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# THE USE OF IN-SITU PROCEDURES FOR SEISMIC EQUIPMENT QUALIFICATION IN CURRENTLY OPERATING PLANTS

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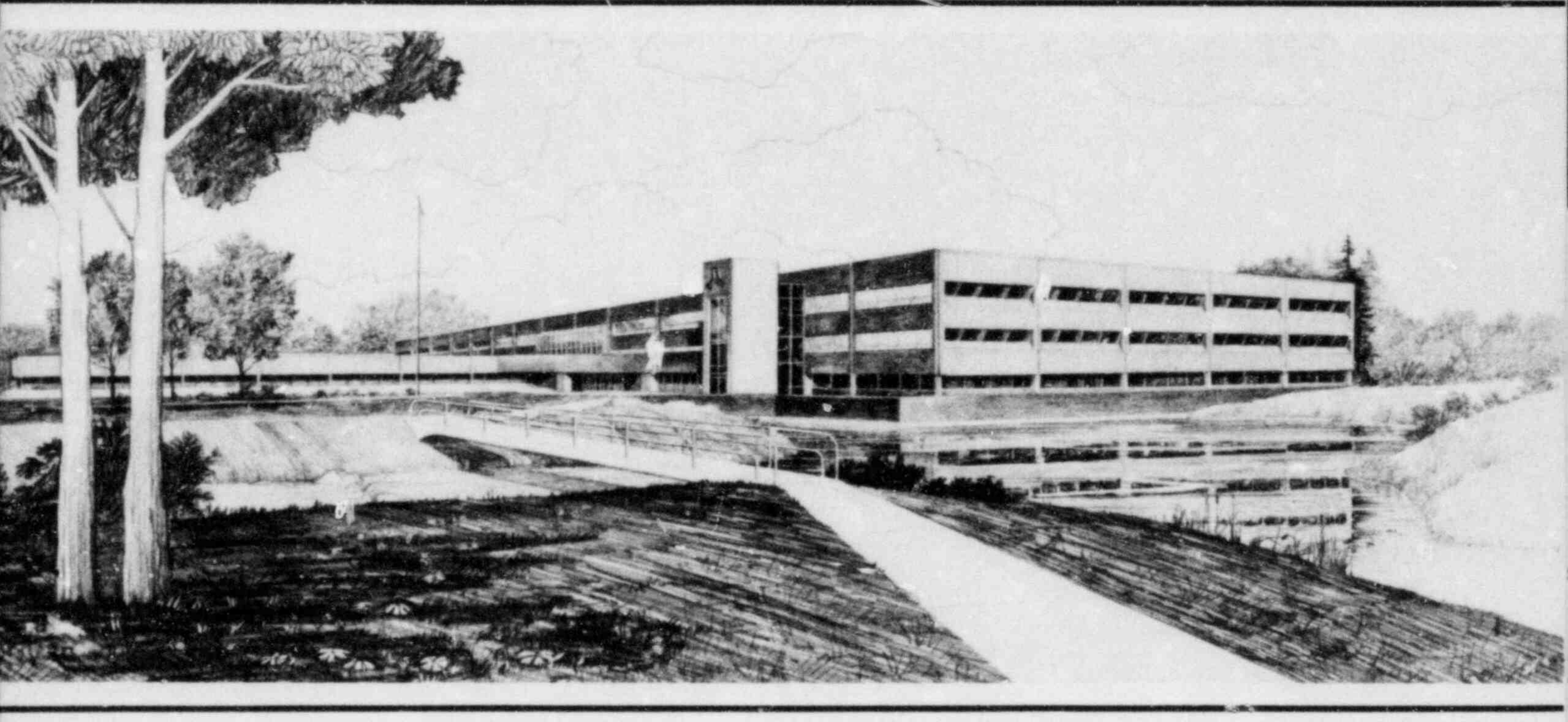

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# INTERIM REPORT

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## ABSTRACT

The Nuclear Regulatory Commission has designated dynamic equipment qualification of active safety related equipment (Class 1) in currently licensed and operating nuclear power plants as unresolved generic safety issue A-46. EG&G Idaho, Inc. has provided technical assistance toward the resolution of unresolved safety issue A-46 by considering the uses of in-situ testing in this regard. A brief description of the intent, requirements, and approved qualification procedures in the current licensing process is presented to provide a basis for discussion of qualification in currently operating plants. The potential uses and limitations of in-situ procedures in qualifying equipment are presented. The most important future application will be in streamlining the process for design basis environment (the required seismic capacity) determination. The broader problem of qualifying existing equipment has been reviewed and a proposed alternate method is outlined. The proposed method involves a formalized definition of four failure modes, a failure mode analysis, design evaluation, similarity review, and estimation of seismic capacity using test data from other equipment. The effect of aging degradation on seismic capacity has been reviewed. The potential use of the above proposed similarity method for aging degradation assessments is evaluated. Aging degradation appears to be less important for equipment which has no safety function (beyond structural integrity) during seismic events. Analysis procedures to be used in conjunction with in-situ procedures are discussed and evaluated. Recommendations on the use of in-situ procedures for operating plant equipment qualification are presented.

SUMMARY

The Nuclear Regulatory Commission (NRC) has designated dynamic equipment qualification of active safety related equipment in currently licensed and operating nuclear power plants as unresolved generic safety issue A-46 (USI A-46). During the period since licensing of older plants qualification criteria, qualification methods, and safety Class 1 categorization of equipment have been modified. Thus various questions concerning the existing and the required level of dynamic qualification for these currently operating plants are being addressed by USI A-46.

EG&G Idaho, Inc. has provided technical assistance toward the resolution of USI A-46 by examining the potential uses of in-situ testing in operating plant equipment qualification. The efforts included a limited review of in-situ procedures. The potential applications and limitations of in-situ testing to equipment qualification were examined. Alternate qualification criteria and methods have been considered and a new methodology is proposed. The effective use of in-situ procedures requires the use of associated analysis methods and these methods have been examined or developed, as required. These efforts are summarized in the following paragraphs along with the recommendations derived from the studies.

Potential applications exist for in-situ procedures, especially when used in conjunction with analysis procedures. A limited review aimed at finding developed technology or technology which is near full development was performed. This review has not uncovered any practical and widely applicable in-situ methods which can be employed as the sole means of qualifying or determining the relative level of equipment qualification. In-situ procedures performed at low excitation levels can be employed to determine dynamic natural frequencies and mode shapes of support devices. The majority of equipment qualified by testing is mounted in such support devices. These quantities can then be employed in combination with analysis procedures to estimate the design basis dynamic environment for equipment. Several detailed routes are discussed in the report to achieve this end. Thus in-situ procedures will be most useful in determining the required seismic capacity for equipment.

For the majority of active safety related equipment, a seismic qualification chain can be defined. The chain consists of qualifying the support device anchorage, the support device dynamic response during the earthquake, the mounting of equipment to the support device, and the functional operability of equipment during (if required) and after the seismic event. Recommendations on support device response and mounting adequacy have been developed and are presented.

Alternate qualification criteria and procedures have been considered. No further alternatives are required for estimating required seismic capacity. Since the missing link in the qualification chain is estimating the seismic capacity of equipment, an alternate method based on similarity between equipment which has been tested and the equipment in question is presented. The basis of the method is a categorization of failure modes into four types. Basically, a critical failure mode is established, a tested piece of equipment with less than or equal seismic capacity is identified, and a conservative seismic capacity for the item of interest is inferred from the tested item. The method is most applicable for simpler pieces of equipment where a design evaluation can provide the justification for similarity.

Analysis procedures are employed in combination with parameters determined from in-situ testing to predict the required seismic capacity of equipment. Seismic analysis procedures based on linear modal superposition require knowledge of the frequencies of significant modes, the associated mode shapes, damping, and the mass distribution. In-situ procedures provide frequencies and mode shapes, and damping is specified in NRC regulatory guidance. Methods for determination of mass distribution, or alternately the modal participation factor of seismic structural analysis, have not been extensively discussed in the literature. A relatively straightforward, verifiable technique which rewards accurate determination of the significant mode shapes is presented in detail in the report. Other methods are also discussed.

Seismic inputs and outputs are commonly described by means of response spectra. In performing seismic analysis it is necessary to transfer response spectra through structures such as the reactor base mat to a building floor and then to a specific location in a support device. The commonly employed process involves the generation of synthetic time history inputs followed by a time history analysis. Direct methods of response spectra transfer would combine the systems mechanical characteristics directly with input response spectra to yield output response spectra. No intermediate time history generation or analysis is required. Direct methods would provide a substantial gain for operating plant qualification because the analysis procedures are algebraic thus providing considerable streamlining of the current analysis procedures. However no validated method for direct response spectra transfer could be established. The difficulty occurs in determining the response spectra when the spectral (or oscillator) frequency is very near one of the structural natural frequencies.

Specific recommendations for qualifying equipment in operating plants have been developed and are discussed in more detail in section 5 of this report. In-situ procedures have been recommended as an acceptable procedure for determining structural mode shapes and natural frequencies. The combined use of analysis and in-situ procedures for determining required seismic capacity without the development of a finite element model is described. The modal participation factor is calculated from a verifiable procedure which is described. This method is the recommended method for the direct use of in-situ parameters for determination of required seismic capacity. If the required seismic capacity is calculated using a finite element model then it is recommended the model be validated by showing close correspondence between model and in-situ determined frequencies and mode shapes of significant modes. Seismic qualification is achieved if prior testing has shown the equipments' capacity to exceed the required capacity.

A procedure for establishing similarity of seismic capacity between two pieces of equipment has been recommended. Successful use of the procedure would yield an estimate of seismic capacity in situatons where data for the equipment in question is not available. Finally recommendations for two considerations unique to older currently operating plants have been made. One recommendation is to experimentally (in-situ) determine the fundamental natural frequencies of all support devices containing safety related equipment to identify if they align with the amplified region in the floor response spectra. The final recommendation is that all mountings for safety related equipment be screened for potential shortcomings. The recommended screening procedure is a plant walk-through.

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## 1. INTRODUCTION

The growth of the nuclear power industry during the 1960s and 1970s coincided with increasing emphasis on safety issues inherent in commercial nuclear facilities. As a matter of public safety the industry is federally regulated, requiring standby safety systems capable of controlling and stabilizing a facility in the event of environmental transients or equipment failures.

These safety related systems are categorized into passive and active groups where active safety related equipment must perform some operation in fulfilling its safety related function. They are subject to design control measures[1] whereby the design must be qualified to specific criteria established by the Nuclear Regulatory Commission (NRC). In the field of seismic safety the movement of the state-of-the-art and the accompanying regulatory stance has resulted in qualification criteria where newer plants and plants currently undergoing licensing review are seismicly qualified to a greater degree than older plants. The NRC therefore has implemented Unresolved Safety Issue-A46 (USI-A46) whose focus is restricted to active equipment. Several contractors are active in developing technical assistance to USI-A46. Generally speaking the technical assistance is concentrating on practical methods for evaluating the seismic qualification of older facilities, assessments of the level of qualification required for public safety, and the development of procedures which will expedite the industry's achievement of these qualification criteria.

### 1.1 The Qualification Process

While the first nuclear power plant (NPP) designs were based more or less on conservative engineering judgment, recent advances have provided enhanced methodology for seismic design. Initiated by requirements found in Chapter 10 of the Code of Federal Regulations as well as a recognition of need within the major professional engineering associations, design and testing criteria have evolved over a period of time. These criteria are contained in foundation documents such as the IEEE and ASME publications which are sanctioned by the NRC via NRC Regulatory Guides. Additional guidance and data are presented in NRC NUREGs and professional papers. The criteria above outline procedures for design verification through the use of similarity to previously qualified configurations, analysis, and finally, testing. Testing is the preferred qualification procedure for active equipment.

Components used in nuclear power plant systems have been categorized based on the importance of their safety functions. Those components with the greatest safety impact are designated Class 1. These safety related components are further grouped into two areas--those which must maintain structural integrity under seismic loading and those which must also maintain the ability to actively perform a safety function either during or after a seismic event. The qualification of very large or very complex equipment in either group often involves special criteria due to technological limitations.

## 1.2 Introduction to Task

Many currently operating nuclear plants were designed, licensed and placed on line prior to adoption of the current seismic qualification criteria. These criteria implement recent developments in experimental and analytical methods. As operating plant equipment may not meet the current criteria, there is a need to consider the amount and level of requalification needed to ensure integrity of the Class 1 equipment in these facilities. Due to the character of operating plants, application of current qualification criteria may result in substantial impact on the plant. Excessive plant downtime, shipment of irradiated components to test labs, and extended manhours in contaminated areas are but some potential concerns.

EG&G, Idaho is assisting the NRC by providing technical assistance to the resolution of USI-A46. Our task has been to consider the methods by which in-situ procedures can be applied to qualifying equipment in operating plants. Toward this end a limited review of in-situ testing practices has been performed. This review has consisted of examining technical literature as well as personal contacts with professionals active in the field. Analysis procedures are inherent to the utilization of data derived from in-situ measurements. Thus a limited review of potentially applicable analysis procedures has also been conducted. The focus has been primarily on well developed methods. However the relative lack of literature has necessitated independent developments as well. The combined use of analysis procedures and modal parameters determined by in-situ procedures has been outlined.

One goal of USI-A46 is to develop alternate qualification criteria for currently operating plants. The use of in-situ procedures as the basis for major alternatives to current criteria and procedures has, therefore, also been examined. The negative results of this examination led to a broader study resulting in a definition of failure mode categories. Evaluating a design for each failure mode provides a basis for seismic similarity between two non-identical pieces of equipment that can be used as a qualification tool. Aging degradation has been examined from the standpoint of in-situ testing and also failure modes.

