe-supported items of equipment, such as instrumentation and control components, devices, HVAC damper actuators, and valve actuators and their attached functional accessories for which operability must be demonstrated, requires special consideration. In establishing a seismic qualification program for such equipment, it must be recognized that the most critical seismic loading condition for line-mounted components will occur as a result of the response of the piping or duct system in which the component is located. This most critical condition provides an input motion to the component that is predominantly single frequency, that is, the natural frequency of the piping system in the vicinity of the component.

The following test method has been used to envelop the SSE seismic qualification requirements for power-plant pipe-supported equipment.

The pipe-supported equipment should be exposed to a series of single-frequency tests at equipment resonant frequencies, and one-third octave frequency increments throughout the range of 2 Hz through 32 Hz, or higher, if hydrodynamic loads must be considered. At each test frequency, the input amplitude should correspond to the levels specified by pipe system designers. This amplitude may be independent of direction. Therefore, the motion should be applied at the same frequencies and accelerations in each of the three orthogonal axes separately. It must be shown that the test amplitude is due only to the frequency of interest. Typical methods that can be employed include the use of bandpass or tracking filters. The test duration at each frequency should be the period of time required to establish full operability of the equipment or 10 s, whichever is longer.

The test procedure must be supplemented by an evaluation of any applicable pipe reaction nozzle loads imposed on the equipment. The definition of procedures for nozzle loads evaluation is considered to be beyond the scope of this recommended practice and is, therefore, not discussed further.

Further clarification and guidance may be obtained from ANSI/IEEE Std 382-1985 [3].

7.7 Test Documentation

See Section 10. for documentation procedure.

8. Combined Analysis and Testing

8.1 Introduction

Some types of equipment cannot be practically qualified by analysis or testing alone. This may be because of the size of the equipment, its complexity, or the large number of similar configurations. Large equipment, such as motors, generators, and multibay equipment racks and consoles, may be impractical to test at full levels due to limitations in vibration test equipment. This section specifically treats these types of equipments.

8.2 Modal Testing

Modal testing and analysis can serve as an aid to qualification of large and complex systems that have not been qualified by the methods given in Section 7. Modal testing is a useful method for determination of resonant frequencies, mode shapes, and often as a lower bound for modal damping. As a part of a model verification for a complex structure, a modal test may be performed to correlate the frequencies and mode shapes, determined during the analysis, with the measured response of the complex system. Two fundamentally different methods of modal testing are currently in use. These are commonly referred to as the normal-mode and the transfer-function methods. The normal-mode method involves mounting shakers to the structure and exciting the structure one mode at a time. The transfer-function method involves exciting all structural modes within a particular bandwidth simultaneously, computing the transfer function between points of excitation and response, and employing computer aided techniques to determine the resonant frequencies, damping, and mode shapes within that bandwidth.

8.2.1 Normal-Mode Method

With the equipment to be tested and mounted to simulate in-service mounting conditions, portable exciters should be attached to the structure at points previously determined to best excite the vibration modes to be analyzed. The structure should be instrumented with accelerometers, displacement transducers, or other motion-sensing devices with sufficient bandwidth to determine structural response. The structure should then be excited with a slowly swept sinusoidal vibration covering the frequency range of interest.

8.2.2 Transfer-Function Method

The transfer-function method is based upon the use of digital signal processing techniques and the fast Fourier transform algorithm to measure the transfer function between input and response locations on the structure. Transfer functions are obtained by exciting the structure with an impulse, sine sweep, or random vibration employing the type of exciters used for the normal-mode method. Caution must be exercised when selecting the location for exciting the equipment. A transfer function is obtained by measuring the input and the corresponding response and then dividing the Fourier transform of the response by the Fourier transform of the input. Modal parameters are identified by performing computations on the transfer function, at each node, until sufficient data is acquired to accurately describe the mode shapes and other modal parameters. Caution must be exercised so that the number of averages acquired correspond to the desired accuracy of the transfer function.

8.2.3 Analytical Methods Utilizing Test Data

Various analytical options exist for using the test data obtained. The resulting measurement of dynamic response parameters, such as resonant frequencies, mode shapes, and amplitude, can be used to verify the calculated values of previously formulated analytical models of the equipment. Alternatively, the measured mode shapes can be used directly in a response spectrum or time-history analysis. Specifically, the measured deflection between points for a participating mode shape can be scaled up according to the mode's deflection in the specified response spectrum. Finally, mathematical techniques are available to extract models directly from the parametric measurements. A mass and stiffness matrix can be extracted from the data by a series of formulae involving the matrix of mode shapes and the vectors of the modal mass, stiffness, and characteristic frequencies. These mass and stiffness matrices define a mathematical model of the structure that reproduces the measured characteristic response data.

If the structure exhibits significant nonlinearity in its response as a function of excitation level, the parametric measurements made in low-level excitation tests should be used with caution.

8.2.4 Qualification

Combined analysis and testing methods can adequately evaluate Class 1E equipment. These methods may be used to establish input response requirements at subcomponent locations. The qualification of the subcomponent is demonstrated by full-level testing of that component to a level equal to or greater than the established response at that location.

