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Summary

A Research Program for Seismic Qualification of Nuclear Plant Electrical and Mechanical Equipment

Summary Report

Prepared by D. D. Kana

Southwest Research Institute

Prepared for
U.S. Nuclear Regulatory Commission

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1.0 ABSTRACT

This document constitutes the final report for the indicated research contract on equipment seismic qualification methodology. Although the program was conducted by Southwest Research Institute, the results were periodically reviewed by a Peer Review Panel of ten members from various segments of the nuclear industry, and by various members of the NRC staff. In addition, a continuing communication with the IEEE 344 (Recommended Practices for Seismic Qualification of Class 1E Equipment for Nuclear Power Generating Stations) revision committee was maintained throughout the program to ensure that the results were disseminated to the industry. Thus, although the results are principally the findings of SwRI, acknowledgement of input from various other sources is recognized.

The program has spanned a period of three years and resulted in several technical summary reports, each of which covered in detail the findings of tasks and subtasks. Therefore, the purpose of this final report is to summarize the entire program from an overall philosophical point of view. It includes a description of the state-of-the-art for equipment qualification at program initiation, a summary of the program task results, an indication of how the results have been implemented in revised qualification procedures, and finally a discussion of some overall issues that still remain to be explored.

2.0 STATE-OF-THE-ART AT PROGRAM INITIATION

The original proposal for the program was submitted in May 1980, and the program was not initiated until June 1981. At that time (and still today) equipment qualification methodology was essentially governed by IEEE 344-1975, although it was complemented by a variety of other industry standards and NRC guidelines. It was recognized in the original Request for Proposal that a thorough review of the methodology and identification of potential anomalies and issues was in order. It was further recognized that a significant discrepancy existed between methodology for qualification (or lack of it) of pre-1975 equipment and equipment qualified thereafter. However, the currently-identified unresolved Safety Issue (Task A-46) did not exist at the time, but was initiated later about the middle of this program.

A summary of the program tasks and subtasks is given in Table 1. Further information on the results of these tasks will be given in the next section. At this point it may briefly be stated that Task 1 required an overall review and evaluation of methodology; Task 2 required a development of correlations between pre-1975 and post-1975 methodology; Task 3 principally required a summary of recommendations from the findings; and Task 4 required a special review and evaluation of fragility methodology.

It should also be recognized that at program initiation, the IEEE 344 Working Group 2.5 was already in the process of developing a revision for that document. In fact that group had already been active for about four years. Table 2 shows a list of specific areas that were being discussed. The SwRI program principal investigator is a member of Working Group 2.5, and has contributed to that effort throughout the program. Some additional members of the group served on the Program Peer Review Panel. Therefore a continuous exchange of information was accomplished throughout this program.

TABLE 1. IDENTIFICATION OF PROGRAM TASKS

1.1, 1.2, 1.3	Review methodology, aging, and static loads; Identify anomalies
1.4	Evaluate multiple frequency excitations
1.5	Consider combined dynamic environments
1.6	Develop in-situ test criteria
1.7	Study procedures for line mounted items
1.8	Publish Task 1 Summary Report
2.1, 2.2, 2.3	Investigate response level and multiple-parameter correlations
2.4, 2.5	Consider single parameter and damage severity factor correlations
2.6	Develop general correlation method
2.7	Publish Task 2 Summary Report
3.1	Recommend updating of qualification criteria
3.2	Publish Task 3 Summary Report
4.1, 4.2	Extraction of fragility data
4.3	Evaluate and reduce data
4.4	Publish Task 4 Summary Report

TABLE 2. REVISION CONSIDERATIONS FOR IEEE 344-1975
AT PROGRAM INITIATION - JUNE 1981

1. Margin in Development of RRS*
2. Artificially Broadened Response Spectra
3. Spectral Damping Values
4. Accuracy of Enveloping RRS with TRS**

5. Multiple Peak RRS
6. Complex Wave Tests
7. Frequency Distribution and Stationarity
8. Combination of Other Dynamic Loads

9. Spectrum Intensity or Damage Severity

10. Low Impedance or In-Situ Testing

11. Generic Testing
12. Type Testing

13. Analysis Recommendations
14. Multiple Cabinet Considerations

15. Line Mounted Equipment

16. Measurement of ZPA***
17. OBE Testing
18. Identification of Natural frequencies
19. Nonlinear Effects
20. Duration of Tests
21. Triaxial Test Considerations
22. Documentation

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*RRS = Required Response Spectrum

**TRS = Test Response Spectrum

***ZPA = Zero Period Acceleration

3.0 SUMMARY OF TASK ACCOMPLISHMENTS

A brief summary of results from each task will be given by referring to the several summary reports already published.