### 1.3 Report Scope

This report covers interim progress during the period 4-15-82 to 11-1-82. Pertinent topics covered by this report include the following:

- A limited discussion of the current qualification process is presented in Section 2. Intent, requirements, and approved procedures are discussed consistent with the limited examination necessary for this program. Current qualification procedures for active equipment are emphasized.

- Section 3 discusses the use of in-situ procedures in qualifying equipment. The discussion is general and identifies uses for which no technology base exists as well as discussing its potential uses.

- Section 3 discusses alternate qualification methods which are not necessarily dependent upon in-situ testing. These considerations have been limited to methods which are strongly aligned to current qualification criteria. Probabilistic techniques, for example, are not employed. The result is a proposed basis for establishing similarity of seismic capability between nonidentical components. Section 3 also addresses other considerations affecting seismic equipment qualification in operating plants. These are the effects of aging degradation on seismic capacity, equipment mounting evaluations, and cabinet dynamic response.

- Section 4 discusses the use of analysis procedures in conjunction with in-situ testing. An analysis procedure is presented which directly employs modal parameters (quantities determined by in-situ procedures) to predict the design environment on equipment contained in support devices (cabinets, racks, etc.). Dynamic response within support devices is very important because they contain the bulk of active safety related equipment. The use of in-situ procedures in conjunction with standard finite element methods is also discussed.

# 2. FUNDAMENTALS OF QUALIFICATION

Developing and understanding guidance related to seismic requalification of operating plants requires a prerequisite knowledge of the current qualification process. This chapter is designed to provide necessary background information while introducing many of the issues to be examined later. The chapter is divided into four sections containing, in order, a description of the current safety philosophy, a discussion of seismic events and their simulation, an outline of the current qualification criteria, and a summary of the application of the criteria in the qualification of components in plants applying for operating licenses. The discussions provided on each topic are not intended to be exhaustive. The knowledgeable reader may wish to concentrate on the final section concerning current criteria application.

## 2.1 The Safety Philosophy

The philosophy utilized to assure integrity of nuclear facility safety systems is a combination of redundancy and separation. Redundancy minimizes the impact of the random failure whose source is usually traced to less than adequate quality in a particular item. The separation and isolation of redundant systems eliminates many of the common mode failures usually associated with loading extremes or insufficiency of design. In the seismic arena the common mode failure is of the greater import as separation cannot be assured, leaving the facilities' safety systems open to a failure mode which attacks several redundant systems simultaneously. A major portion of seismic qualification involves verification of design by proof test to ensure sufficient hardness of components with safety related functions against these common failure modes.

## 2.2 Seismic Phenomena

### 2.2.1 Seismic Events

In the nuclear industry seismic events include any natural action which produces a vibratory ground motion. An earthquake will produce pressure and shear waves, the properties of which depend on earthquake magnitude, distance from the site and the intervening structures of rock and soil. These waves will produce motion along all three axes of any reference coordinate system, the most important property for design being the statistical independence of the relative motions.

Seismic events are recorded and categorized by a variety of methods. Information that is considered for plant design include the location of historic epicenters and hypocenters and the potential ground accelerations at the plant site if a similar event were to occur during the plant operating lifetime. Recorded data can be used to determine site properties such as soil damping, filtering, or possibly amplification caused by the rock and soil substructure. By considering the site specific properties in conjunction with recorded time histories from natural or induced events the effect of potential events can be predicted at the plant foundations. These effects are reduced into response spectrum form.

### 2.2.2 Seismic Design Loads

The response spectrum graph (Figure 1) is the main descriptor of a seismic event currently used in the design and qualification process. A number of response spectra from actual events are overlaid and a smooth curve is drawn enveloping all peaks. This curve is the "required response spectrum" (RRS) used in the determination of design loads.

If a response spectrum is developed for a specific plant site based on local geology, it is referred to as a site specific RRS. The NRC has developed a generic RRS which, while usually more conservative in shape, can be used at most sites without modification. The design earthquake spectra is based on this generic curve scaled to the maximum or zero period acceleration (ZPA).

The response spectrum has properties which limit its use to certain analysis techniques. It does not indicate the duration, exact shape, or phasing of the exciting waveform. Without this information the exact response of a particular piece of equipment cannot be determined. For this reason all testing and some analysis requires that a synthetic time history be developed.

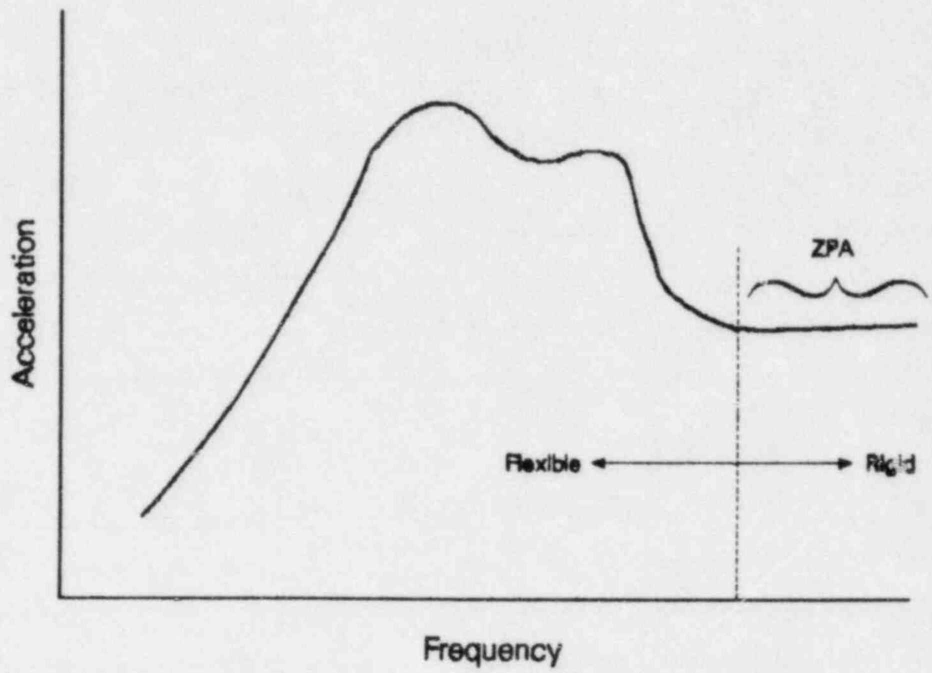


Figure 1. Typical response spectrum

Test waveforms must produce a test response spectrum (TRS) which envelopes the RRS within certain tolerances. An undesirable characteristic of this enveloping process is an artificial overly conservative increase in the ZPA which results in an overdesign of inherently rigid components. While a sine sweep can exactly follow the RRS shape, use of this waveform is usually limited to low magnitude testing for frequency and mode shape determination. This is due to the inability of this waveform to provide ample duration of motion over a range of frequencies simultaneously--a requirement for producing the interaction of multiple vibrational modes needed for design verification.

The requirements for enveloping, frequency content, strong motion duration and multiple axis excitation will be discussed in the next section.

## 2.3 Qualification Criteria

Qualification criteria have undergone considerable evolution during the last decade. Plants designed in the 1960s for the most part had no official criteria other than the Uniform Building Code[2]. Initial criteria were published in the early 1970s and subsequently revised a few years later. In the intervening period a large amount of feedback was received and reviewed. The present criteria reflect technical refinement and recognition of testing and analysis limitations derived from these reviews.

The present criteria are based on the directive of Chapter 10 of the Code of Federal Regulations, primarily 10 CFR 50 Appendix A (see Figure 2). This appendix establishes principal design, testing and performance requirements for safety systems and components to "provide reasonable assurance that the facility can be operated without undue risk to the health and safety of the public." Criteria 2 of Appendix A addresses the method of risk mitigation: "structures, systems and components important to safety shall be designed to withstand the effects

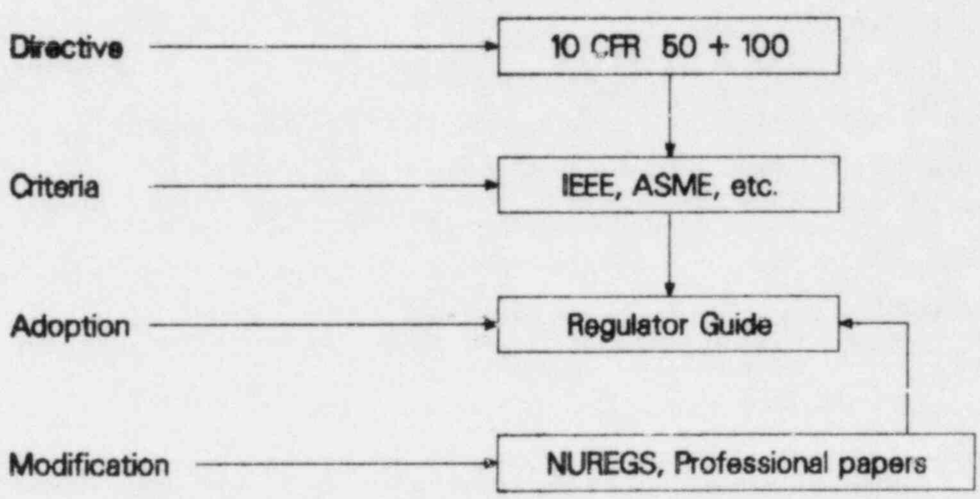


Figure 2. Structure of criteria instigation

of natural phenomena--without loss of capability to perform their safety functions." Thus the thrust of qualification is truly public safety.

In response to the need for specific design and testing standards to meet the 10 CFR directives professional societies have published documents for industry use. Many of these documents, such as the ASME codes, address materials and structural design criteria. The scope of this discussion will be limited to criteria for equipment with operability requirements.

### 2.3.1 IEEE Standards

In 1968 IEEE-279[3] was first presented to the industry. This standard, revised in 1971, gives general design criteria for plant safety systems. Section 4.4 addresses equipment qualification as follows:

> "Type test data or reasonable engineering extrapolation based on test data shall be available to verify that protection system equipment shall meet, on a continuing basis, the performance requirements determined to be necessary for achieving the system requirements."

IEEE-308[4] publication followed IEE-279, with the original version released in 1970. This standard specificly addresses criteria for safety related electrical equipment. While this document is limited only to electrical equipment, it addresses the problem of functionality of components with operability requirements and so has been used as a guide for the design scope of pumps, valves and motors which also have these requirements. IEEE-603-1980[5] addresses the same safety related electrical components as IEEE-308 as well as mechanical equipment; however the approach is from the system view rather than the component view.

The historic lead document for qualification criteria, IEEE-323-1974,[6] is again specifically limited in scope to electrical equipment but is used as the standard for all equipment qualification. This document presents the specific types of qualification (by test, by experience and similarity, and by analysis) as well as the scope of the qualification process (loads, interfaces, etc.). IEEE-627-1980[7] addresses all components, both electrical and mechanical, from a generic view. While IEEE-627 has a broadened scope compared to IEEE-323, it does not contain the same depth of information when subject matter overlaps.

IEEE-323-1974 was the first document to significantly address the problem of equipment aging. Aging tends to induce or assist common mode failures; therefore the development of some method of simulating and incorporating aging into the qualification procedure was required.

IEEE 344-1975,[8] specifically treats seismic qualification of electrical components. This standard provides a brief description of earthquakes and then examines the simulation of earthquakes in detail.

The frequency range of concern in an earthquake is stated as typically 1 to 33 Hz. An approximation used in the earthquake description is that the magnitude of the vertical component of excitation will be between 67 and 100% of the horizontal magnitude below the frequency of 3.5 Hz and equal to the horizontal above 3.5 Hz.

Three methods of seismic simulation allowed by the standard are the time history, response spectrum and power spectral density (PSD) function.

Two methods of damping value determination are endorsed. These are the decay rate method and the resonant peaks method, also referred to as the bandwidth method. The first involves measurement of the decay rate of a particular "pure" mode of vibration while the second is based on measurements of the width of the resonance peaks for different vibration modes when the equipment's response is frequency plotted. Other justified methods of damping determination are also acceptable.

Three primary methods of qualification are described in detail in the document:

- Predict the equipment's performance by analysis

- Test the equipment under simulated seismic conditions

- Qualify by combined analysis and test.

The following summary of qualification by analysis is taken from the standard's text:

> "The general procedure is to first study the equipment to assess the dynamic characteristics; second, to determine the response using one or more of the several methods described in Section 5 of the text; third, to analyze the stresses which result from the response; and, finally, to determine if the design is adequate."

In Section 6 of the document proof testing and fragility testing are discussed. Mounting for either test must simulate the intended service mounting. This simulation must account for electrical lines, conduits, etc., as well as mounting bolts and brackets.

The following is a list of the considerations involved in testing:

- Frequency bandwidth of the RRS compared to that of the TRS and equipment characteristics and responses

- Duration of the test compared to the design seismic event

- Peak acceleration of the test input motion and the amplification observed

- Natural frequencies and modes of equipment vibration

- Typical equipment damping

- Fragility levels

- Number of test cycles and fatigue failure simulation.

The basic criteria for the number of tests requir is five Operating Basis Earthquakes (OBEs) followed by one Safe Shutdown E thquake (SSE). The duration of each test must equal or exceed the strong motion portion of the original time history used in the development of the RRS for the SSE. Single axis tests will be allowed if they are conservative or if crossaxis coupling is zero or very low; otherwise multiaxis testing is required.

Combined analysis and testing can be utilized in qualification of over-large equipment by exciting equipment to SSE levels using analysis to perform the excitation, and validating the mathematical model for analysis by favorable comparison with low excitation test results. A second use of combined methods is in the qualification of equipment based on extrapolation of test results for similar equipment using analysis techniques. A third use, related to the second, is for extrapolation from test loads to a (different) required loading for the same equipment.

### 2.3.2 Regulatory Guides

The IEEE standards are endorsed by the NRC through the use of Regulatory Guides. These documents present the basis for the requirements (10 CFR and others) and then comment on the standard to be endorsed. Exceptions in the endorsement and additional criteria are presented. A partial list of the IEEE standards and the endorsing regulatory guides is shown in Table 1.