8.3 Extrapolation for Similar Equipment

The qualification of complex equipment by analysis only, without justification, is not recommended because of the great difficulty in developing an accurate equipment model and in obtaining numbers to describe the model physical parameters (see Section 6.). There are, however, many instances of equipment, similar to a type that was qualified, which differs only in size or in the specific qualified devices located in the assembly or structure. In such cases, it is neither practical nor necessary to test every variation of the basic qualified version. Furthermore, it may be shown that a given equipment to be qualified is similar to another that has experienced actual documented earthquake conditions. Qualification by combined test and analysis applies in these situations.

8.3.1 Test Method

A full test program, as described in 7.6, and preliminary exploratory (resonance search) tests, as described in 7.1.3, are conducted on a typical piece of equipment. Data on modal frequencies, damping, and responses throughout the equipment must be taken and recorded.

8.3.2 Analysis

When it can be shown that no resonances exist in the frequency range of interest, the equipment may be analyzed as a rigid equipment (see 6.2). When a resonance search is utilized, assurance should be obtained that adequate test methodologies are followed to verify the absence of resonant frequencies. In addition, assurance should be obtained that changes from the originally tested equipment did not result in the formation of previously nonexistent resonances. This can be done by simple testing or analysis.

When the equipment is not rigid, the effects of the changes shall be analyzed using the techniques of 6.2 or other justifiable means. For very complex equipment, this requires sufficient knowledge of the equipment to include the significant structural parameters to enable the responses at all points of interest to be calculated.

The test results combined with the preceding analysis allow the model of similar equipment to be adjusted to take into consideration the parametric quantities affected and allow revision of the analysis for the modal frequencies of the similar equipment. The result is a verified analytical model that can be used to qualify the similar equipment.

8.4 Shock Testing

Laboratory shock testing performed in conformance with various military standards (for example, MIL-S-901C-1963 [5]), consists of subjecting the component to high-impulse shock-type loads (accelerations). Unless these accelerations are of sufficiently high magnitude (far higher than the earthquake levels) and sufficient duration, shock testing without additional vibration testing is not considered adequate seismic simulation. Since the primary objective of testing is to verify the seismic adequacy of components, the use of shock data can provide only an approximation of the adequacy of the equipment tested. This is the result of the difficulty encountered in matching the frequency content and duration with that of the shock experienced in seismic service.

8.5 Extrapolation for Multicabinet Assemblies

In many cases it is impractical to test a multicabinet assembly of similar cabinets due to limitations in the size of testing facilities. The qualification of a single cabinet, or a few connected cabinets, may not be extrapolated to qualify a larger number of cabinets connected together in a lineup without adequate justification. This is because

1) Individual cabinets in the array may have different mass loading or mass distribution, or different structural stiffness, or both
2) The connected cabinets may exhibit different dynamic response, such as different torsional modes compared to the smaller number originally qualified
3) The response of subcomponents mounted in different locations may be affected

The approaches given in 8.3 may be used to justify the extrapolation of tests on a single cabinet, or a small number of connected cabinets, to qualify an assembly.

8.6 Other Test/Analysis

In addition to 8.2 through 8.5, analysis may be used to

1) Explain unexpected behavior during a test
2) Obtain a measure of expected response before a test
3) Obtain a better understanding of the dynamic behavior of the equipment so that the proper test can be defined

9. Experience

9.1 Introduction

There are many types of equipment that are similar in function and physical characteristics to equipment that has been previously qualified by testing, analysis, or a combination of testing and analysis. In addition, other equipment types are similar to equipment that has been in service for various periods of time and has been exposed to in-plant vibration and natural seismic disturbances. Qualification of the aforementioned equipment types may be accomplished by justifying their similarity with the previously qualified equipment or with equipment that has been exposed to other more severe environments. Similarity of the equipment characteristics and of the excitation environment must be established by techniques that can be technically justified. Due consideration to differences in design and manufacturing techniques must be considered as part of the technical justification supporting similarity.

9.2 Experience Data

Experience data may be derived from a variety of sources. It may be

1) Analysis or test data from previous qualification programs
2) Documented data from equipment in facilities that have experienced earthquakes
3) Data from operating dynamic loading or other dynamic environments.

Depending on the source and level of documentation detail available, various approaches are appropriate. Additional guidance specific to each case is given in 9.2.1 through 9.3.4.

9.2.1 Previous Qualifications

Many seismic and dynamic qualification programs have been conducted for various equipment items by the nuclear industry and can be used to develop an experience data base. Some of these equipment items may have been qualified by incorporating a full test program as described in 7.6, together with preliminary exploratory (resonance search) tests as described in 7.1.4. Others have been qualified using analytical techniques as described in Section 6. or by using a combined test and analytical technique as described in Section 8.

To utilize this experience data base, the input motions to which the equipment was previously qualified must have been clearly documented, together with pertinent qualification parameters, such as resonant frequencies, damping, and responses throughout the equipment.