3.1 Evaluation of Seismic Qualification Methodology

3.1.1 Survey of Methods for Seismic Qualification of Nuclear Plant Equipment and Components

This topic is addressed as Task 1 Summary Report Part I [Ref. 1]. An extensive review of methodology for seismic qualification of nuclear plant equipment was presented, and some associated anomalies that can effect the results were identified. Emphasis was on qualification by testing, although some information on all currently-used methods was also included. The contents were intended to complement those of other recent review efforts which have emphasized evaluation of analytical methods.

A brief historical overview of equipment qualification efforts was described, and a list of equipment under consideration was presented. Eleven groups including thirty-one subgroups were identified. A summary of equipment description, typical mounting, seismic qualification methods, failure modes, and other information was given for each equipment subgroup. Typical qualification methods that have been applied in the past were identified. It was found that more than one method may have been applied for qualification of different specific hardware that falls within a common subgroup. As a result, it was recommended that comparisons be developed for the identified methodologies, regardless of which subgroup they have been applied to. Some comparisons are essential for evaluation of the validity of earlier simpler tests, compared with more recent complex requirements.

Various technical issues/anomalies associated with qualification by testing, analysis, and combined test and anlaysis were identified in Reference [1]. These items are repeated in Table 3. A description of continuing research efforts intended to alleviate some of the anomalies were given, along with recommendations for further work to shed light on the other anomalies.

TABLE 3. TECHNICAL ISSUES/ANOMALIES IN QUALIFICATION OF NUCLEAR PLANT EQUIPMENT*

QUALIFICATION METHODOLOGY

1.0 Qualification by Testing

- 1.1 Uncertainties in Use of Response Spectrum
- 1.2 Effects of Cross Coupling
- 1.3 Comparison of Test Severities
- 1.4 Nonlinearities
- 1.5 Test Sequence
- 1.6 Methods for Dynamic Load Combination
- 1.7 Fragility

2.0 Qualification by Analysis

- 2.1 Degree of Model Complexity
- 2.2 Synthesis of Damping
- 2.3 Acceptance Criteria

3.0 Combined Experimental and Analytical Qualifications

- 3.1 Validation and Refinement of Analytical Models
- 3.2 In Situ Testing

4.0 Synergistic Effects and Aging

- 4.1 Test Sequence
- 4.2 Aging Methods
- 4.3 Arrhenius Model

EQUIPMENT SUBGROUPS

5.0 Fragility Data for Most Equipment

6.0 Aging Data for Most Equipment

7.0 Liquid Vessels and Submerged Structures

8.0 Large and Small Piping

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*From Review Report, Ref. [1].

3.1.2 Evaluation of Methodology for Seismic Qualification of Nuclear Plant Electrical and Mechanical Equipment

The existence of the technical issues/anomalies identified in Table 3 was simply noted in Reference [1], while further evaluation of their importance was subsequently accomplished and the results reported in Task 1 Summary Report Part II [2]. Attention was given primarily to the QUALIFICATION METHODOLOGY issues, which could affect all equipment in general. The Part II Summary Report includes the results of both analytical and experimental studies performed on a typical local instrument rack, in order to evaluate the impact of many of the identified issues. For convenience, a summary of these items was first given, and then followed by important background material on recent developments in relationships between response spectra and power spectra as parameters for earthquake motion description. This was followed by results from an extensive study of the fundamental criteria for earthquake simulation waveforms. Descriptions were given for both analytical and experimental efforts for gathering response information for the electrical rack under various excitation waveforms. The remainder of the report covers extensive results on evaluation of the technical issues/anomalies, and in most cases includes conclusions on the impact of the results on current qualification criteria. Implications of the results for qualification of most types of equipment were included where appropriate.

It must be recognized that the definition of the term technical "issue/anomaly" as used herein includes the occurrence of an unexplained variation of results in qualification. It is paramount to recognize that these issues/anomalies may or may not be significant in influencing the validity of the qualification process. Furthermore, each cited item does not apply to qualification in general, but only to certain cases. As a further clarification, it is extremely important to point out that this identification of technical issues/anomalies must not be taken to imply that any of the equipment qualification performed to date is necessarily inadequate. On the contrary, early seismic test programs recognized that the test methods did not necessarily provide a close simulation of the actual seismic event and, consistent with good engineering practice, qualification testing was accomplished with a degree of conservatism which was judged sufficient to cover the uncertainties. In fact, further study of the issues/anomalies helped reveal to what degree conservatism has been present, and in some cases allowed relaxation of some requirements as a result.