Exceptions and additional criteria are normally concerned with minor details, with a notable exception. A draft version of the necessary revision to Regulatory Guide 1.89 was recently presented for comment. At issue is the method of environmental qualification to be used to account for equipment aging. This is a new area of qualification with a large amount of uncertainty. The testing suggested by IEEE 323-1974 is both expensive and time consuming and possibly not definitive.

TABLE 1 INDUSTRY STANDARDS AND ASSOCIATED REGULATORY GUIDES

| | |
|---|---|
| IEEE-334 | Regulatory Guide 1.40[12] |
| IEEE-382[9] | Regulatory Guide 1.73[13] |
| IEEE-384[10] | Regulatory Guide 1.75[14] |
| IEEE-323 | Regulatory Guide 1.89[15] |
| IEEE-344 | Regulatory Guide 1.100[16] |
| ANSI N278.1[11] | Regulatory Guide 1.148[17] |

Some regulatory guides are designed to supply guidance on a particular issue and are not associated with any particular industry standard. Regulatory Guide 1.60[18] presents a generic ground response spectrum which may be utilized and has the advantage that it is easily defined compared to site specific spectra. Regulatory Guide 1.61[19] details conservative damping values to be used in design. The values are categorized by structure and stress level. Regulatory Guide 1.92[20] treats the combination of loads from different vibration modes. It is considered conservative to combine these loads by a square-root-sum-square (SRSS) method except for modes with closely spaced frequencies. For these modes an absolute summing is needed to account for phasing.

### 2.3.3 Additional Input

The integration of ongoing research in the qualification process is achieved by guidance from professional papers and NRC supported publications. The NRC reports recent findings and recommendations which are used as the basis for the development of rules in the Code of Federal Regulations and are also used as a guide in the actual design and qualification process.

## 2.4 Qualification for Plants with Construction Permits

The current application of seismic qualification criteria for plants seeking operating licenses is a process of comparison and adaptation. Qualification must include proper conservative enveloping of design loads and boundary conditions as well as conservatively accounting for minor design differences within a component type to be both effective and affordable.

### 2.4.1 Approach

Qualification is achieved through two basic approaches--analysis and testing. These methods are often combined for best results.

Analysis. Analysis is utilized most often to confirm structural integrity of a component or its support. Analytic models are utilized to represent a structure and the dynamic properties of the structure are derived. The design load is coupled with these properties and the response is determined. Typically qualification is then a matter of maximum stress determinations; although allowable deflections are also often a consideration, especially in equipment alignment or interference situations.

Another major use of analysis is for very large items. The two forms here are operability determination for equipment too large to test and load transfer characterization of building structures and large supports and mounts.

Testing. Testing is used at full load levels for direct qualification and at lower load levels for dynamic system characterization. Full level tests are almost always utilized to qualify components with operability requirements due to difficulties in analyzing this equipment type. Full load tests are also used to define the response of complex support systems such as electrical cabinets which cannot easily be modeled with sufficient accuracy.

Low level testing is used primarily for determining dynamic characteristics of a system or component and not for direct qualification itself. Often low level exploratory tests are conducted prior to high level testing to determine fundamental frequencies in the range of interest. Similarly low level testing, often in-situ, can be used to find mode shapes, frequencies and damping values for equipment qualified by analysis. Here the testing is utilized to verify the accuracy of the analytical model.

### 2.4.2 Load Types

A major factor in the present qualification process is proper determination of design loads. In equipment qualification the design basis events' magnitudes are considered to be known but the actual loading seen by a component must be derived.

Information required to determine component loads are:

- o Loading seen by support system
- o Stiffness, damping and cross-axis coupling properties of the support system
- o Potential sources of high frequency loads
- o Verification that design is adequate to maintain linear response during an SSE.

In simple problems the effects of the last two items are often trivial.

Form. Two loading forms are used in conjunction with analysis in the qualification process. For most problems linearity of properties is assumed in exchange for some added conservatism and the response spectrum is used directly as the load model. In complex situations a load form with phasing and duration information is required, so a time history is synthesized from the required response spectrum. Currently a major use of time history analysis is the determination of large structure response . An example is the modeling of a reactor building with a time history forcing function input at the foundations for determining the response of upper floors.

Load forms for testing are of four types--static loads and three dynamic load forms; the simple waveform such as a sine wave, complex waveforms intended to represent a response spectra and the waveform produced by an impactive or explosive device.

Static load use in qualification is limited to components whose failure modes are structural. Thus a static force is applied and the component is examined for yielding or relative interferences. This form of testing is simple to apply but may only be used in special cases such as valve operator shaft clearance qualification.

Simple waveforms can be used for full level qualification testing under special conditions. If the design load is of a highly filtered type such as might be found for components supported by piping systems then a sine beat, sine dwell or decaying sine at the major frequency of the RRS may sufficiently envelope the magnitude and shape of the RRS. In the case of two major frequencies two simple waveforms could be used, but they must be applied simultaneously and for sufficient duration so as to develop any multimodal effects present.

Artificial time histories and other synthesized waveforms are the most utilized loadings for full level tests. The waveforms can be modified so as to produce a TRS with the basic shape of almost any RRS, no matter how skewed. A common method used to develop a complex artificial waveform is to submit a random multifrequency waveform or a group of decaying sine waves of different frequencies to a series of narrow band filters. These filters, spaced at 1/3 or 1/6 octave intervals, are used in shaping the resultant waveform so as to meet the RRS enveloping requirements while not producing an excessive ZPA.

Waveforms produced via impactive or explosive sources are utilized almost exclusively for low level loading in-situ to determine damping and transfer characteristics. Explosive charges are infrequently used, (primarily in research activities to excite a building) while instrumented impact hammers are used more often to excite smaller structures and components. An advantage of impact hammers and portable shakers is the physical incorporation of the actual mounting conditions.

Direction. The ideal qualifying load form would be applied in all directions simultaneously. This is now a technical possibility but in earlier years only single axis tests were possible.

In practice the specimen is repeatedly tested at full level and rotated so as to expose all three axes to testing. Single axis tests are only to be used when it can be demonstrated that no cross-axis coupling is present in the dynamic properties of the specimen. In biaxial tests if the inputs in the different axes are not independent, then a second set of 180°

rotations is performed so as to examine both positive and negative inputs in one axis relative to positive input in another axis. Presently only two independent triaxial test tables exist. Triaxial machines may become more common mainly due to the ability to perform the biaxial test series without physical rotation of the specimen between tests, producing both a savings on table time and a consistent mounting stiffness. Actual triaxial tests have the asset of requiring only one full level test, thus reducing the possibility of fatigue failures; however extra effort is involved in developing three independent time histories which all produce enveloping TRSs. These time histories cannot necessarily be synthesized separately due to cross coupling in the test machine.

### 2.4.3 Test Types

Three types of full level equipment tests can be utilized for qualification. These types, proof, generic, and fragility, vary in philosophy and severity.

Proof testing is used to "prove" a component to be sufficient for a particular application. In this type of test a RRS is developed for an individual component to be mounted in a particular manner at a particular location in a plant. The proof test is most often used for a one-of-a-kind situation or equipment changeout.

The generic test is used to qualify a component type to a generic RRS. This component type can then be placed anywhere in the plant where the actual RRS is enveloped properly by the generic RRS. The generic test does require a particular mounting configuration and the individual components placed in the facility must be nearly identical to the one tested. The generic test is used often to qualify a large number of items in mass by choosing as the generic RRS the envelope of all the actual RRSs for the items.

The fragility test involves determination of the maximum loads a component type can withstand. There is no RRS for such a test. Specimens are tested at increasing loads until failure occurs. The fragility TRS is the maximum TRS that did not cause a failure for any particular mounting method. The application of this information involves determining the actual mounting method and RRS. If this RRS is enveloped by the fragility TRS for the particular mounting method, the component is qualified for the particular use. Fragility testing is expensive and not always definitive. The main use is by equipment vendors, who then can supply a "qualified" component to a utility with the utility's only effort being determination of the RRS.

### 2.4.4 Testing Equipment

There is a wide diversity of dynamic testing apparatus available for both in-situ and laboratory programs, the main qualifier for in-situ equipment being mobility. The main types of in-situ equipment include portable hydraulic or electromagnetic shakers and impact hammers. The hydraulic shaker is limited by its size and weight, which includes a reactive mass. The portable shakers can produce relatively large loads on small structures, potentially approaching full qualification levels. Most are capable of a wide range of waveforms including random time histories. The impact hammer consists of a mallet with an instrumented replaceable head. By using hammer heads with different stiffnesses , the waveform produced by the mallet impact can be modified for frequency content and relative magnitude.

The most common laboratory test machine is the independent biaxial shake table. There now exist two triaxial independent machines. When large deflections are needed a single axis long stroke machine may be used. A particularly heavy specimen may [illegible] the forcing ability of any of these dynamic simulators, just as an excessive RRS may not be duplicable. Most simulators can produce frequency content throughout the seismic range. One difficulty with lab tests for operability during an event is when extraneous supplies are required. An example would be water for a large pump qualification. When technically feasible testing is not possible, qualification must necessarily be established by analysis.

### 2.4.5 Procedure

Up to this point the main factors in the current qualification process have been noted. The consolidation of these factors into an actual qualification program is now discussed.

A typical procedure for qualification is outlined in Figure 3. Adoption of the best qualification method requires knowledge of the loads to be applied as well as the equipment response to be monitored. For many situations a multiple qualification method will be chosen based on this information. For example, a large electrical cabinet might be qualified in two steps, the main structure analyzed and the subcomponents tested, because the number of variables to be monitored are beyond the capacity of the laboratory equipment or the number of state changes to be verified would take an excessive amount of time.

Once a design's adequacy has been confirmed, a detailed documentation of all factors is needed. This documentation is required for licensing and also aids any modifications or retrofits proposed later in the system. Documentation should include not only the design loads but also the higher test loads. This will aid in requalification without retesting if more stringent criteria are implemented later.

As a part of the licensing process a seismic qualification review is conducted. At this time NRC contractors inspect the accuracy and scope of the qualification records. This review includes inspection of the installed configurations of components and their boundary conditions to verify that the correct situation was qualified.

All qualification programs should include maintenance and surveillance of the installed equipment during the years of plant operation. An ongoing record of component conditions is the most reliable method of excessive aging detection.

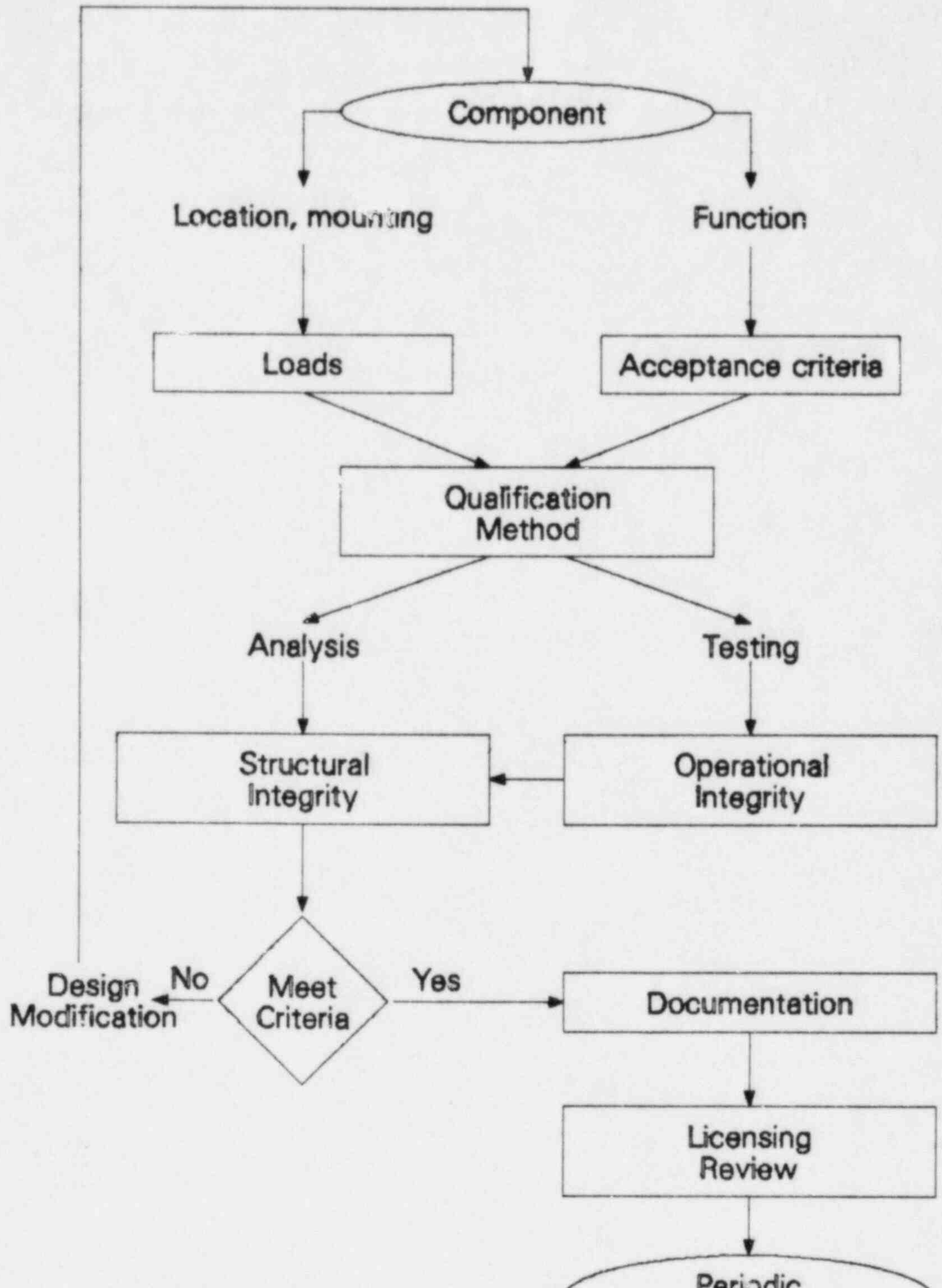


Figure 3. The qualification procedure

At present the requirements for continuing qualification, as well as requalification, are not explicit. The development of procedures in these areas implies a role for in-situ qualification methods. The next chapter examines some aspects of equipment qualification for operating plants and demonstrates the potential for in-situ tests in this process.