9.2.2 Earthquakes

Another type of experience data consists of the documented performance of equipment in facilities that have been subjected to an earthquake. The data-base equipment can be identical or similar (construction, dynamic response, etc) to the equipment being qualified. It is preferable that the equipment excitation be quantified by recorded measurement of the earthquake induced motion at, or near, the equipment mounting location. However, it is recognized that this is not generally available. Alternatively, a documented conservative estimate of input motion may be generated by extrapolation or interpolation of measurements elsewhere (see 9.3.1).

9.2.3 Other Experience

The approach described in 9.2.2 for earthquake data may also be applied to the use of operating dynamic loading or other documented dynamic environments as a basis for qualification. In any case, the principle of similarity must be used to justify the approach.

9.3 Similarity

Qualification by the use of extrapolations from experience data must be based on the concept of dynamic similarity. This concept recognizes that the qualification process for equipment is comprised of the following basic factors:

1) Excitation
2) Physical system (dynamic properties and operability)
3) Dynamic response

Generally, establishing the dynamic similarity for the excitation and physical system will allow a successful qualification to be established by extrapolation from experience data. For example, assume that a given equipment item has been qualified to a specified excitation as quantified by an experience response spectrum (ERS). Then, a second equipment item, whose physical system similarity has been established, can also be qualified to the same ERS or to an RRS that is enveloped by the ERS. Another example is where two or more identical, or at least dynamically similar items, have each been qualified to different excitations. They may. both be demonstrated to be qualified to another composite ERS, which can be shown to be equivalent to the original different excitations.

9.3.1 Excitation

Similarity of excitation constitutes likeness of parameters, such as spectral characteristics, duration, directions of excitation axes, and location of measurement, for the motions relative to the equipment mounting. Ideally, these parameters should' be as alike as is practical for excitations whose similarity is to be established. However, a conservative composite excitation can be generated by extrapolations or interpolations of data whose parameters are not identical but are justifiable. For example, estimates may be based on measurements elsewhere on the structure or on other structures in the vicinity of the given equipment, when the estimates can be justified by calculations based on sound engineering methods using geophysical models, structural models, or both, as applicable. Likewise, ERS whose spectral content are significantly different may be used to generate lower-level composite ERS estimates, providing that an account is taken of possible multimode response or cross-axis coupling, or both. Justification for such approximations must consider all modes of the equipment excitation that are significant in determining its structural integrity and functional operability. A sufficient justification is that equipment is stressed or excited, or both, to at least as high a level by each one of the component ERS used to create the lower-level composite ERS estimate. In this case, the lower-level composite ERS may be higher in some frequency ranges than any one of the component ERS from which it was generated.

To provide for proper vibration buildup and low-cycle fatigue effects, as with qualification by testing, any constituent experience data must be based on a minimum of 15 s of strong motion duration, or a justifiable equivalent (see Appendix D). The qualification must account for the fatigue effects of exposure to the required normal and abnormal conditions such as normal-plant vibrations and the required OBE. When no OBE can be documented in the experience data, then the lack of fatigue effects must be justified or a fatigue analysis must be performed.

9.3.2 Physical Systems

Equipment similarity must be established for an equipment assembly, or a device, or both, or subassembly (including mounting), depending on the configuration of the new equipment to be qualified. For a complete assembly, similarity may be demonstrated through comparison of make, model and serial numbers, and consideration of dynamic properties and construction.

Since the end objective of qualification by the similarity method includes a consideration of the expected dynamic response, a rational approach can be used to establish similarity of dynamic structural properties by an investigation of physical parameters of equipment systems. This can be done by comparing the pre-dominant resonant frequencies and mode shapes. These dynamic characteristics are dependent on parameters such as

1) Equipment physical dimensions
2) Equipment weight, its distribution, and center of gravity
3) Equipment structural load transferring characteristics and stiffness to resist seismic excitation
4) Equipment base anchorage strength and stiffness to ensure structural integrity and adequate boundary conditions
5) Equipment interfaces with adjacent items or connecting accessories such as cables and conduits.

The relative dissimilarity of all the physical parameters of 9.3.2(1), (2), (3), (4), and (5) needs to be bounded to ensure that adequate similarity exists between equipment assemblies. In addition, assurance should be obtained that equipment changes from the original database equipment do not result in the formation of previously nonexistent resonances and do not introduce new mechanisms for malfunction.

For the equipment where seismic qualification can be demonstrated by showing that individual safety devices are performing properly during the earthquake, a device or subassembly similarity evaluation approach may be considered. The similarity of physical systems should be addressed for the individual devices. In this case, the justification for similarity lies in the careful examination of the dynamic properties, anchorage, and the mechanical or electrical operating principle(s), or both. The demonstration that similar equipment behavior will result between the data-base equipment and the equipment under investigation must be based on similarity of physical parameters. When significant differences exist for complex devices it may not be possible to demonstrate similarity by analysis. For such cases testing is the preferred approach.