3.1.3 Evaluation of Qualification Methodology for Line-Mounted Equipment

The evaluation of waveforms for seismic testing of nuclear plant equipment has been one of several objectives of this research program. A complete evaluation of typical waveforms for most types of tests was previously conducted and reported in Reference [2]. However, because of the special nature of waveforms required for simulation of the line (pipe) mounted dynamic environment, as well as other problems peculiar to this application, a separate subtask was assigned to this part of the study. The results of this work are reported in Task 1 Summary Report Part III [3].

Current methodology for testing line mounted items has included sine dwell or sine beat type motions. The philosophy for their use includes the assumption that such motion conservatively represents a near resonance response of a lightly damped piping system to earthquake excitation. On the other hand, other motions, such as narrowband random, appear to be a more suitable representation of a lightly-damped, resonant system responding to broadband earthquake motion. Therefore, a comparison of these several waveforms was performed in this study. For convenience, a linear analog circuit was first used to represent a lightly-damped system, and its responses to several waveforms were studied. Then, similar responses were observed in a typical valve specimen. Subsequently other problems, such as cross-axis coupling, were also evaluated.

3.2 Correlation of Test Methodologies

This task resulted in the report "Correlation of Methodologies for Seismic Qualification Tests of Nuclear Plant Equipment" [4]. In it a general methodology was developed for correlating the severity of one seismic qualification motion of given dynamic characteristics to another motion that may be of very different dynamic characteristics. Its most important application lies in the determination of whether equipment previously qualified to earlier, simpler standards are also qualified to newer, more complex standards. The methodology may also be used to obtain fragility* information about equipment for its own purposes and use.

*A definition of fragility is given in paragraph 3.4.

The approach developed includes the use of a vibrational equivalence concept, which allows a damage comparison between two motions of different basic character. The comparison is in terms of a damage fragility ratio D_{FR}, which is a ratio of incurred damage level to that which the specific equipment item is capable of sustaining at its upper limit of functionality (i.e., fragility level). Measurement of the damage at both levels can be in terms of response spectrum, power spectrum, or a variety of other parameters which may be used, or have been used in typical equipment qualification procedures. Relationships among the various parameters are defined, so that transformations from one to another are possible. The inherent use of the fragility function for the methodology causes some problem in that such data are not generally included in previous qualifiation information. This problem is overcome by defining a lower bound, or acceptable approximate fragility function, which is based on the previous qualification levels. If a correlation based on the approximate function is unsuccessful, then more accurate fragility data must be established before the severity comparison can be made with certainty. In this event, conduct of a completely new requalification program may be more practical.

A method of measuring relative damage severity of two motions was also developed in terms of a relative damage severity ratio D_{SR}. This ratio was shown to be proportional to several other relative severity factors that have previously been established by other researchers. It was shown that these parameters cannot be used for an absolute severity comparison, as can the damage fragility ratio D_{FR}.

3.3 Recommendations for Updating of Criteria

All of the findings of Tasks 1 and 2 as described in the previous four summary reports [1-4] were summarized and included with various recommendations in the Task 3 Summary Report [5]. For simplicity the format of that report presented only a brief identification of the technical issues/anomalies that had been previously described in detail, but further presented a set of specific recommendations for updating of equipment qualification methodology affected by them. The issues and recommendations were grouped into five different categories depending on how they could be implemented. For information, the various recommendations under each of the five categories are summarized in the Appendix to this final report. The first category deals with standardization of procedures that would simplify the overall equipment qualification effort. The second category describes those issues which demonstrate the existence of adequate methodology, while the third category includes a description of new methodology that can enhance the equipment qualification process. The fourth category deals with procedural clarifications or modifications, and the last category deals with recommended further studies. Some of the latter items are further emphasized in the last section of this final report.

3.4 Evaluation of Fragiliy Concepts

A preliminary study of the potential use of fragility concepts in equipment design was performed and the results presented in the Task 4 Summary Report [6]. In accordance with IEEE 344, in this program, fragility was defined as "the susceptibility of equipment to malfunction as the result of structural or operational limitations, or both." Similarly, malfunction is considered to be the loss of capability of equipment to initiate or sustain a required function, or the initiation of undesired spurious action which might result in consequences adverse to safety. Thus, the conduct of fragility tests to establish the fragility level or conditions for a given equipment generally requires more elaborate considerations than do proof tests, which simply demonstrate the ability of equipment to function properly at one preselected set of conditions. Furthermore, since many types of equipment are used in nuclear plants, operation at the fragility (or malfunction) level for a given item may or may not include the occurrence of permanent damage in the device, and the device may or may not resume proper operation if the conditions are subsequently reduced below the fragility level.