## 3. ASSESSMENT OF QUALIFICATION PROCEDURES FOR OPERATING PLANTS

### 3.1 Technical Inputs to USI-A46

One aspect of current NPP licensing requirements is to verify the design of active safety related equipment to the design basis seismic environment. Current practice is that operability of safety related equipment must be verified by testing when such testing is within the state-of-the-art. The testing chain for new plant equipment is very specific and was discussed in Section 2. If currently operating plants are required to demonstrate seismic performance via current criteria and procedures the cost impact will be large. Thus alternative approaches which can be used to satisfy the intent of equipment qualification are being examined in USI A-46.

Several studies currently in progress will provide information helpful to resolving qualification issues associated with operating plants. These include studies to examine the effect on plant probabilistic risk arising from changes in the qualification status and/or the seismic hardness of equipment. Other studies include evaluating the use of seismic experience in nonnuclear power plants to establish minimum seismic hardness levels. EG&G, Idaho is considering the manner in which in-situ procedures can be applied to equipment qualification. The first two studies may involve significant departures from the qualification chain described in Section 2.

The use of in-situ procedures is geared more toward a modification of current qualification procedures and criteria. Later in this section those applications are discussed in detail. Our considerations with in-situ testing have also addressed whether these procedures provide a basis for more diverse qualification criteria. No useful relationship was found. However the same investigation did identify an approach for estimating seismic capability based on similarity. As discussed in Section 3.3 this entails an analysis of specific equipment failure modes, test data, and similarity. The most immediate use would be for simpler types of equipment such as pumps or valves.

The goal in the present effort is to examine the most important uses of in-situ testing on the assumption that some level of substantial requalification of safety related equipment will be required. This assumption does not indicate a predisposition but rather an assumption from which to proceed.

## 3.2 In-Situ Testing Procedures

Alternate qualification procedures are sought which will yield procedures in lieu of shaker table qualification testing. One set of potential methods involves performing dynamic tests with equipment in-place in the plant.

In-situ test procedures could potentially be applied in the following techniques:

1. Testing at full load level with equipment in-place

2. Low load level testing, especially on support devices which position and support safety related equipment.

3. Periodic intermediate or low load level testing to support a continuing surveillance data base.

Method 3 could in principle be useful for identifying aging degradation. However for the types of equipment of interest in this program no potential applications are apparent. This is because changes significant to operability of safety related equipment (particularly in a seismic environment) cannot generally be detected by in-situ procedures.

### 3.2.1 Full Level In-Situ Testing

This process allows self-standing qualification of a given component design. If it can be justified that no significant mechanical aging degradation has occurred during testing, then the component can be employed in service for its nominal useful lifetime. However full load level testing with equipment in place is not a developed technology.[21,22] Our literature review has uncovered no examples of this type of testing for the purpose of qualification. Dynamic testing has been proposed for commercial facilities but at less than design loads. The major goal is to validate computer models used in structural design. In fact, this type of testing has not been performed to date on a nuclear power plant in the United States. Evaluating operability in this type of test is useful but does not qualify equipment to design basis environments. It is also possible to consider removing equipment and testing this equipment on portable shaker units at full load levels. This appears to have little advantage over shipping the equipment to a testing laboratory for testing.

In cases where full load level in-situ testing has been performed, facilities built explicitly for testing are used. These are primarily research facilities designed to determine the integrated response of relatively complex systems. Testing in these facilities does not provide a basis for in-situ testing in commercial facilities. Some considerations which cannot be adequately addressed are assessment of damage on tested components, control of loading environment, and isolating adjacent (presumably qualified) components and support devices from excessive loads.

Some conditions may exist where it is possible to load the mounting position of a piece of equipment and result in a motion equivalent to the required response spectra. Required conditions are that

- The support structure motion which occurs during the test must not excessively load the support device, appurtenances, or other components mounted on or in the vicinity of the support device

- Sufficient access must exist in order to load the equipment mounting

- No damage occurs local to areas where load is applied.

Again, no substantial mechanical aging should occur during testing. This is a special set of conditions which severely limits the usefulness of full load level in-situ tests. Valve operators are one equipment type that have been dynamically qualified in-situ by using a static load to perform an interference evaluation. However, the potential for performing full load level in-situ testing is so limited that it is not considered further in this report.

### 3.2.2 Low Load Level In-Situ Testing

Structural systems can be subjected to low level in-situ testing where small loads are applied to the structure. Typically the mechanical system is excited by a hammer, electromagnetic, or hydraulic type exciter. The input force and output, normally acceleration, are recorded on a computer's memory as loads are applied at various positions. The recorded quantities are converted from time histories to a frequency representation by use of the Fourier transform. Using the frequency representation, transfer functions are calculated between the points of interests. These calculations are typically performed with minicomputers which are part of the modal analyzer system. Software internal to these computers then identifies natural frequencies and mode shapes. The mode shapes encompass points on the structure where data was recorded.

By combining the dynamic characteristics of a system with a load description the elements for predicting the dynamic response are complete. The dynamic characteristics of a linear structural system are its mode shapes, natural frequencies, mass distribution, and damping. In-situ procedures identify the natural frequencies and mode shapes. In certain cases the mass distribution can also be estimated (alternate methods for determining the mass distribution are discussed in Section 4). A characterization of viscous damping is also available which represents the damping which actually occurred during the test. Since damping may depend on response level[23], values obtained from low level in-situ tests may not necessarily be valid and current NRC guidance should be followed. Thus the basic product of low load level in-situ procedures is a structural description. A final note is that the mass distribution, while represented in in-situ testing, is normally not directly available. Estimation procedures which use the results of in-situ testing have been suggested but are unverified. Consequently a method is described in Section 4 which is not dependent on the in-situ measurements but is readily verified.

The basic use of low load level in-situ testing in operating plants will be to determine the required seismic capacity of equipment. That is, in establishing the required seismic hardness of equipment, support devices, and mountings. Even on the same floor of a plant the environment experienced by components varies from one support device to the next and from component to component within a support device. To determine the design basis environment for equipment the SSE floor motions are used as input to the support device. For new plants, shaker table testing is used to determine the environment for contained equipment. For operating plants the alternative is to use the modal parameters from in-situ procedures in determining the design basis environment. This environment, represented in a RRS, is thus determined by a process where shaker table testing has been replaced by low level in-situ testing.

Several methods which use in-situ modal parameters are available for determining RRS's. One approach is to develop a finite element computer model of the support system and mounted equipment. A computer program analyzes the modeled system and calculates the natural frequencies, important mode shapes, and modal participation factors (MPF's). These quantities are then used in determining the response of individual modes (see Section 4.1) which are superimposed to determine the total response. It is felt that the basic procedure is potentially unreliable because of system complexity and unreliability of boundary condition modeling. Consequently, it can only be used if the equipment is already installed and in-situ procedures are used to verify the calculated modal parameters. A major disadvantage of the approach is that it is relatively costly because of the cost associated with developing a finite element model. An advantage is that if minor equipment modifications are made at a later date the model can be updated and a new set of RRS's calculated. The procedure is discussed in more detail in Section 4.2.

It is also possible to develop an equivalent model by using in-situ modal parameters. This procedure, as described in Section 4.3, depends on an accurate spacial resolution of the mode shapes. Testing is accomplished rapidly so that accurate mode shapes do not substantially increase cost. Here the mode shapes and frequencies used in calculations are those determined by in-situ procedures. As with the finite element approach, the response of individual modes is calculated and then superimposed for the total response. No development of a finite element model is necessary thus substantially reducing the cost.

In the typical situation, equipment is mounted in a support device. A safety related system may consist of:

1. A support device which houses the safety related equipment
2. The anchorage of the support device to the building
3. The mounting of equipment to the support device
4. The equipment which must be qualified to operate
5. Various appurtenances which affect equipment operability.

Item 4 is the most basic qualification requirement. Once the design basis environment has been determined, the final qualification step consists of comparing this RRS with the seismic capacity of the existing equipment. The equipment's seismic capacity must be based on full load level testing. In-situ testing provides no help in this regard. Qualification tests of identical designs are the preferred type of data. There are some indications that much of the data may exist, scattered throughout the industry. Other forms of useful data include dynamic tests of very similar designs, as well as field experience during earthquakes. At any rate, an assessment of seismic capacity based on test experience is required to complete the qualification chain.

The other items above constitute a lesser share of the qualification burden. Certain considerations pertinent to items 1, 2, and 3 are discussed further in Section 3.6. Note that with any method of determining the RRS for equipment the acceleration of the entire system has been predicted. This information should be useful, in evaluating anchorage loads. The same statement is true of mountings. In qualifying support devices structural integrity is the primary consideration. The commonly used models for stress analysis include beams and plates which employ rotational degrees of freedom. Currently, rotational degrees of freedom are not developed using in-situ procedures. However stress analysis using in-situ data is being investigated and qualified methods may be available in the future.

The most important uses of in-situ testing have been discussed. In-situ procedures lend themselves toward situations where a substantial level of requalification is desireable (an exception is discussed in Section 3.6). These procedures can be used in predicting the required seismic capacity of a piece of equipment. The seismic capacity of the equipment must also be assessed using experimental data to complete the chain. Recapping, the recommended qualification strategy is to

- Determine the dynamic characteristics from in-situ procedures
- Complete the model required for analysis procedures
- Subject the model to the input response spectra
- Determine the equipment RRS
- Evaluate the seismic hardness of the existing equipment
- Evaluate adequacy by comparing seismic hardness and the RRS.

### 3.3 Alternate Qualification Criteria and Procedures

Qualification by test (overtesting) is the highest possible level of qualfication. Such a level of qualification for all Class 1 equipment may not be appropriate for operating plants in view of a potentially low value/impact ratio. Thus consideration has been directed at defining alternate qualification criteria and procedures. An imposed ground rule has been that the intent of qualification as currently implemented by the NRC be maintained. This intent is interpreted as meaning that each safety related component be qualified to perform its safety related function for SSEs. This approach precludes the broader value/impact and probabilistic risk assessment avenues which could be used in developing alternate criteria. Thus the alternatives sought in this program are methods which can be applied at lower impact to equipment which must be qualified in some way.

As discussed in Section 3.2.2 the required seismic capacity of equipment in operating plants can be determined. The actual seismic capacity of equipment is the final link in the qualification chain. If test data specific to a given piece of equipment is not available then alternate methods for estimating seismic capacity will be beneficial. Alternatives based on in-situ testing have been considered. These considerations have revealed no applicable criteria or procedures. However another concept based on operability failure modes may be a useful basis for alternate criteria under certain circumstances.

#### 3.3.1 Failure Modes

With the substantial qualification testing which has occurred in the recent past, the evaluation of seismic capacity using test data from similar equipment may be feasible. To develop such methods a systematic treatment of operability and inoperability is necessary. The failure modes which result in inoperability are an essential ingredient to these methods. In this section, operability and inoperability are defined. The failure modes which cause inoperability are defined and discussed. Since this categorization is new it should be critically reviewed. The procedure for conservatively estimating seismic capacity is discussed along with the circumstances which facilitate its use.

Operability Failures. Operability failures are defined here as any action or interacting of component parts or interfaces which prevent a component from performing an active operation or maintaining a state continuously. Equipment with operability requirements are distinguished by the need for a controlled state:

- A condition is monitored which is coupled with the equipment state
- State change is initiated when the condition enters or exits a preset range
- The state transition must occur within applicable performance limits.

Inoperability can result from:

- Inability to monitor the control condition
- Inability to change states when so directed by the monitor
- Inability to maintain the current state when no state change is directed.

It is suggested that inoperability during dynamic environments occurs through the following failure modes:

a. Structural integrity-stress limits are exceeded, permanent deformation occurs, flaw initiation or extension occurs.

b. Operability loss due to temporary or permanent reconfiguration-vibratory elastic motion results in a state change or prevents a state change from occurring.

c. Structural interference-excessive relative motion results in a tolerance mismatch.

d. Nonstructural changes in state-peizoelectric effects, effects of dynamics on contact resistance, and others. Anywhere a fundamental nonstructural response is affected by vibration or stress.

Violation of structural integrity yields a system which is measurably changed as a result of the dynamic environment. Its ability to maintain or to change state are no longer assured. Loss of separation is also a potential consequence. Aging degradation can impact structural integrity when susceptible subcomponents exist along load paths. Dimensional changes resulting from aging are a consideration if they can affect operability. In many systems qualification testing has demonstrated that structural integrity is not an active failure mode.

If structural integrity is eliminated as a failure mode then permanent structural reconfiguration can only occur if some portion of the design is inherently unstable to large deflections, or "unstable in the large." For example see Figure 4 which shows a switch contact which is inherently unstable in the large because excessive relative motion causes a loss of restoring force. Temporary reconfiguration is a potential failure mode if the equipment has a safety function during the earthquake. This is the situation where vibratory motion results in a change of state. The prototypical example is a switch inadvertently breaking or making contact. This failure mode is certainly the most complicated of the modes. The design aspects controlling the configuration during dynamic events must be evaluated thoroughly to justify using test data from non-identical equipment. Of course, if the equipment has no safety function during the seismic environment then temporary reconfiguration is not an issue and qualification is more readily achieved.