9.3.3 Dynamic Response

A physical system response can be described through the same quantities as those applied to excitaton (for example, duration, frequency content, amplitude, etc), or through a physical system description, such as failure modes, or failure criteria acceptance, or rejection, or a combination of these. When the physical system characteristics are known through the experience data (by any one of the previously mentioned methods of 9.2.1 through 9.2.3) and the excitation characteristics are also available, then the system response can be evaluated and extended toward similar systems. On the other hand, there are occasions where only response and physical system characteristics are available. For these situations the excitation requirement can be evaluated in light of the known response quantities and the physical system characteristics (obtained by the methods of 9.2.1 through 9.2.3). Such information for the input excitation may then be utilized to qualify similar equipment.

9.3.4 Operability

Equipment being qualified must be capable of performing its safety function during and after an earthquake. The safety function during the earthquake, may, or may not, be the same as after the earthquake. Therefore, for each qualification the safety function must be defined for both during and after the earthquake. The experience data must provide documented evidence to support the demonstration of proper operability, as defined, for each application. Where an active function, or absence of a spurious function, is required during the earthquake, the experience data must provide sound evidence that the equipment performed as required in a similar electrical system.

10. Documentation

10.1 General

The documentation for each equipment type should demonstrate that the equipment performs its safety function when subjected to the seismic motions for which it is to be qualified. Therefore, proper documentation requires a clear statement of the specific requirements and an accurate recording of the procedures and results of the test, analysis, or combined analysis and testing method.

NOTE — Proprietary data should be available for audit and source documents identified and referenced.

10.2 Specification Requirements

Directions for the preparation of specification information required for either analysis or test of the specified equipment are as follows:

1) The RRS for the surface on which equipment will be mounted should contain the data for the horizontal axes and the vertical axis as a minimum. The RRS should include the damping values for which it was calculated and should indicate artificially broadened areas (see Section 5. and 7.6.1.1). General specifications, which contain RRS for many different locations, should indicate which ones are applicable to a given type of equipment.
2) Floor motion: When an RRS is not furnished, maximum accelerations of either floor or structure motion at all significant frequencies, or a time history, should be provided.
3) Operational settings: Typical operational settings (or ranges) for adjustable devices should be provided.
4) Devices: Identification of safety-related devices and circuitry and their safety functions, both during and after the SSE, should be provided.
5) Duration: The earthquake's strong motion time duration should be specified.
6) OBE: The required number of OBE should be specified.
7) Loading: Applicable loading and interface requirements should be specified.
8) Acceptance: Acceptance criteria should be specified.
9) Tests versus analysis: Special requirements for tests or analyses on specific equipment should be provided.
10) Margin: All margins already included in the requirements of 10.2(1) through 10.2(9) should be identified (see ANSI/IEEE Std 323-1983)[2].
11) Equipment mounting details, including all interface connections, should be furnished.
12) The physical description of equipment should be provided.
13) Deflection requirements, if applicable, should be furnished.
14) The environment in which the equipment is designed to perform its safety function should be described.

Once these requirements have been defined, it can be determined whether qualification will be obtained by analysis, test, or a combination of both.

10.3 Seismic Qualification Report

The Seismic Qualification Report should include a test or analysis report, or both, and should present a clear, logical explanation of how the data has been used to achieve qualification of a particular equipment. Toward this end, it should include the following information:

1) Equipment being qualified should be clearly identified. For complex equipment, identify each Class 1E component and specify the component's functional requirement. The qualification package should include the original testing or analysis report, or both. Documentation should include references to all drawings, bills of material, instruction manuals, etc, necessary to perform an adequate review.
2) RRS levels for equipment that is being qualified should be shown.

3) A detailed summary of the test or analysis procedure, or both, and results (including pertinent anomalies and their dispositions) should be included. Details defining the test fixture, when used during testing, should also be provided. When a component is tested or analyzed separately, the procedure used should also be summarized.
   The evaluation of equipment operability should be based on a prespecified set of acceptance criteria. Any revision or adjustment of the criteria after a test failure, or a test with observed anomalies, to make the test satisfactory should not be considered acceptable instead of a retest without proper justification. When an anomaly is experienced during any test, it should be documented in the report. When the equipment is not modified to eliminate the anomaly, then the use of the equipment must be justified and this justification filed with the equipment qualification report. Any equipment refurbishment performed during testing must be carefully documented in the test report and reconciled by the equipment supplier. This data should become part of the post-earthquake field maintenance checks and procedures for that equipment to maintain required seismic qualification.
4) Conclusions should be drawn based on 10.3 (1) through 10.3(3).
5) An approved signature and date are required.

10.3.1 Analytical Data

When analysis is performed, the method and data used and failure modes considered, should be presented in a step-by-step form that is readily auditable by persons skilled in such analysis. Boundary conditions, including anchoring and any other interfaces, must be clearly defined. Input/output data required to support performance claims and any mathematical model verification testing performed should be included in the report. The reaction force(s) at the interface connection(s) to the support structure should also be included.

A statement should be made verifying that any computer programs used were validated on the computer hardware on which the program was executed. Computer programs, options, version numbers, dates, and systems utilized should be identified.