Although the concept of fragility has been recognized for potential use in equipment qualification since 1975, it has never been widely implemented. This circumstance results from the relative ease with which proof tests can be employed, and the independence of individual equipment manufacturers in their quest to qualify their own specific hardware. Thus, the state-of-the-art in proof tsting has progressed with vigor, while that for fragility has remained comparatively stagnant. However, at this point in time it has become apparent that, while proof testing offers advantages for qualifying individual items of equipment, fragility concepts may be much more useful for quantifying the risks associated with an entire plant. Therefore, a review of all aspects of fragility and its use in nuclear plant design is in order.

The Summary Report [6] seeks to study the potential of fragility in the design of nuclear plant equipment and its relationship to the plant in which it resides. In the most general sense, the fragility level of a device may depend on several different types of environmental stress or challenge factors (i.e., heat, nuclear radiation, moisture, etc.) that influence its operation. However, in the report emphasis is placed principally on the fragility levels of equipment which result from seismic induced stress. The most general definition of dynamic fragility and various methods for its measurement are explored. The state of published data on nuclear equipment fragility is discussed, and limitations on its use delineated. From there, the concept of a standardized fragility data base and its potential uses are considered. Various gaps in the methodology are identified, and recommendations for futher research are outlined.

4.0 IMPLEMENTATION OF PROGRAM RESULTS

This section describes several means by which the results of this program have been implemented, besides the publication of the program summary reports. As a result, the findings have been disseminated to the industry in a most expeditious manner.

4.1 Revision of IEEE 344 Standard

It has been mentioned that the SwRI Principal Investigator has served in an active capacity on both the IEEE Working Group 2.5 and its Writing Subgroup for revision of the IEEE 344 Standard. Table 4 lists nine meetings that have included these revision efforts during the course of the program. By direct participation, many of the recommendations given in Reference [6] have already been implemented in the revision to this document. Specifically, these recommendations are noted by an asterisk in the Appendix to this final report. A complete review of the draft revision has recently been summarized by Shipway and Skreiner [7].

4.2 Briefings of NRC and Peer Review Staff

During the course of the program a total of seven different briefings were conducted to reivew program results and describe new information. Table 5 lists the various meetings and the general subject of each. These briefings allowed new information to be passed on to significantly interested recipients shortly after each task or subtask had been completed.

4.3 Technical Presentations and Publications

Much of the program results has already been presented at national technical meetings or excerpts from the Task Summary Reports already published as technical papers, while several such presentations and publications are now scheduled for the near future. Table 6 lists nine oral presentations that have or will result from the program, while published technical papers are given as References [8-13]. We anticipate that at least two more technical papers may be generated from the program's results beyond those already scheduled.

TABLE 4. IEEE 344 WORKING GROUP 2.5 MEETINGS DURING PROJECT TERM

1. Pittsburgh, PA, June 1981
2. Washington, D.C., August 1981
3. Los Angeles, CA, December 1981
4. San Jose, CA, March 1982
5. Hartford, CT, June 1982
6. Boulder, CO, August 1982
7. Atlanta, GA, January 1983
8. Florissant, CO, April 1983
9. Denver, CO, January 1984

TABLE 5. BRIEFINGS FOR NRC AND PEER REVIEW STAFF

1. Program Initiation Discussion
   NRC Project Officer
   SwRI, June 1981

2. Program Review and Task 1 Part I Report
   NRC Project Officer and Peer Review Group
   SwRI, January 1982

3. Program Progress Briefing
   NRC Project Officer
   Bethesda, MD, April 1982

4. Program Review and Task 1 Part II Report
   NRC Project Officer and Peer Review Group
   Rockville, MD, November 1982

5. Program Review and Task 2 Report
   NRC Personnel
   Bethesda, MD, June 1983

6. Program Review and Task 3 Report
   Peer Review Panel
   SwRI, September 1983

7. Program Review and Task 4 Report
   NRC Personnel
   Rockville, MD, February 1984

TABLE 6. TECHNICAL PRESENTATIONS AT NATIONAL MEETINGS

1. "Current Research on Methodology for Seismic Qualification of Nuclear Plant Electrical and Mechanical Equipment", by Daniel D. Kana, ASME Pressure Vessels and Piping Conf., Orlando, FL, June 1982.

2. "Characteristics of Adequate Seismic Test Waveforms", by Daniel D. Kana, Panel Session on Seismic Qualification of Nuclear Plant Equipment", IEEE Winter Annual Meeting, New York, February 1982.

3. "Other Technical Areas of Concern in Equipment Qualification", Panel Session on Evolving Philosophy for IEEE Standard for Seismic Qualification, ASME Pressure Vessels and Piping Conf., Portland, OR, June 1983.

4. "Suitability of Synthesized Waveforms for Seismic Qualification of Equipment", Paper No. 83-PVP-22, by Daniel J. Pomerening, ASME Pressure Vessels and Piping Conf., Portland, OR, June 1983.