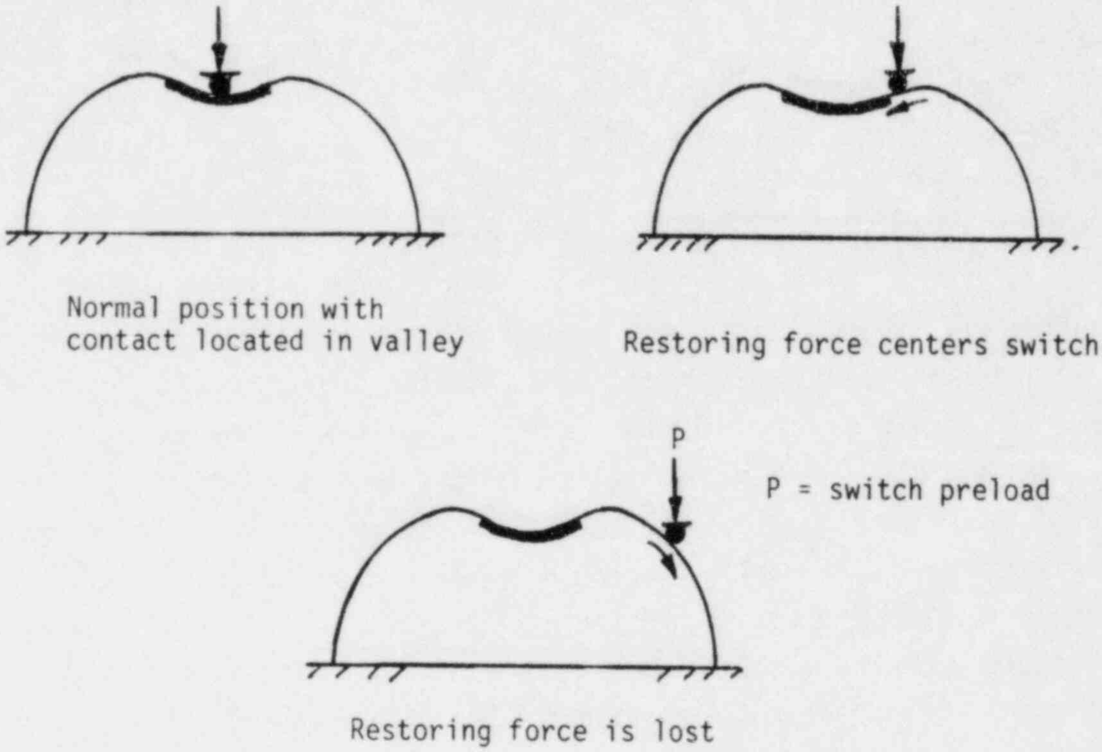


Figure 4. Instability in the large.

In the absence of structure integrity failures structural interference is a mechanical mode of failure and can exist only during the seismic environment . Structural interference is of particular importance in valves, valve operators, and rotating equipment. Structural interference could for example seize an operating motor or prevent a valve operator from functioning on demand. This qualification is often performed by analysis. Identifying the design features controlling interference is the crucial step to establishing equivalence between two pieces of equipment in this failure mode.

Many safety related components employ nonstructural phenomena, perhaps electromagnetic, in their basic operation. Nonstructural failure modes occur when motion or stress affects a basic operability function. For example contact resistance in degraded contacts can be increased by vibratory reduction of preload across contacts. Piezo-electric devices are affected by stress. These types of effects must be considered in evaluating the seismic hardness of equipment. If their effect can be significant then equipment similarity is based partially on similarity in these non-structural phenomena.

### 3.3.2 Alternate Criteria Based on Failure Modes

Alternate qualification criteria based on similarity of seismic capacity can now be considered. The four failure modes described earlier are the starting point for these alternate criteria. By justifying qualification in each mode total qualification is justified. Similarity between two equipment designs can be defined as similarity in potential failure modes. The basic premise involves two pieces of non-identical equipment having a common critical failure mode. The first piece has been qualification proof tested and its controlling design features are either identically or inherently more fragile than the equipment in question. In that case qualifying the first amounts to qualifying the other to the same environment. This process is facilitated if the equipment being compared have strong physical similarity in the design features which control failure and seismic capacity.

The following procedure is suggested for establishing seismic capacity based on similarity:

- o Specify operability requirements: take into account whether equipment is required to operate and/or maintain a continuous state during earthquakes. If there are no requirements during the earthquake then certain failure modes will be eliminated and qualification is simplified.

- o Identify the design features/subcomponents which affect operability. The procedure will be impractical if there are to many.

- Identify potential failure modes and the critical failure mode if possible. Qualification testing with other equipment will in many cases facilitate identification of the critical failure mode. Analysis procedures or a design review may also be useful in this regard.

- Identify similar pieces of equipment, i.e., equipment with nominally the same or less seismic capacity in the potential failure mode(s). Some form of design evaluation/comparison will be required in making this assessment. Equipment used for comparison must be of known seismic capacity.

These pieces of equipment are similar because they have the same failure mode and because a design evaluation has shown that the seismic capacities are related. Now the seismic capacity of the equipment in question is conservatively taken to be that of the similar article.

Clearly the design evaluation and similarity analysis described above will not always be practical. If two pieces of equipment are nearly identical in all features affecting operability then establishing similarity may be practical for moderately complicated systems. However the most potential exists with simple systems where operability is a simple process and failure modes are readily identified. Another assest is large seismic capacity. In this case equipment and tests useful for comparison are more readily identified and justified. If the actual failure level is not sufficiently high it will be difficult to find another similar article qualified to the required capacity. Finally, it will be helpful if the equipment belongs to an equipment group which has been extensively tested or analyzed.

Examining the application of this process to any specific equipment type is beyond the program scope. However, application to equipment such as pumps, valves, and motors appears to be one practical option. Identifying classes of equipment which are inherently hard seismicly and therefore requiring minimal qualification is another potential application. The methodology may be useful in conjunction with the Seismic

Qualification Utilities Group program[24] by providing a formal design control measure.[1] This program is gathering nonnuclear power plant service experience data during seismic events. Finally, it is foreseeable that rationalizing seismic capacity will have benefits in both seismic (and other) qualification and design of equipment.

## 3.4 Environmental Aging Consideration

The environmental history of a piece of equipment can produce changes in properties and dimensions which affect its seismic hardness. An assessment of all potential property changes and the integration of property variances in equipment dynamic capacity is a part of the current NPP qualification process.[25] Addressing the total environmental qualification of equipment in operating plants is impractical. An approach based on the interaction of aging with dynamic capacity is adopted here. Such an approach suggests that since some aging mechanisms will not affect seismic capacity these cases need not be considered in seismic qualification.

The use of in-situ testing in evaluating the affects of aging on seismic qualification has been considered. However no well developed technologies were identified. Consequently aging has been examined in a broader context where:

- The consequences of aging degradation are examined. This allows the relationship between dynamic qualification and aging degradation to be organized in a fashion which more clearly demonstrates the interaction.

- Alternate criteria based on the failure mode and similarity analysis of the last section are discussed. This provides both an organized aging assessment procedure and a method for using test data from "similar" equipment.

- Equipment without specific operability requirements during seismic events have been identified as less vulnerable to aging.

### 3.4.1 The Effect of Aging on Seismic Capacity

The effect of aging on seismic capacity is illustrated in Figure 5 First, if it can be demonstrated that no significant aging can occur then no potential problem exists. Routine maintenance programs, where subcomponents susceptable to aging are replaced and can be examined, and in-service experience (earthquake experience) can provide a data base for this assessment. For components where environmental aging is anticipated, the first branch (Figure 5) depends upon whether or not the dynamic response is affected.

Situations where the dynamic response is affected by aging will be discussed first. For operating plant equipment the observation of an interaction is based on reviewing equipment design and finding that aging degradation exists on an active load path. Inadequate seismic design cannot be discounted. Since every failure mode may be affected, the condition is potentially serious. If the effect on seismic capacity cannot be shown to be benign or supported by test data on similar systems then qualification to current criteria is recommended. However the dynamic response of many components can be shown to be unaffected by aging degradation and thus the problem may arise infrequently.

If dynamic response is shown to be unaffected by expected environmental aging then the remaining branch in Figure 5 applies. Inoperability results directly from non-structural aging degradation. It is assumed that degradation has not been so extensive as to render this equipment inoperative in normal environments. This level of degradation should be addressed by routine in-service surveillance. If structural integrity has been assured, operability after the event is also assured. However it is necessary to qualify the degradation effect was temporary and associated with the dynamic response. At this point such an assumption

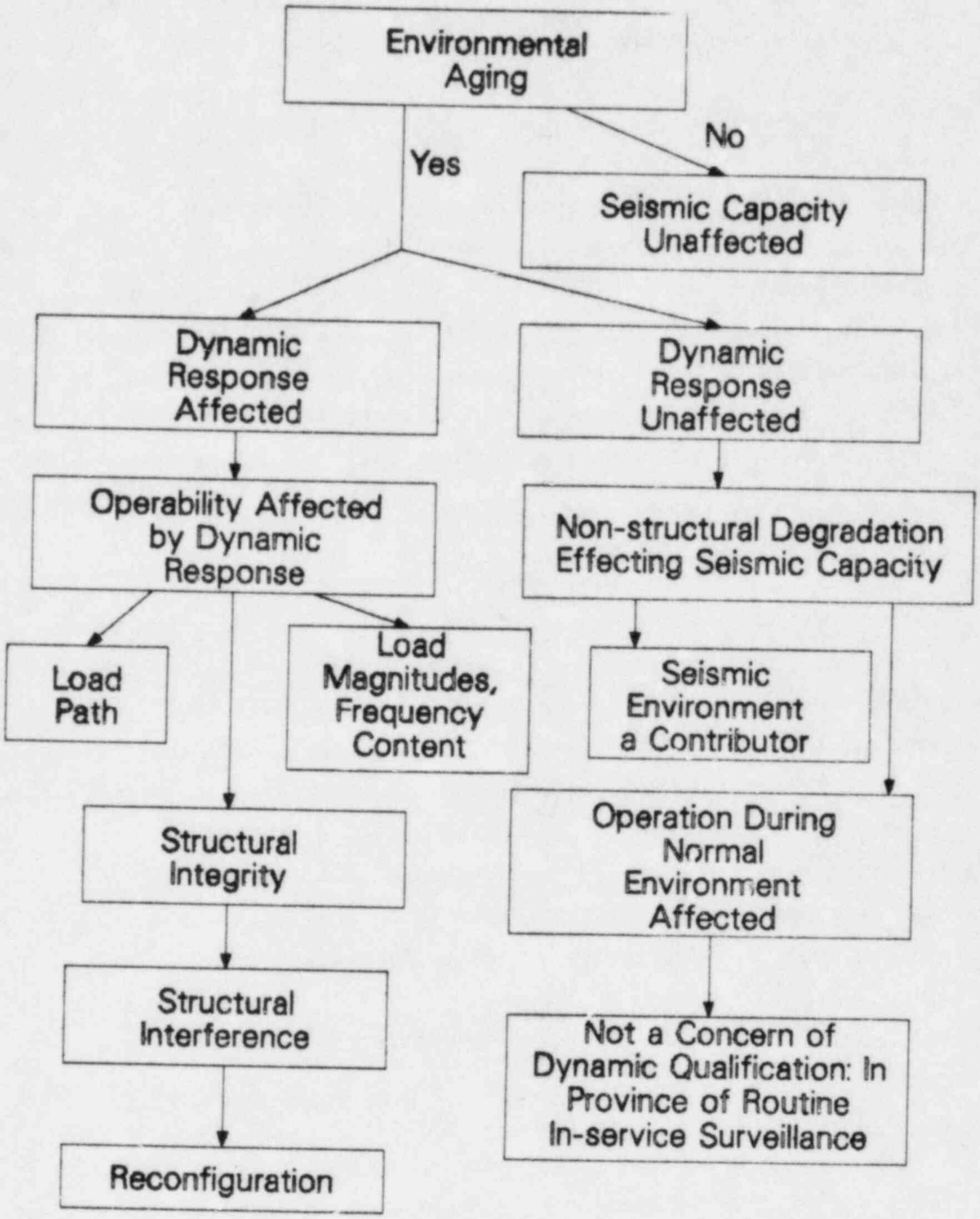


Figure 5. Effect of aging on seismic capacity

seems reasonable. If this form of degradation is anticipated and the equipment has a safety function during the seismic event, then a more thorough evaluation is required.

### 3.4.2 Qualification Considerations

A systematic basis for evaluating aging degradation is provided by the failure mode analysis of Section 3.3 and the procedures embodied in Figure 5. Again this methodology will be most readily applicable to simple equipment. The method is now discussed.

First, a determination of any aging effects produced by the design basis environments should be conducted. This involves listing all vulnerable materials and examining environmental data for each. Presently such data is only available for some materials. Those components demonstrating no environmental aging require no further examination.

For components containing materials affected by the design environments the aging mechanisms should be defined and categorized as follows:

- Category I aging includes all aging mechanisms which modify the dynamic response. The changes in dynamic response can affect all four failure modes: structural integrity, system reconfiguration, structural interference, and nonstructural effects. Each failure mode must be examined in light of the anticipated degradation. If it cannot be established that no significant change in seismic capacity occurs then the critical failure mode(s) should be established. A similar system with a known aged seismic capacity may provide data on which to base the aged seismic capacity. Realistically, equipment designed for dynamic environments should not be susceptible to this type of aging and the problem may be infrequent. Otherwise, adversely affected items should be qualified to current criteria.

- Category II aging is any aging mechanism which could affect the operability of safety equipment when combined with the predicted seismic loads. It is assumed that the dynamic response has not been affected. This is a type of aging mechanism which impacts only the nonstructural effects. It need only be examined if a known aging effect exists in a component. Again seismic capacity can be inferred from tests on similar equipment. However the requirements on similarity are somewhat more stringent in this case. Any loss of seismic capacity will be due to degradation combined with local structural dynamics. Thus similarity requires that both be simulated.