10.3.2 Test Data

If testing is used as a qualification method, the test data should contain

1) For the equipment being qualified:
   a) Tested equipment identification (including devices)
   b) Tested equipment functional specification
   c) Tested equipment settings and limitations when appropriate
2) Test facility information:
   a) Location
   b) Testing equipment and calibration
3) Test method and procedures including monitoring for operability and acceptance criteria
4) Equipment mounting details, including all interface connections
5) Test data (including proof of performance, TRS plots, time histories, PSD or Fourier analysis, coherence checks as necessary, number of OBE and SSE applied, duration, etc), whatever the type of multifrequency testing employed, the acceleration time history of the input motion should be provided in the test report in addition to the TRS. As a minimum, a time history of the SSE table motion should be provided for one test in each of the three directions of excitation.
6) Test results and conclusions (including statement of any anomalies and justification that the equipment is still qualified).

10.3.3 Combined Methods of Analysis and Testing

If proof of performance is by analysis and testing or by extrapolation from similar equipment, the report should contain

1) Reference to the specific method of combined analysis and testing used
2) Description of equipment involved
3) Analysis data
4) Test data
5) Justification of results

When extrapolation of data is made from similar equipment, a description of the differences between the equipments involved is required. Justification that the differences do not degrade the seismic adequacy below acceptable limits (may require some additional analyses or testing) and any additional supporting data should be included.

10.3.4 Experience Data

If experience data is used to qualify a candidate equipment, then the data-base equipment with its supports and interface conditions, its safety-function requirements, and the experience response spectra should be documented to establish similarity. Documentation must be retained in an identifiable and auditable manner. The records should include at least

1) Analysis reports, test-data records, and logs of measurements
2) Contemporaneous operating logs and the results of reviews, inspections, or interviews recorded sufficiently soon after an experience event to provide a valid data source to demonstrate that the equipment performed its safety function during and after the experienced event prior to any repairs or adjustments

Documentation should establish sufficient identification of materials, parts, and components including partially fabricated assemblies. This is to ensure that identification of database equipment is maintained by year of manufacture, part number, serial number, or other appropriate documentation traceable to the equipment. Documentation must establish the status of the equipment just prior to the experience event including any modifications that were made since installation. This identification shall be designed to ensure the use of database equipment, that conforms to the similarity criteria described in 9.3.2, for the qualification of candidate equipment.

Control measures must be in place to ensure that documents, records, specifications, drawings, procedures and instructions maintain the design basis of the plant. Design changes, field changes, modifications, and replacement parts should be subject to the same control and requirements commensurate with the original equipment specification.

Particular attention must be accorded documentation on data-base equipment taken from past earthquakes, which may have been recorded a considerable period of time after the experience event, to establish its authenticity and applicability. The basis for the use and acceptance of such data should be clearly stated in the qualification report.

10.3.4.1 Excitation

The origin of the experience response spectra (ERS) must be justified and documented. This must include a description of any measurements, calculations, and assumptions used in the development of the ERS from single-or multiple-experience data sources. The method of accounting for the lack of fatigue effects due to OBE, or the fatigue analysis, should be documented.

10.3.4.2 Physical Systems

Justification must be provided to show that the equipment to be qualified is similar to the data-base equipment together with support and interface conditions. When extrapolation of experience data is made for similar equipment, a description of the differences between the data-base equipment and the candidate equipment is required. Justification that the differences do not degrade the seismic adequacy below acceptable limits may require additional analysis or testing. Any additional supporting data should be included.

10.3.4.3 Operability

Documentation should demonstrate that the data-base equipment performed its required function under conditions equal to or more severe than the normal and abnormal qualification levels required for the candidate equipment. The effect of any malfunctions must be recorded and their effects traced to justify that the performance of the safety function is not jeopardized. The documentation should include records of all such malfunctions, repairs, periodic maintenance, calibration, part replacement, and records of periodic test results to establish the status of the equipment prior to the data-base event. This should include any pass/fail criteria used as a basis to determine the equipment's status prior to, during, and after the data-base event.

Annex A Measurement of ZPA (Informative)

(These Appendixes are not a part of IEEE Std 344-1987, IEEE Recommended Practice for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations, but included for information only.)

ZPA is one of the parameters that must be measured to show that the TRS properly envelops the RRS. The ZPA for the TRS is required to envelop the ZPA of the RRS considering only frequencies of the test-table motion time history lying within the RRS amplified region. To clarify concepts that follow, this may be called the ideal ZPA of the TRS.

The ZPA is the value of the response spectrum analyzed to a frequency higher than those contained in the motion time history. Typical test-table time histories usually contain frequencies higher than those corresponding to the RRS amplified region. The higher frequencies are usually generated by

1) Waveform distortions from the hydraulic excitors
2) Any looseness and rattling between the test-machine table, fixturing, and the test item
3) Any looseness and rattling within the test item itself

Any of these influences may preclude the accurate measurement of the true or actual ZPA for the test even when the analysis is performed to 100 Hz or 200 Hz. In addition, even when the true ZPA of the TRS has been obtained by an analysis to a sufficiently high frequency, there is no direct way of knowing when the true ZPA magnitude equals the ideal ZPA of the TRS without further analysis. The following methods may be employed to obtain the true and the ideal ZPA.