5. "A Method for In-Situ Test and Analysis of Nuclear Plant Equipment", Paper No. 83-PVP-21, by James F. Unruh, ASME Pressure Vessels and Piping Conf., Portland, OR, June 1983.

6. "Some Research on Methodology for Seismic Qualification on Nuclear Plant Equipment", by Daniel D. Kana, Panel Session JK-P, VII Structural Mechanics in Reactor Technology Conf., Chicago, IL, August 1983.

7. "Recent Developments in Methodology for Dynamic Qualification of Nuclear Plant Equipment", by Daniel D. Kana, ASME Pressure Vessels and Piping Conf., San Antonio, TX, June 1984.

8. "A Method for Correlating Severity of Different Seismic Qualification Tests", by Daniel J. Pomerening, ASME Pressure Vessels and Piping Conf., San Antonio, TX, June 1984.

9. "Power/Response Spectrum Transformations in Equipment Qualification", by James F. Unruh, ASME Pressure Vessels and Piping Conf., San Antonio, TX, June 1984.

5.0 CONCLUDING DISCUSSION AND RECOMMENDATIONS

This section is devoted to some final observations about the program results and emphasizes those areas where some additional thoughts have developed since the submissions of the previous summary reports. Generally, all of the recommendations given in the Task 3 Summary Report [5] still apply except that some augmentation of several of them is in order.

5.1 Standardized Equipment Categories

The standardized equipment list recommended earlier in this program is shown in Table 7 for convenience. Besides establishing generic categories of equipment this table includes a designation of equipment as either or both electrical and mechanical. The revised IEEE 344 Draft for qualification of electrical equipment should be available for public comment by early 1985. On the other hand, the issue of a single guideline document for qualification of mechanical equipment is still very much in a state of uncertainty. Current information [7] states that the ASME has formed a committee to consider the issue. If this is so, then that committee should be encouraged by all to proceed with haste to produce a guideline for dynamic qualification of mechanical equipment. If the experience at revision of IEEE 344-1975 is any precedent, then a long deliberation is in store for the ASME committee. Hopefully, the use of much information from the revised IEEE 344 can shorten the task, if the ASME committee chooses to take advantage of it.

5.2 Qualification of Equipment in Operating Plants

In this program we have developed an approximate equivalent vibration procedure for direct comparison of simple, pre-1975 qualification tests with more complicated post-1975 tests. This procedure is described in detail in References [4, 5]. On the other hand, during the last year a method of direct use of operating experience data has been developed by the Seismic Qualification Utilities Group for qualification of some equipment in operating plants. Therefore, it is appropriate to discuss these two methods of qualification of equipment in operating plants, their relationship to one another, and in particular, their potential direct use in the resolution of the Unresolved Safety Issue (Task A-46).

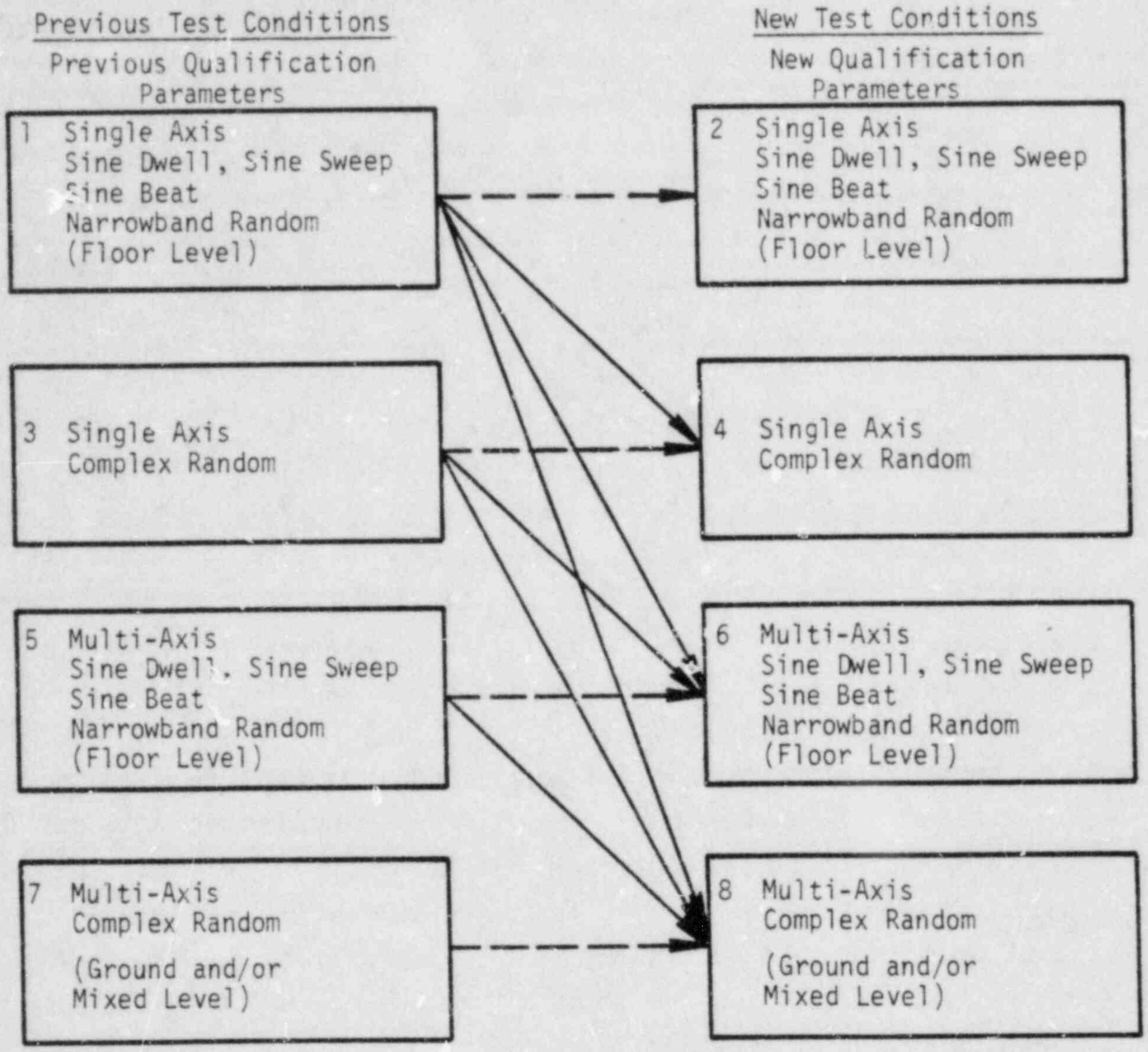
TABLE 7. EQUIPMENT AND COMPONENT CATEGORIZATION
(From Reference 5)