- Category III aging mechanisms are those identified mechanisms which have no effect on seismic qualification.[26] For a typical component many mechanisms would typically fall in Category III.

The application of the above approach would probably be most economical if conducted in stages. Initially all equipment would have a cursory examination for a) no aging, b) some aging, though with no effect on seismic capacity, c) aging with a potential effect on seismic capacity, or d) too complex to determine easily. For situations where further consideration is warranted the steps are similar to those of Section 3.3. The failure modes are used to establish similarity and data from similar equipment is transferred to the equipment in question. The important factor is that much equipment will exhibit no significant seismic aging interaction of concern and thus screening can narrow the field effectively without overlooking substantial aging degradation.

Currently, limited qualification research is being conducted in the Category III aging effects.[27] The expected future result of this effort is the identification of a Class 1E equipment subclass showing no seismic aging interaction. Such preliminary work will develop a data base also useful for qualifying equipment in operating plants.

Finally, a specific and potentially useful class of equipment can be identified. This is the equipment which has no safety related function during the seismic event. If structural integrity for the earthquake environment is validated then one can be reasonably assured it will operate after a SSE. Minor checks on the adequacy of design for permanent reconfiguration and dynamic effects on nonstructural aging degradation are required. These should be straight forward if equipment is not overly complicated.

### 3.5 Support Device Response and Mountings

The level of support device response during a seismic event can be related to the corresponding floor response spectra. The design floor response spectra will generally contain a region with significantly amplified magnitude. The center of this amplified region will generally lie between 2 and 10 hertz and coincides with the fundamental frequency of the building. The motion of the support device is reckoned as a combination of its free vibration modes whose maximum values are determined from the floor response spectra. Generally the first mode has the largest modal participation factor (MPF) and is the most important. Knowing the first mode frequency and its MPF the maximum response is estimated readily from the floor response spectra.

Tuning of the support device and the building containing the device occur when a natural modal frequency of a device coincides with the fundamental building modal frequency. As an example, cabinet frequencies between 5-15 hertz are typical so that tuning is possible. In case tuning occurs the floor response spectra dictates a response level 2-5 times a non-tuned response. A complicating factor is that the lowest natural frequency of a support device depends upon how it is attached to the floor as well as its physical properties. For instance a welded mounting will result in a higher frequency than a mounting with a minimum number of bolts. Thus for operating plants uncertainties relating to support devices include both physical properties and the mounting boundary condition.

Hence equipment design environment will depend heavily on the relationship between support device and building fundamental frequencies. It is clear that most of the safety related systems were not intentionally designed to function in highly amplified dynamic environments (i.e., tuned conditions). Systems that may be subject to these loads should be identified by in-situ procedures. Here an abbreviated process can be followed where all support device natural frequencies below 15 hertz are experimentally determined. Mode shape determination is not required. A modal analysis crew should be able to check a number of cabinets in a single day so cost is not an overwhelming burden. Currently operating plants are mainly located in regions of low seismicity and this utilization of in-situ procedures insures that actual response loads are as low as generally perceived.

Where amplified support device response is identified two options are recommended. Regardless of the criteria applied to other equipment in operating plants, this equipment should be qualified vigorously. The first option is to determine the design basis environment (see Sections 3.2 and 4.2) and qualify equipment to that environment. The second option is to modify the support device by either altering its mounting or stiffening the device, depending upon which is appropriate. That a lower response is assured should be verified by in-situ procedures.

If one analyzis a support device, verifies its structural integrity, and provides evidence that all mounted components have seismic resistance exceeding their RRSs, it still remains to qualify the mounting design. Review of proprietary qualification documents indicated that mounting inadequacy has been a major cause of retrofit and retest in qualification programs. The current qualification process essentially qualifies mountings during shake table testing. For operating plants several options are available. Analysis procedures using data from in-situ testing can predict the maximum acceleration of equipment. Thus the loads that mountings must transmit can be predicted. It should be a straight forward process to assess existing designs. The main distraction is the large number of mountings that exist. Enveloping the maximum acceleration could be an approach to reducing this work load.

Examining mountings on a theoretical basis may not address some (perhaps the major) problems. There is some feeling that quality of installation or use of problem prone designs may be a stronger influence on mounting adequacy than strength considerations. To address these conserns a physical mounting review by practitioners experienced in seismi qualification testing as well as current mounting design practice would be an effective design control measure. This process would be enhanced if the reviewers were supplied with an equipment table identifying an enveloping acceleration, equipment weight, and a simple description of the mounting. The plant walk-down would then screen mountings for those requiring in-depth review or retrofit. The effectiveness of this process is that it screens out items which are clearly adequate and concentrates more costly review on questionable items.

# 4. ANALYSIS PROCEDURES

It has appeared reasonable that knowledge of a structures linear mechanical characteristics along with a mechanical input description are sufficient to define the resulting environment anywhere in the structure. Toward this end, a review of analysis procedures has found that several procedures can be used. Part of the mechanical description required can be determined from in-situ procedures, the natural frequencies and the mode shapes. Damping is a third mechanical property and should be based on current NRC guidance. The mechanical input is reckone via the ground or floor response spectra. The methods for using in-situ generated mechanical characteristics in determining response are described in this section.

The primary purpose of these procedures is to develop response spectra within support devices. The predicted response spectra then act as the required response spectra for component qualification. The analysis procedures can be divided into methods which use the parameters determined by in-situ procedures directly in the analysis, and methods which use the in-situ results to validate a computer model.

## 4.1 Basic Theory

It is assumed that all structures transmitting inputs act linearly. The structure is considered as an "n" degree of freedom system and represented by matrix equations as:

$$[M]\{\ddot{X}_r + \ddot{Y}_b\} + [K]\{X_r\} = 0 \qquad (1)$$

or

$$[M]\{\ddot{X}_r\} + [K]\{X_r\} = -[M]\{\ddot{Y}_b\} = -\{M_i\}\ddot{Y}_b \quad . \qquad (2)$$

Damping will be ignored in these developments. However it can be incorporated into the modal equations of motion at any convenient time.

[M] = n x n diagonal mass matrix

$[K]$ = n x n stiffness matrix

$-\{M_i\}\ddot{Y}_b$ = n x 1 load vector due to base motion

$\{X_r\}$ = n x 1 solution vector.

Next the use of the modes of free vibration is incorporated.

$$\{X_r\} = [\phi]\{\alpha\} \tag{3}$$

$[\phi]$ = consists of columns of free vibration modes; $\{\phi\}_1, \ldots \{\phi\}_n$

$\{\alpha\}$ = consists of 'n' time varying functions $\alpha_i(t)$.

The free modes of vibration satisfy several relationships including

$$[\phi]^T[M][\phi] = [I]$$
$$[\phi]^T[K][\phi] = [\omega_n^{\ 2}] \tag{4}$$

Now by using Equation (3) above in Equation (2) and premultiplying by $[\phi]^T$ we have

$$[\phi]^T[M][\phi]\{\ddot{\alpha}\} + [\phi]^T[K][\phi]\{\alpha\} = -[\phi]^T\{M_i\}\ \ddot{Y}_b \quad . \tag{5}$$

Because of the diagonal nature of the matrices in Equation (4) we see the equations in Equation (4) are effectively uncoupled.

$$\{\ddot{\alpha}\} + [\omega_n^{\ 2}]\{\alpha\} = -[\phi]^T\{M_i\}\ddot{Y}_b \quad . \tag{6}$$

The quantity $[\phi]^T\{M_i\}$ is a constant vector $\{\Gamma_i\}$ with

$$\Gamma_i = \{\phi\}^T{}_i\{M_i\} \quad . \tag{7}$$

Thus for a given mode "i" we have

$$\ddot{\alpha}_i + \omega_i^2 \alpha_i = -\{\phi\}_i^T\{M_i\}\ddot{Y}_b \quad . \tag{8}$$

The maximum values for $\alpha_i$ can then be interpreted from the ground response spectra. The ground response spectra provides the solution for the equation

$$\ddot{g} + \omega^2 g = -\ddot{Y}_b \quad . \tag{9}$$

for a specified range in $\omega$. By identifying the ground response spectra value at structural (i.e., free vibration) frequencies and multiplying by the modal participation factor (MPF) it is evident that the solution to Equation (6) has been determined. One proceeds on this basis for all "n" structural modes, finding the maximum values of $\ddot{\alpha}_i$ and $\alpha_i$. Now,

$$\alpha_i = \Gamma_i \; g_i(t)$$

$$(\alpha_i)_{max} = \Gamma_i \; (g_i)_{max}$$

$$\Gamma_i \; (\ddot{g}_i + \omega_i^2 \; g_i = -\ddot{Y}_b)$$

$$\Gamma_i \; \ddot{g}_i + \omega_i^2 \; g_i \; \Gamma_i = -\Gamma_i \ddot{Y}_b$$

and $\ddot{\alpha}_i + \omega_i^2 \; \alpha_i = -\Gamma_i \ddot{Y}_b$

so the desired equation is recovered. The final step concerns combination of the modes. For modes whose motion is statistically independent of one another the "square-root-sum of the squares" (SRSS) is used to determine maximum values. These values are called "most likely maximum values" and are purported to have that statistical property.

Consequently one can see the natural correspondence of the ground response spectra with the structure's equations of motion when they are rewritten in the modal degrees of freedom.

## 4.2 Model Validation

The response of support devices during design basis dynamic events is central to equipment qualification because a large portion of the equipment qualified by test is mounted in these devices. Furthermore each support device may contain many pieces of equipment. While it is possible to estimate the dynamic response of these systems using computer models this procedure has not been accepted for equipment qualification. It has been considered that the only reliable procedure is to subject the support device system to testing thus simulating design basis events. The support device may contain instrumented masses instead of components in which case the required qualification environment is recorded or it may contain prototype components in which case the entire system is qualified.

Specific in-plant situations have occurred where some feature of the installation was not compatible with the qualification testing performed. In some of these situations finite element analysis has been performed to predict the dynamic response during a design basis event.[28] To validate the adequacy of the computer model in-situ tests are performed which identify the fundamental natural frequencies and associated mode shapes. The experimentally based parameters are compared with the same parameters computed from the model. If required, the model and its boundary conditions are adjusted until an adequate correspondence is achieved. The final computer model is used to determine both the RRS at specific points in the support device and stresses within the support device.

The analysis procedures involved here are those of the typical time history method. In this process, 1) a synthetic time history is developed from a specified floor response, 2) the modes, frequencies, and modal participation factors are calculated from the model, 3) a time history analysis is performed on each significant mode, 4) the modes are algebraicly combined to determine total time histories, and 5) the time histories are converted to RRS for the components of interest. This process requires the development of a finite element model which in the writer's assessment is the dominant expense in the process. This process can be directly applied to equipment in operating plants. It has the advantage that once a finite element model is developed and validated, this same model can be used to evaluate the qualification of future changes to the system. Reiterating, the use of in-situ procedures is to validate a finite element structural model.

### 4.3 Analysis Using Modal Parameters Directly

It is possible to perform analyses yielding support device motion and RRSs without developing a finite element model. A note of caution is that no detailed theoretical discussion or case studies have been found in the literature. However the writer knows of several organizations currently active in developing methodology. The process involves using the frequencies and mode shapes determined from in-situ procedures directly in constructing a numerical solution. By contrast in Section 4.2 these parameters were determined from a finite element computer model. Analysis procedures based on the direct use of modal parameters is now discussed.

As a starting point refer to the linear equations of motion (damping neglected) written using the free vibration mode shapes and frequencies.

$$\{\ddot{\alpha}_n\} + [\omega_n^2]\,\{\alpha_n\} \equiv -[\phi]^T[M]\{1\}\ddot{Y}_b(t)$$

$$,\ \{X_r\} = [\phi]\,\{\alpha\}$$

$$\{Y\} = \{X_r\} + Y_b\,\{1\} \qquad (10)$$

These equations are (3) and (6) repeated from Section 4.1. Note that equation (8) for a particular mode is

$$\ddot{\alpha}_i + \omega_i^2 \alpha_i = -(\Sigma\phi_{ji}M_j)\ddot{Y}_b = -\Gamma_i\ddot{Y}_b$$

To completely specify this equation (the equation for the "ith" mode) it is necessary to know the natural frequency, mode shape, and the modal participation factor for the "ith" mode. Then, since $Y_b$ is known, a time history analysis can be performed to determine $\alpha_i$ (t). Once the time histories of all significant modes have been calculated then equations (6) and (10) are used to construct the complete response.

To proceed, it is assumed that in-situ testing procedures have identified a given set of modal shapes and frequencies accurately. The number of points (refered to as 'n') at which measurments were taken is of central importance. It represents the number of points used in describing a mode shape, the maximum number of natural frequencies, and the maximum number of mode shapes which can be determined from a particular test. In situations where well resolved (large 'n') mode shapes are sought the experimentally determined transfer functions will not allow accurate resolution of all 'n' mode shapes and frequencies. Thus an incomplete set of accurately known modal parameters is determined from in-situ testing. This set is quite adequate provided it contains all significant modes.

The final step required is to determine the MPF's for the significant modes. If a complete set of accurate modes were available the MPF's could be determined directly using the complete modal matrix. The procedure is discussed later in this section. For the situation in which an incomplete set of modes is known, the writer is aware of several proposed schemes [29,30,31] for estimating the MPF's. Currently these procedures are proposed resolutions whose limitations and validity have not been verified. Thus it is not possible to recommend their use today.