The principal TRS must be the analysis of the total waveform that exists at the point of measurement at the same value of damping as the RRS. When the shape of the TRS is similar to the shape of the RRS, a reasonably accurate measure of the ZPA can be obtained from the TRS high-frequency asymptote. When the TRS tends to increase in the high-frequency region, a supplemental analysis may be performed at a significantly different damping value. The true ZPA is indicated at the high-frequency end where the two TRS curves coincide. When the two curves do not meet then the true ZPA can only be found by carrying the analysis out to a higher frequency.

When the true ZPA of the TRS indicates that no high frequencies beyond the amplified region of the RRS are contained in time history, then it is also the ideal ZPA.

When the true ZPA of the TRS indicates that high frequencies are present a supplemental analysis may be performed on the waveform by low-pass filtering the signal at or above the RRS cutoff frequency. This will show the value of the ideal ZPA that must equal or exceed the ZPA of the RRS.

For digital systems, there may be hardware/software constraints associated with block size, sampling rate and anti-aliasing filters. It is recommended that analysis be performed only to the maximum RRS frequency of interest. The ZPA should then be determined by

1) The peak acceleration shown on the digitized time history with the anti-aliasing filters set at the cutoff frequency
2) Examining a strip chart time history that has been filtered at the cutoff frequency.

Care should be taken to ensure that the upper frequency selected does not exceed the response of the chart recorder. An alternative to the strip chart is an oscillograph that inherently has a greater frequency response.

These analysis techniques may also be used where a response point is being measured for use as an RRS for a subsequent component or device test. For this test application, it is suggested that a waveform to the filtered RRS be synthesized first with the higher frequencies added as required to obtain the overall RRS. Use of PSD to ensure adequate frequency tent may be used as an alternate procedure.

Annex B Frequency Content and Stationarity (Informative)

This topic is best divided into two sections, (1) frequency content and (2) the stationarity of the frequency content. The objective of both concerns is to produce an input waveform that is a good simulation of the postulated seismic excitation. Even with the TRS enveloping the RRS, as the TRS shape deviates from that of the RRS, the frequency content of the waveform can change radically. Although this will usually mean considerable over-test at some frequencies, it may not always be conservative at others. There are a number of techniques that may be used to show that the frequency content of the synthesized waveform is adequate, for example,

1) The enveloping of the RRS by the TRS is obtained with similar spectrum shapes so that similar amplifications result at significant spectrum peaks in the amplified regions of the spectra
2) The frequency content of the Fourier transform of the test waveform is compatible with the amplified region of the RRS
3) The frequency content of the PSD of the test waveform is compatible with the amplified portion of the RRS

Having shown a proper frequency content, it is also required to show that it is statistically constant with time within a reasonable tolerance.

To satisfy stationarity, all the required frequencies in multifrequency waveforms must be statistically present during the strong motion portion. One way to show this is with the time interval TRS. A definition of this follows.

The time interval response spectrum is different from the conventional response spectrum analysis in that the peak detection of the SDOF oscillators' responses is performed as a function of time intervals. For example, a 30 s duration could be divided into five 6 s intervals with a response spectrum produced for each time interval. It should be noted that the input time history is continuous for the full duration, that is, it is not divided into time intervals. As a practical matter, the minimum time interval must be some multiple of the period of lowest frequency. A basis for comparison can be formed from a similar analysis of actual representative earthquake time histories.

Another method of showing frequency stationarity includes use of a time-interval PSD. The strong motion portion of the table acceleration time history can be separated into several intervals and a PSD computed for each. Comparison of the several PSD must show that all frequencies are statistically present to a similar degree for each time interval. A basis for comparison can be formed from a similar analysis of actual representative earthquake time histories.

Another method of showing adequate frequency stationarity is to show time histories of the test input waveform components. This can be accomplished by dividing the waveform into narrowband (for example, 1/3 octave) components and showing the time history for each. Each frequency component should be statistically continuous during the test duration. Thus, the peak amplitude probability density for each 1/3 octave waveform should be a Rayleigh distribution. Any other method that has been justified can be used to show stationarity.

It is anticipated that each test waveform synthesis methodology should demonstrate stationarity once, that is, the demonstration of stationarity would not be required for each test.

Annex C Fragility Testing (Informative)

Fragility testing may be performed by using any of the various excitation waveforms described in 7.6. For example, to determine its fragility level to single-frequency transient excitation, the equipment may be subjected to any single-frequency excitation such as sine-beat motion. The sine beats may be applied over a frequency range from 1 Hz to 33 Hz. The sine-beat motion is in turn applied at each natural frequency of the equipment as determined by a resonance search test. However, where equipment resonances are not well defined, the frequency interval between tests may be narrowed to 1/2 octave, or less, for more conservatism. On the other hand, when broadband resonance response occurs because of nonlinear effects in the equipment, the frequency interval can be broadened to avoid unwarranted fatigue. The amplitude at each frequency should be increased until malfunction occurs. The number of oscillations per beat should be in the range of 5 to 10 with the number of beats dependent on the test frequency and the duration of the earthquake being simulated. From this data, curves showing input level versus frequency may be plotted. Additionally, fragility response spectra can be plotted at desired values of damping from the single-frequency input data.