Generic Group	Generic Subgroup	Primary Function*
Electric Equipment Mounts	Panels	M
	Racks	M
	Cabinets	M
Electrical Instruments and Devices	Transducers Including Integral Signal Conditioners	E
	Computer Systems	E
	Communication Systems	E
Electrical Power Devices	Switch Gear	E
	Transformers	E
	Invertors	E
	Emergency Diesel Generators	E, M
	DC Power Limiters, e.g., Batteries, etc.	E
	Control Cabinets	E
Valves	Large Power Operated Valves Air or Electric	M
	Relief Valves	M
	Check Valves	M
	Instrumentation Valves	M
Pumps and Drives	Main Coolant Pumps	M
	Medium to Large Pumps and Compressors	M
	Safety Related Pumps	M
Heat Removal Systems	Heat Exchangers	M
	Emergency Pump Drive Systems	M
	Large Cooling Fans, Motors and Generators	E, M
Air Conditioning Systems	Air Ducting Devices	M
	Air Conditioning and Filtering Devices	M
System Support Facilities	Cable Trays	M
	Fuel Storage Racks	M
Miscellaneous Components	Snubbers	M
	Fuel Rod Assemblies	M
	Control Rod Drive Mechanisms	M
	Reactor Internal Devices	M

* E - Electrical and Electronic
M - Mechanical

Figure 1 is offered as a means for comparison of the two qualification methods. It is similar to Figure 4.3-1 of Reference [5], but has been modified to provide a more direct comparison between the use of actual operating experience data and the approximate equivalent vibration approach developed in this program. The figure depicts the desired comparisons between the previous qualification parameters which appear on the left, and new requirements which appear on the right. Furthermore, the complexity of waveforms increases from the top of the figure (which represents narrowband floor level motion) to the bottom (which represents broadband groundlevel motion). Note that the use of like parameters (such as response spectra with similar frequency content) available from previous tests for making comparisons involves a horizontal transition on the figure. It is extremely important to recognize that the use of operating experience (including nonnuclear equipment) represents one of these horizontal transitions, or like-parameter comparisons. Therefore, where valid like-data is available, includes the appropriate frequency content, and can be appropriately substantiated, we enthusiastically say that this approach is the simplest possible means of equipment qualification verification, and should be used where possible.