Fortunately a method of determining modal masses and MPF's is available. This method estimates the MPF to the same accuracy level as the mode shapes. Although the method is straight forward it has not been previously suggested in the literature. Consider the equation for the exact modal participation factor[a] based on the exact continuous "i th" mode shape where a one dimensional system is considered for simplicity.

$$(MPF)_i = \int_a^b \phi_i(s) \frac{dm(s)}{ds} ds \qquad (11)$$

s = independent coordinate

m(s) = mass distribution along coordinate "s"

$\phi_i(s)$ = continuous mode shape

The quantity dm/ds is evaluated from the actual, existing mass distribution and thus can be evaluated to any desired degree of accuracy. Since the mode shape is estimated at discrete points, the approximations in (11) are inherently governed by the estimate of $\phi_i(s)$.

The discrete approximation to (11) is

$$(MPF)_i \doteq \sum_{j=1}^{n} \phi_{ji} \, \Delta M_j \qquad (12)$$

$$\Delta M_j = \frac{\int_a^b \phi_i(s) \frac{dm(s)}{ds} ds}{\phi_{ji}} \qquad (13)$$

---

a. If the modes are not mass-orthonormalized then equations (11) and (12) must be modified by the factor

$$\left[ \int_0^s \phi_i^2(s) \frac{dm(s)}{ds} ds \quad ^{-1} \right]$$

The equations above clearly indicate the modal participation factor can be more accurately predicted by increased resolution of the discrete mode shape. Equation (13) also shows that if $\phi_i(s)$ is relatively constant over a span then $\Delta M_j$ will be nearly the mass in the span. Estimating the continuous mode shape allows for calculating $\Delta M_j$ directly from equation (13). Note that generally it will not be precisely the mass in the interval. This is the recommended procedure for calculating nodal masses and the MPF. It is recommended because it is theoretically sound and verifiable, it does not penalize accurate description of modes, and it can be performed in a straightforward fashion. A minor drawback is that the distribution of mass in the system must be described. Figure 6 illustrates the flow diagram for the proposed analysis procedure.

A method has also been proposed[31] in which a complete set of modes is always generated. This is accomplished by using a number of nodes equal to the number of significant modes from which the solution will be constructed. In this case it is possible to invert the pseudo-modal matrix and predict the pseudo-MPF factor directly as follows (the word "pseudo" is used to identify quantities which are not mass-orthonormalized)

$$[\psi]^T[M][\psi]\{\ddot{q}\} + [\psi]^T[K][\psi]\{q\} = -[\psi]^T[M]\ \{1\}\ \ddot{Y}_b$$

and $[\psi]$ = psuedo-modes, i.e., modes which have not been mass-orthonormalized

$$[\psi]^T[M][\psi] = [M_e]$$

$$[\psi]^T[M][\psi] = [M_e]\ [\omega_n^2]$$

and $\{\ddot{q}\} + [\omega_n^2]\{q\} = -[M_e]^{-1}[\psi]^T[M]\{1\}\ \ddot{Y}_b = -\Gamma_i{}^*\ddot{Y}_b$

and $[M_e][\psi]^T[M]\{1\} = [\psi]^{-1}\{1\}$

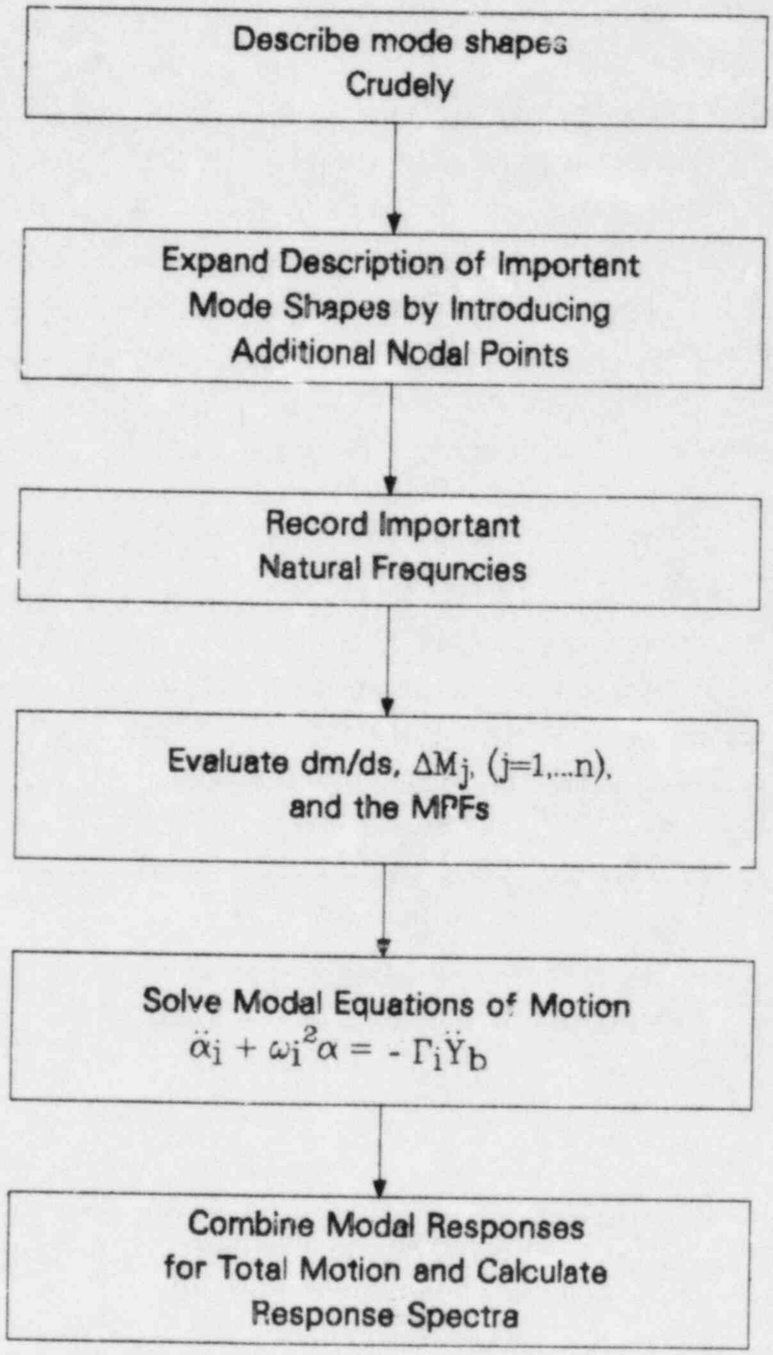


Figure 6. Proposed analysis procedure

which is the puesdo-modal participation factor and can be readily determined. While this process is very straightforward it employs a relatively crude discretization of the system. The limitations and conditions where it can be accurately employed have not been determined, and it also cannot be recommended at the current time.

Finally there are several notes of caution to be mentioned. Generally as the natural frequency increases it becomes more difficult for in-situ procedures to resolve the associated mode shapes. For seismic analysis it is felt that higher modes, or modes with several antinodes will result in low or negligible MPFs. Consequently accurate calculation of only the lower mode shapes will probably be necessary. The situation must be checked for every individual case. The second comment concerns closely spaced modes. The decomposition of the total frequency response into modal frequency response functions is one step in the development of the mode shapes. Closely spaced mode shapes (i.e., two modes with nearly equal frequencies) reduce the accuracy with which the modal frequency response functions are calculated from the experimental transfer functions. The existence of closely spaced significant modes could render the direct use of modal parameters infeasible. This issue will be examined further in follow-on investigations. It is anticipated that this situation will occur infrequently in which case the alternative of Section 4.2 can be used to determine RRSs.

A final comment is that the advantage of the direct use of modal parameters is that the modal parameters are relatively inexpensive to generate experimentally. Generation of modal parameters by the finite element method will require substantially more cost and will be effective on a less general basis. Consequently analysis procedures which use experimentally determined modal parameters are the prime candidate for predicting RRSs in operating plants.

## 4.4 Direct Response Spectra Transfer

Sections 4.2 and 4.3 discussed several procedures for predicting the RRS of equipment located in support devices. Both of the procedures employed variations of time history analysis where a synthetic time history is used to define the load. Using these procedures an input response spectra can be transferred to an output location yielding an output response spectra. Since the input is initially specified by a response spectra, the use of time history analysis in transferring response spectra is essentially artificial and the output response spectra is not uniquely defined by the input spectra. Methods for transferring the input response spectra in a unique, more meaningful, and less costly way are preferable.

Direct methods for response spectra transfer have been sought by various investigators.[32--38] A direct method uses the input or floor response spectra in combination with the modal parameters and modal participation factor to determine output response spectra. The associated analytic procedures are algebraic. The initial motivation for developing these methods was to reduce the effort involved in generating floor response spectra for buildings. Any direct methods will eliminate the time history analysis portions of the transfer process. In addition by using mode shapes and frequencies determined from in-situ procedures the need for a finite element model can be eliminated, yielding a very cost effective method. However, more recently another equally important motivation has arisen.

Response spectra transferred by the time history method are dependent on the synthetic time history used as base input. Ideally the transferred response spectra would depend only upon the input response spectra and the dynamic characteristics (mode shapes, natural frequencies, damping, and MPFs) of the system. But large variations have been reported when transferring spectra consistent synthetic base time histories. The variations, or response spectra dispersion, are an inherent aspect of the time history process. The large variation possible in the amplified region of the response spectra is an inherent weakness of the time history method of transfer. A direct method of transfer, identifying a consistent or average transferred spectra would eliminate the arbitariness associated with time history transfer.

Some aspects of response specta transfer are presented in more detail in Appendix A. Two distinct modes of dispersion, i.e., the features by which the transferred response spectra become non-unique, seem to exist. In areas where the spectral frequency is not near one of the structures natural frequencies, Equation A.13 shows the dispersion is a result of arbitary modal combination. The SRSS rule for modal combination allows the prediction of a "most likely response spectra" as in Equation A.13. Thus the correct transfer in these areas of the response spectra curve is resolved. In areas where the spectral frequency is near one of the structures frequencies, i.e., tuned conditions, the problem is more complicated. The explanation for dispersion in this area has not been found in the literature. One potential explanation is motivated by observing that frequency content in the structure's motion near the tuned frequency is the dominant contributor to the oscillator's motion. In this frequency range/band the mode with the corresponding natural frequency dominates the structure's spectral response, i.e., the other modes can be neglected in these arguments. This motion (one mode shape with a narrow frequency band) then acts as input to the tuned oscillator. However, the frequency response function of the oscillator shows that phase angle changes depend strongly on the exact frequency within the band of interest (see Figure A-1). For low damping, large variations in phase angle change occur within a narrow frequency band. Consider two different input spectra consistent time histories for a structure which has an attached light oscillator. The oscillator can achieve significantly different peak motions because of the phasing changes within the dominant frequency band as the structure's motion is transferred into the oscillator.

The acceptance of a method for direct response spectra transfer awaits a firm resolution to predicting response at tuned conditions. Several methods have been proposed, but none have received total recognition. It is the writer's assessment that development of an acceptable procedure will be a major benefit in equipment qualification because only knowledge of the input spectra and the dynamic mechanical properties are necessary. No time history analysis or finite element model is required and the calculated response spectra is not subject to dispersion. The RRSs can probably be determined while a modal analysis crew is actually conducting in-situ experiments.

## 5. RECOMMENDATIONS

The following recommendations concerning equipment qualification in operating plants have been developed in the course of these studies.

1. It is recommended that in-situ procedures be accepted as a method for determining dynamic structural mode shapes and natural frequencies. A standard or preferred format should be evolved for presenting test procedures and results to assist in validating the data reduction and analysis procedures used for construction of mode shapes.

2. It is recommended that the application of analysis procedures combined with in-situ derived dynamic properties (discussed in Section 4.3) be accepted as a method for determining the RRS of components mounted in support devices. The dynamic chracteristics are the mode shapes and natural frequencies. The modal participation factor required for analysis may be calculated by any justifiable method; one such approach was described in Section 4.3. Use of the above parameters with the time history method is one acceptable analysis procedure for transferring the floor response spectra to a mounting position in a support device.

3. It is recommended that the seismic qualification requirements for retrofitted equipment be based on a RRS that has been either confirmed by in-situ testing or developed using in-situ dynamic characteristics. In-situ procedures may be employed to validate the finite element model used in developing a component RRS. Validation is achieved by showing close correspondence in the frequencies and mode shapes of significant modes. On the other hand, as described in recommendation 2, the dynamic characteristics may be used with analysis procedures to predict the RRS. In either case, seismic qualification for the retrofitted equipment is achieved if prior testing has successfully enveloped this RRS.

4. It is recommended that all support devices containing safety related equipment be subjected to an in-situ frequency evaluation, and that a comparison of these natural frequencies with floor response spectra be performed as a screening technique to identify highly loaded systems. It must be insured that the natural frequencies of buildings are sufficiently removed from the as-installed support device natural frequencies. The alignment of these frequencies will result in substantially larger support device motion. In such cases modifications to the support device which alter its natural frequency are required. An alternative is to qualify the equipment and support device to the higher load levels.

5. It is recommended that all mountings attaching Class 1 equipment to support devices be subjected to a walk-through examination. Suspect mountings should be retrofitted to current practice. The examination should be performed by someone experienced in seismic qualification testing as well as current mounting design practice in the nuclear industry.

6. It is recommended that design evaluations based on the failure mode analysis of Section 3.3 be accepted as one method of establishing seismic similarity between different pieces of equipment. The seismic qualification of one piece of equipment implies the qualification of similar designs in operating plants.

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# APPENDIX A

## STRUCTURE WITH APPENDAGE

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### A.1 Response at Untuned Conditions.

If an oscillator is attached to a structure with 'n' degreees of freedom, the combined system takes the form of an 'n + 1' degree of freedom system.

The oscillator's frequency is identified as

$$\omega_o^2 = K_o/M_o \tag{A.1}$$

and if the oscillators mass is small compared to any in the structure then the natural frequencies of the total system are made up of the frequencies near the structures 'n' frequencies and the oscillator's frequency ($\omega_o$). Here the factors required to transfer the ground input response spectra to any point on the support device are sought.