In a manner similar to that used for sine beats, and at the same frequencies, the equipment may be subjected to continuous sinusoidal excitation. Additional frequencies may be used to more completely define the low points on the input excitation fragility plot. Further, a series of fragility response spectra can be plotted at desired damping values from the steady-state continuous sine data. The response spectra thus obtained are classical resonance curves centered at the test frequencies.

To demonstrate the equipment's fragility level capability to multiple-frequency excitation, it should be subjected to random excitation. The overall spectrum level and shape must be adjusted to determine the fragility response spectrum.

When there is an additive effect of multimodal response, the fragility response spectrum is lower than that determined from the single-frequency excitation.

C.1 Application of Results

The general guidelines for applying the fragility data are as follows:

1) When the RRS is broadband, then the multifrequency fragility curve of the appropriate damping should be overlaid on the RRS and demonstrated to be higher than the required spectrum.
2) When the requirement permits single-frequency testing, it may be permissible to use the fragility spectrum obtained from the single-frequency test data to overlay the RRS.
3) When the RRS consists of a high narrow peak (for example, a peak due to a predominant horizontal building resonance), then the frequency fragility response spectrum of the appropriate damping should be overlaid on the required spectrum and demonstrated to be single-higher than the required spectrum.
4) When the RRS is a combination of (1), (2), and (3) then a combination of the fragility data may best demonstrate the equipment's capability and may be used with appropriate justification.

The fragility response spectrum may be further used as input to a probabilistic risk assessment study of the system in which the tested component is to be included. In this case the fragility response spectrum is first transformed to a probabilistic fragility function, which gives the frequency of failure for the tested component as a function of excitation amplitude. More details of this use can be obtained from appropriate texts on probabilistic risk assessment.

Annex D Test Duration and Number of Cycles (Informative)

Test duration alone may not be sufficient to ensure adequate equipment response relative to low-cycle fatigue capability. When the strain range in structural elements is doubled, the fatigue effect is increased exponentially, such as by a factor of six. The strain range of significance for low-cycle fatigue consists of a malfunction occurring in approximately 100 cycles or less. Therefore, a conservative seismic test requires, in addition to adequate duration, that the input causes a sufficient number of strong motion-response cycles in the equipment. In accordance with 7.6.5, the input waveform should generate a response at any point in an equipment sufficient to cause a total amount of fatigue at least equivalent to that produced by the earthquake input motion at the mounting of the equipment. The number of strong motion cycles in a filtered (for example, building floor, cabinet, pipe, etc) response time history depends on several factors, such as the amplification by resonances (soil, building, equipment), the damping, and the location of the equipment in the building.

Typically, the filtered response will contain one or more maximum peak cycles plus an assortment of cycles with peaks of varying fractional amplitude. The fractional peak cycles can be converted to equivalent maximum peak cycles by the use of Fig D-1, which is based on a fatigue S/N curve with an exponent of 2.5. This figure plots the number of fractional cycles, as a function of the percentage of maximum peak amplitude, which is needed to obtain one equivalent maximum peak cycle. Any combination of number and amplitude of fractional cycles could be used. For example, to obtain five equivalent maximum peak cycles, any of the following combinations is adequate:

1) Fifteen fractional cycles at 65% of maximum peak
2) Ten fractional cycles at 75% of maximum peak
3) Four fractional cycles at 70% plus ten fractional cycles at 65% of maximum peak.

Thus, by determining the distribution of peak amplitudes in a given filtered response waveform, and using Fig D-1, the total number of equivalent maximum peak cycles can be determined.

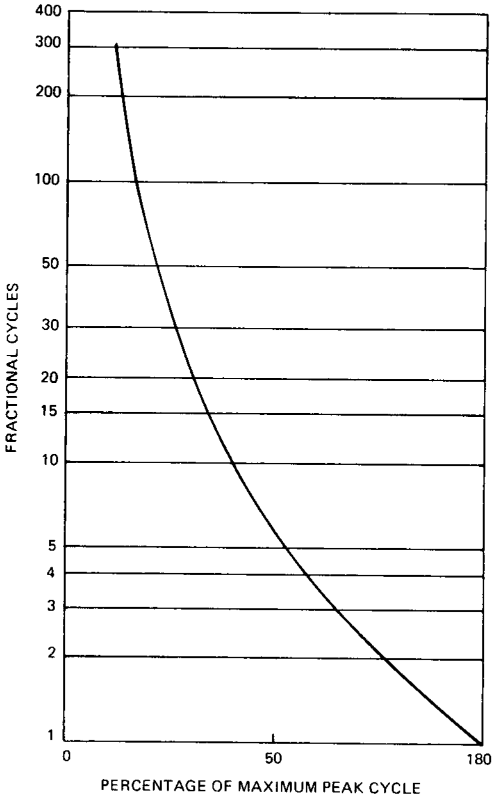

Figure D-1—Fractional Cycles to Obtain One Equipment Maximum Peak Cycle

A typical filtered response to earthquake strong motion can be approximated by a narrowband random waveform whose peak amplitude probability distribution is given by a Rayleigh distribution. This property, together with the center frequency and time duration of the filtered motion, permits determination of the number of equivalent-peak stress cycles by use of Fig D-1. A subsequent relationship that results between equivalent maximum peak cycles and filter center frequency for stationary random motion is given in Fig D-2 for three different strong motion durations. Therefore, any equipment response that results from stationary random motion should approximate these results.