On the other hand, there are many practical situations where the use of operating experience cannot provide a sufficient determination of qualification directly, without some further transformation of the data. For example, operating experience data may be available in a narrowband form, which represents conditions at a given floor level of a building that contained certain natural modes (i.e., response spectra corresponding to Box 1 of Figure 1 with narrowband peaks at the building resonances). These data may not be applicable directly to qualify equipment at another floor level in a different building whose resonances occur at other frequencies (i.e., response spectra corresponding to Box 2 of Figure 1 with narrowband peaks at different building resonances). For this case test data may be useful if the test was carried out at sequential single-frequency dwells, say at 1/3-octave intervals, which included the frequencies of the new requirement. Similarly, floor level operating data (corresponding to Box 1 of Figure 1) cannot be used directly to qualify equipment to be used at ground level (Box 8 of Figure 1), since broadband frequency content is required. Generally, single frequency dwell test data also cannot be used directly to qualify equipment in the latter case, since all multiple freqency content is not present simultaneously.



Note:

- - -► Horizontal transitions include use of actual operating experience or qualification test data of identical parameters (i.e., response spectra).

——► Other transitions include change of actual operating experience or qualification test data from a narrowband waveform to a broadband waveform by means of equivalent vibration concepts.

Figure 1. Methodology for Qualification of Equipment in Operating Plants

Nevertheless, this case is especially important because of the current trend toward qualification under generic seismic environments.

From the above, it is easy to see that many such practical situations exist for which a method is needed to transform the narrowband existing qualifications into new broadband requirements for comparison. If the spectral levels from narrowband operating data are used directly for the broadband requirements, this is equivalent to ignoring the frequency interaction between the excitation and the specimen, which of course can lead to serious error. We maintain that the approximate equivalent vibration method developed in this program, which is summarized in Table 8, is the only known approach for solving this problem. However, it does require some additional consideration because of its ability to extend a previous qualification based on simple parameters to one based on more complex parameters (i.e., the more complex left-to-right downward transition in Figure 1).

TABLE 8. APPROXIMATE EQUIVALENT VIBRATION PROCEDURE FOR CHANGE FROM NARROWBAND OLD TO BROADBAND NEW QUALIFICATION TEST

1. Transform the old qualification input to a TRS or a PSD.
2. Make a conservative assumption about the location of the critical item or location of maximum response on the equipment.
3. Obtain transfer functions for that location (may need to perform in-situ test or analysis, or simply make a best estimate).
4. Check if multiple modes are present in energy range of new RRS.
5. Develop weighting factors for multiple modes from transformed PSD of new RRS.
6. Calculate interaction correction factor α_1.
7. Calculate cross-coupling correction factor α_2 (e.g., 1/1.2) to allow for potential cross coupling.
8. Calculate corrected, old TRS and compare with new RRS.
9. Consider demonstration of functionality for previous test and verify whether excitation frequencies are similarly applied in new test.
10. Repeat procedure for each axis, if appropriate.

In view of the above we feel that the use of operating experience and the approximate equivalent vibration method may be considered as complementary approaches to solve the problem of qualification of equipment in operating plants. Operating experience data may be used where possible, but the approximate equivalent vibration method must be used for those comparisons which require a transition to a more complex form of requirements, or to requirements which include a change in excitation frequencies.

Finally, we wish to emphasize again that the use of the approximate equivalent vibration method does not require the acquisition of new fragility data. That is, the method is based on the use of existing fragility data for developing a vibration equivalence between two unlike vibration environments (or between two sets of unlike parameters that may have been used to describe the same environment). That is, existing qualification (or operating experience) data are used as a lower bound for fragility data in order to make the comparison. For any situation where the existing data is of narrowband form (floor level or test), the severity of the environment is often greater than that for any typical new broadband environment, since the energy is more concentrated in the narrowband form. Thus, the equivalent vibration method has a high probability of success under such conditions.

5.3 Complementary Use of Random Process Parameters

In our previous reports we have repeatedly used to advantage a transformation between response spectra and power spectra. We note from other publications that other researchers and design engineers are using the process more or less routinely. This appears to be part of a trend to use power spectra and other statistical parameters as complementary tools for producing a better seismic simulation. We wholeheartedly support this trend. However, we also note one pitfall that is entering some of the work by people who are not so familiar with the use of statistical parameters. That is, the details of computation must be included on any such parameters, or serious errors can be incurred. For example, a PSD should be labeled with its frequency resolution bandwidth, and the number of sample averages (or statistical degrees of freedom) with which the computation was performed. Otherwise one can easily be comparing apples and oranges in the form of two PSD's. We might add also that frequency resolution should be given for response spectra as well, but this is almost never done.

5.4 Cross-Axis Coupling

This issue has been discussed at length in Reference [5]. However, some additional emphasis is still in order. The results of the present work show that cross-axis coupling can make a significant difference in qualification requirements under both ground level and floor level excitation of equipment. However, the requirements are different in each case. Low coherence between motion along each axis is appropriate for ground level motion only. In those cases for floor level motion that are influenced by building torsional modes, low coherence will be present over most of the frequency range, but high coherence will occur near the torsional building modes. Implementation of a motion of the latter type is not addressed in any present guidelines or requirements. In fact, the use of response spectra alone doesn't even provide sufficient information with which to develop such a motion simulation. Furthermore, it is presently unknown whether any results from producing such a simulation on multiaxis shakers is outside the inherent infidelity of the simulation that results from mechanical compliances and nonlinearities in the system.