Assuming the coupling between oscillator and structure is weak, the equations are organized such that the first 'n' mode shapes and frequencies are those associated with the structure and the structural frequencies. The 'n + 1' modal component in each mode is the oscillator's motion relative to the moving base in each mode. We can solve for that modal component directly from the eigenproblem equations:

$$\left[\begin{array}{c:c} K^*-\omega_k^2 M^* & \begin{array}{c} 0 \\ \vdots \\ 0 \\ -K_o \end{array} \\ \hdashline 0 \;\ldots\ldots\ldots\; 0 \;\; -k_o & (k_o - \omega_k^2 M_o) \end{array}\right] \begin{Bmatrix} \phi_1 \\ \vdots \\ \phi_n \\ \phi_{n+1} \end{Bmatrix}_k = 0 \tag{A.2}$$

where $\omega_k$ is one of the structures frequencies.

The final equation provides that

$$\frac{\phi_{n+1}}{\phi_n} = \frac{K_o}{K_o - \omega_K^2 M_o} = \frac{\omega_o^2}{\omega_o^2 - \omega_K^2} \quad . \tag{A.3}$$

Since the mass '$m_o$' is taken to be very small compared to $M_1 \ldots M_N$, the first N frequencies are very close to those of the structure alone, then by partitioning the eigenproblem equations to eliminate the last two equations

$$\left[\begin{array}{ccc|cc} & & & K_{1n} & 0 \\ & & & K_{2n} & \vdots \\ & K' - \omega_K^2 M' & & \vdots & \vdots \\ & & & \vdots & \vdots \\ & & & K_{n-1,\,n} & 0 \\ \hline K_n & \cdots & K_{n,\,n-1} & (K_o + K_k - \omega_k^2 M_n) & -K_o \\ 0 & \cdots & 0 & -K_o & (K_o - \omega_k^2 M_o) \end{array}\right] \begin{Bmatrix} \phi_1 \\ \vdots \\ \vdots \\ \phi_n \\ \phi_{n+1} \end{Bmatrix}_K = 0 \tag{A.4}$$

the first 'n - 1' equations become

$$\left[K' - \omega_K^2 M'\right] \begin{Bmatrix} \phi_1 \\ \vdots \\ \phi_{n-1} \end{Bmatrix} = \phi_n \begin{Bmatrix} K_{1n} \\ \vdots \\ K_{n-1,\,n} \end{Bmatrix} \tag{A.5}$$

These are exactly the equations solved to determine the first 'n - 1' components of the structural mode shape at any of its natural frequencies. So that for the first 'n' mode shapes

$$\{\phi\}_K = \begin{Bmatrix} \phi_1 \\ \phi_2 \\ \vdots \\ \phi_n \\ \left[\omega_o^2 / \left(\omega_o^2 - \omega_K^2\right)\right]\phi_n \end{Bmatrix} \tag{A.6}$$

where $\phi_1 \ldots \phi_n$ is the structure only mode. Provided that the mass $M_o$ is very small the eigenvector need not be re-mass-orthonormalized.

The final frequency of the total system is very near $\omega_{n+1} \simeq \omega_o$, the oscillator frequency. Again we view the last equation from the eigenvalue problem

$$\frac{\phi_n}{\phi_{n+1}} = \frac{\omega_o^2 - \omega_{n+1}^2}{\omega_o^2} \sim 0 \quad . \tag{A.7}$$

It is expected that the other 'n - 1' modal components are also negligible. To motivate this examine the eigenvalue equations after partitioning and rearranging

$$\left[K_s - \omega_o^2 M_s\right]\{\phi\}_{m+1}^{m} = \phi_{n+1,n+1}\begin{Bmatrix} 0 \\ \vdots \\ 0 \\ K_o \end{Bmatrix} \tag{A.8}$$

$\{\phi\}_{n+1}^{n}$ = first 'n' modal components of 'n + 1' mode shape

$K_s$ = structure's stiffness matrix

$M_s$ = structure's mass matrix.

It will be shown that $\phi_{n+1,n+1} \sim 1/\sqrt{m_o}$ so that

$$K_o{}^*\phi_{n+1,n+1} = \frac{K_o}{\sqrt{m_o}} = \sqrt{m_o}\,\omega_o{}^2 \tag{A.9}$$

and thus the right hand side is a very small number.
Since $\omega_o$ is <u>not</u> an eigenvalue of the structure

$$\left[K_s - \omega_o{}^2 M_s\right]\left\{\phi^*\right\}_{n+1}^{n} = 0 \tag{A.10}$$

yields that

$$\{\phi^*\}_{n+1}^{n} = \{0\}$$

identically.

The right hand side of Equation (A.9) is small and thus (not proved here) the first 'n' modal components will be small in each component. Thus the final mode shape is

$$\{\phi\}_{n+1} = \begin{Bmatrix} 0 \\ \cdot \\ \cdot \\ 0 \\ \phi_o \end{Bmatrix}$$

and since

$$\sum_{j=1}^{n+1} m_j \ \phi_j^2 = 1$$

we obtain $\phi_o = 1/\sqrt{m_o}$. In examining the final mode shape further we see that

$$\Gamma_{n+1} = \{\phi\}_{n+1}^T * \{M_i\} = \sqrt{m_o} \tag{A.11}$$

and

$$\ddot{\alpha}_{n+1} + \omega_o^2 \ \alpha_{n+1} = - m_o \ \ddot{Y}_B \tag{A.12}$$

thus $\alpha_{n+1} = \sqrt{m_o} * g(t,\omega_o)$

where $g(t,\omega_o)$ is the solution to the SDOF oscillator whose maximum response is represented on the ground response spectra. Thus the oscillator's motion in this mode is

$$\begin{Bmatrix} 0 \\ \cdot \\ \cdot \\ \cdot \\ 0 \\ X_o \end{Bmatrix} = \begin{Bmatrix} 0 \\ \cdot \\ \cdot \\ \cdot \\ 0 \\ 1/\sqrt{m_o} \end{Bmatrix} \sqrt{m_o} \ g(t,\omega_o) = g(t,\omega_o)$$

Now it is a direct matter to employ the ground response spectra to predict the maximum values of the motion in each mode and combine these motions. For modes not close to one another that are also less than 33 Hz [or below the frequency of the zero period acceleration (ZPA) of the ground response spectra] the Square Root Sum of Squares (SRSS) will be the appropriate summation to employ. If more than one important structural mode has frequency greater than 33 Hz then these two modes are combined by an algebraic rule that maintains their correct relationship relative to one another. This total maximum value can then be combined by SRSS directly with the other structural modes. If there is only one structural mode above 33 Hz, it is combined as usual using SRSS. Thus we can construct certain portions of our in-structure response spectra.

For '$\gamma$' important modes we write

$$\text{ACC. MAX.}\ (\omega) = \sum_{i=1}^{\gamma} \left( \Gamma_i \phi_{n+1,i}\ S_A(\omega_i)^2 + S_A(\omega_o)^2 \right)^{1/2} \quad \text{(A.13)}$$

It is noted that the response spectra is constructed except near the structures natural frequencies. Note that the frequency on the abscissa is the oscillator frequency $\omega_o$. Examining the modal matrix in Equation (A.8) makes it evident that the situation is singular at the points where $\omega_n = \omega_o$. A special treatment is required near these conditions.

## A.2 Response at Tuned Conditions

In developing an in-equipment response spectra (or a floor spectra for that matter) one imagines placing a small mass supported by a variable spring in the position for which the response spectra description of the motion is sought. The structure must then undergo the same time history a number of times while the variable spring is taken through a range of values. The maximum oscillator acceleration is recorded and plotted versus the oscillator frequency. As the oscillator spring frequency is varied it will at some time be near to one of the support devices natural frequencies. When this occurs we can say we have tuning

($\omega_o \sim \omega_n$). The equations provided earlier degenerate when they are close to these conditions. It is necessary to examine these conditions further to determine the special modal responses which occur with light appendages and tuning simultaneously.

At the current time, in-structure (i.e., floor) response spectra are often determined by a time history method. As discussed later this is a procedure which can lead to variable results. However, it does point out the central feature of response when the oscillator frequency, at tuned conditions, aligns with structural frequency. That feature is a substantially amplified oscillator motion. Over a period of time various investigators have attempted to rationalize the response for tuned systems (i.e., $\omega_o \sim \omega_n$) that dominate the peaks in these time history transferred response spectra. Some of the analysis are ad hoc and depend on arbitrary amplification to drive their proposed methods. Others use numerical calculations that themselves may be somewhat suspect due to the highly singular nature of the response when the oscillator is tuned to the support device.

Unpublished numerical results have indicated that when several synthetic time histories are developed from a single input response spectra, the transferred response spectra can show wide variations at the tuned frequencies. The source of these variations has not been discussed in the literature. This delima must be understood both for understanding the inconsistencies of time history transfer and developing a direct method of transfer. The complete answer does not appear to be available at the current time. However a proposal for the underlying mechanism is presented below.

Recall that the response spectra at a specific point in a structure is not the structure's motion but rather a description of the motion experienced by an oscillator mounted in that position. To proceed, the structure's motion is decomposed into components in its free vibration modes. Of interest is the structural motion in the mode whose frequency is equal to that of the oscillator (bear in mind the motion of the oscillator in the non-tuned modes is characterized by the equations in Appendix A.1).

In order to proceed the base input is decomposed into a series of trignometric functions (or alternately a Fourier integral). The total response of the tuned mode is the superposition of the response for each term in this series. For an earthquake the load duration is of sufficient length to consider the response as steady state in each of these trignometric components. The steady state response to a trignometric input component occurs at the same frequency and can be written using the "frequency resonse function" (FRF). The FRF[39] is the solution to

$$\ddot{x} + 2\omega_o \xi \dot{x} + \omega_o^2 x = \sin \omega t.$$

The FRF for displacement and acceleration are

$$FRF_d = (1/\omega_n^2) \Bigg/ \left[\left(1 - \left(\frac{\omega}{\omega_n}\right)^2\right)^2 + \left(2\xi\left(\frac{\omega}{\omega_n}\right)\right)^2\right]^{1/2}$$

$$FRF_a = (\omega^2/\omega_n^2) \Bigg/ \left[\left(1 - \left(\frac{\omega}{\omega_n}\right)^2\right)^2 + \left(2\xi\left(\frac{\omega}{\omega_n}\right)\right)^2\right]^{1/2}$$

The forced steady state solution is

$$x(t) = FRF_d * \sin (\omega t - \phi).$$

The FRF shows that inputs near the natural frequency are enhanced (amplified) and others are either filtered out or transmitted without amplification. Thus the motion of the tuned mode is richer in frequency content banded around its natural frequency $\omega_o$. Now exactly the same enhancement occurs once again as the signal is transmitted through the oscillator and the motion of the oscillator is especially rich in frequency content near $\omega_o$. Thus the response of the oscillator to the structure's motion in the tuned mode is dominated by inputs associated with frequency content in a tight band around $\omega_o$.

Consider the oscillator response for several different base input time histories with the same response spectra. Since the input spectras are the same the maximum response of the structure's tuned mode will be the same for the several time histories. The time histories of the structural motion, however are not identical. To see the potential effect of non-unique time histories the FRF and phase angle for the single degree of freedom equation are taken from Reference 39 and shown in Figure A.1.

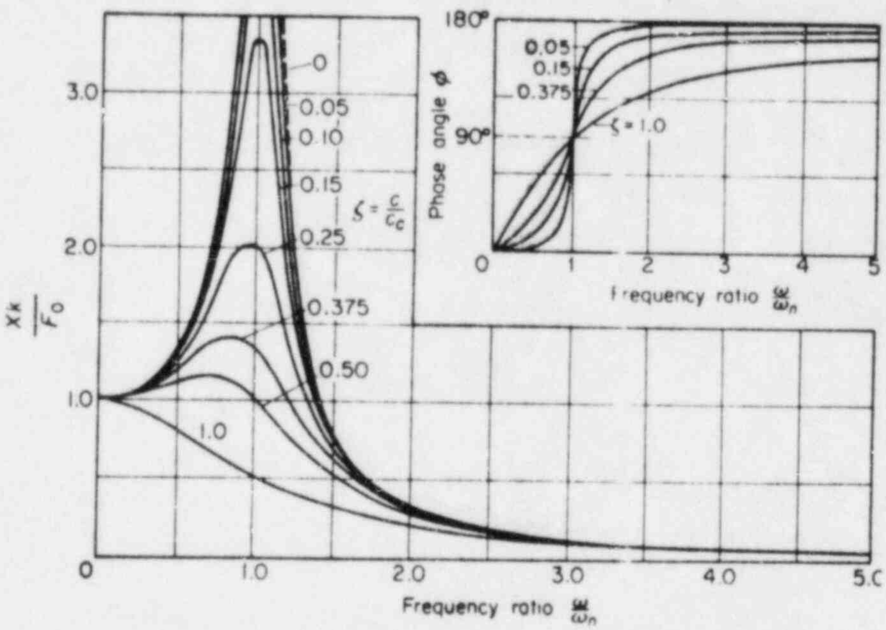


Figure A.1. Frequency response function and phase angle at various damping values.

The structural motions that act as an input to the oscillator are the result of different time histories and thus each has a unique frequency content and phasing in the frequency band which dominants the oscillator resonse. The several inputs to the structure were such that the phasing in the structure's motion yielded a common maximum value in the tuned mode. The oscillator response in that frequency band is determined by applying the FRF amplification (slowing varying) throughout the band as well as the phase angle change. As seen in Figure A.1 the phase angle is modified in a variable fashion over the frequency band. Thus the phasing in the oscillator and the structure are not similar. If several time histories are considered the oscillator's components within the frequency band need not combine to yield a unique maximum value. This appears to be the fundamental mechanism for variations near tuned conditions, i.e., rapidly varying phase angle changes.