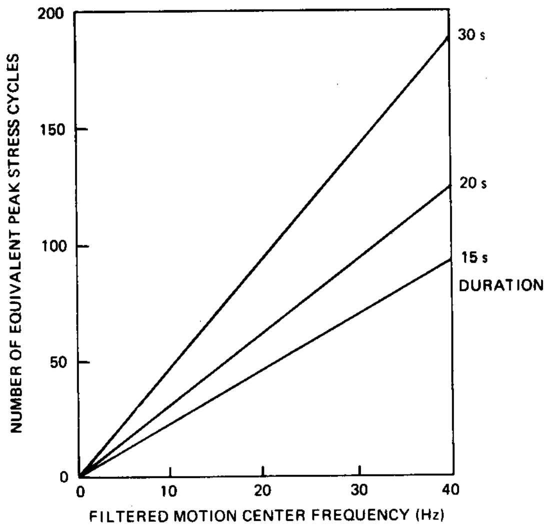

Figure D-2—Equivalent Peak-Stress Cycles Induced by Stationary Random Motion

For ground-level excitation, simulation should include multifrequency content up to the cutoff frequency, and the equivalent number of fatigue cycles for any equipment resonance up to the cutoff frequency can be determined directly from Fig D-2.

For equipment excited by structural floor motion, only resonances up through the predominant building frequency range need be considered, since building response is negligible beyond that range. For the case with a 5 Hz predominant building frequency, an average number of at least ten equivalent stress cycles should be used for 15 s duration.

For some test input waveforms, that is, sine dwell or sine beat, the peak distribution of the filtered structural response waveform produced is similar to that for the input itself. Therefore, the peak-stress cycle potential can be determined directly from the input waveform, which in accordance with 6.5, should contain at least ten equivalent maximum peak cycles. For single-frequency sine-beat testing, the total number of cycles for a test at any frequency is defined in 7.6.2.3 by the number of beats and cycles of motion within the beat. This will ensure at least five maximum peak (ZPA) cycles and several other fractional peak (less than ZPA) cycles, for a test at any frequency. The fractional peak cycles can be resolved into a smaller number of equivalent maximum peak cycles with the use of Fig D-1. For example, the total fractional peak cycles in five sine beats with ten cycles and five cycles of motion per beat are equivalent to approximately 17 and six maximum-peak cycles, respectively.

Therefore, for these motions, a total of 22 and 11 equivalent maximum-peak cycles are obtained, respectively. For other types of test motions whose response waveforms are also similar to that of the excitation, a similar computation of equivalent peak cycles using Fig D-1 should be performed.

For narrowband response waveforms that result from approximately stationary random synthesized excitations, the peak amplitude distribution is known to be Rayleigh. Therefore, Fig D-2 can be used directly to determine the equivalent number of peak-stress cycles for a given filtered frequency and duration. However, the existence of adequate fatigue potential in an excitation waveform of this type is assured providing that adequate stationarity has been included. Thus, for this case, establishing the number of equivalent peak-stress cycles is not necessary when adequate stationarity is shown to be present in the waveform. Nevertheless, the equivalent peak-stress cycle count procedure can be used as a check on the adequacy of stationarity in the waveform.

Annex E Statistically Independent Motions (Informative)

The three orthogonal earthquake motion components (two horizontal and one vertical) are known to be approximately statistically independent, when measured at a distance from the epicenter. Thus artificially generated time histories, to be used for either analysis or test simulations of multiaxis motions, should possess a similar amount of statistical independence. This can be verified either by the use of the coherence function or by the correlation coefficient function.

Coherence is defined specifically as the ratio of the squared magnitude of the cross-spectral density and the product of the two power spectral densities for the two time histories whose independence is compared. Thus, it is also a function of frequency, with a value of zero for perfectly independent signals and a value of 1.0 for perfectly dependent signals. The coherence between two record motions given simultaneously can be computed by separating them into multiple segments (data samples), computing the coherence for each corresponding pair, and averaging the results. The estimated values of the resulting coherence function are very much dependent on the number and duration of the individual time segments utilized. The required minimum 15 s of strong motion for one simulated seismic event can conveniently be separated into at least 12 such segments. This should lead to a plot whose maximum value is less than 0.5 for sufficient statistical independence.

For time histories whose mean value is zero, the correlation coefficient is defined specifically as the ratio of the cross correlation function and the product of the RMS values of the two signals whose independence is compared. Thus, it is a function of time delay (or time shift) between the two signals and has a value of zero for independent signals, tending toward + 1.0 for dependent signals. Computation of correlation coefficient is typically performed for time delays up to completion of the strong motion. This should lead to a function whose absolute value is less than 0.3 for sufficient statistical independence.

Orthogonal components of instructure floor motions may or may not be statistically independent, depending on whether building cross coupling occurs. The degree of motion independence may vary with frequency in such cases.