All of the above considerations grew in importance in the latter half of the present program. As a result only limited emphasis was given to shedding some light on them. Thus, they constitute an important area for immediate future work.

5.5 The Role of Fragility in Equipment Design

Our preliminary evaluation [6] of fragility concepts indicates that essentially two forms of fragility data need to be developed, direct laboratory or experience fragility functions that can be used to determine whether a device is appropriate for a specific application, and seismic risk fragility parameters that can be used for plant risk studies. These two forms may be merged into one set, providing that all fragility data are reduced to a standard broadband form. It appears that a standard broadband excitation waveform such as one that matches the RG 1.60 ground level criteria would be the most appropriate for any future measurement of fragility data. Thus, a TRS which has the shape of the RG 1.60 spectrum, and is adjusted to the appropriate fragility level, would form the fragility function. If all equipment were tested with such a waveform, then only the ZPA level of the input need be listed, with the frequency content understood. (An alternative waveform might be a flat random excitation to 33 Hz or higher.) If a device is suspected of having a rigid threshold fragility level (i.e., it is not frequency sensitive), the suspicion can be verified by using several narrower bands, as well as the 1-33 Hz range for acquiring fragility data. It should also be recognized that typical seismic duration such as 30 seconds, must also be used for measurement of the fragility function, if the threshold definition (i.e., time independence beyond 30 seconds) is to be practical.

Several advantages are immediately suggested by the use of standard ground level data. Multifrequency excitation is present so that the matter of multimode interaction is satisfied. Furthermore, fragility at any floor level can be determined by direct comparison of response spectra. If a floor level fragility response spectrum is desired, then a transformation from ground level to floor level may be accomplished by the use of the building transfer functions and the intermediate use of PSD to response spectrum and vice versa transformations. These comments suggest that starting with a standard ground level fragility function and developing a more specific narrowband application is much more viable than the reverse process.

The latter statement prompts the question of what one can do with currently available fragility data, much of which may have been acquired with narrowband excitation waveforms? It would appear that the approximate equivalent vibration method discussed in Section 5.2 also may be appropriate for transformation of the narrowband to broadband data. Furthermore, by the use of similar techniques, existing qualification proof test data may be transformed to become lower bound fragility data. Thus, any narrowband qualification data (i.e., sine dwell, sine sweep, sine beat, etc.) becomes a potential source of development of fragility data. It should also be emphasized that any attempt to use spectral or peak values from narrowband data directly for fragility measures under broadband excitation is subject to the same potential neglect of frequency interaction errors that were described in Section 5.2.

Perhaps the most important aspect of the equipment fragility concept is that it ties the important process of equipment qualification to the entire plant qualification through risk analysis. However, the state-of-the-art for fragility data today appears to demonstrate a rather wide gulf between the understanding of fragility held by equipment manufacturers, and that of analysts who seek to perform plant risk studies. Furthermore, there is a great diversity in the form of what little fragility data there are available at this point. Therefore, the potential of fragility use in design should be explored with vigor. Consideration of the development of a standardized ground level data base should be pursued, and methodology for the practical use of this data developed. More specific tasks (in order of priority) include:

1) Perform a series of experiments which provide data to verify the use of fragility in the design of equipment and facilities. This should include fragility measurement on select sample devices to verify whether a single standard ground level fragility data base is feasible, or whether subgrouping of equipment under several different types of fragility functions is necessary.
2) Compile and review existing fragility data, and develop methodology for its transfer to a standard ground level format. Include steps necessary for development of risk parameters from standard fragility data that has been obtained from equipment qualification procedures (response spectra).
3) Develop more accurate correction factors α_1 for multimode interaction, and α_2 for cross-axis coupling, for transfer of narrowband data to broadband data.
4) Perform an analysis of existing Corps of Engineers ground shock data accumulated under the SSMRP program to develop a correction factor for nonseismic characteristics.
5) Develop methodology for transfer to broadband data for devices whose fragility has been measured on mountings such as cabinets and other flexible structures whose elevated responses typically include pronounced narrowband peaks which result from structural resonances.
6) Develop a risk ranking for equipment (or devices) from sensitivity studies so that most attention can be given to those items in most need of it. Then develop a program to measure fragility on select items that are of highest sensitivity. Fragility measurements on selective items are also essential to determine the degree of reliability inherent in data compiled from previous tests. With the results, update the existing fragility risk parameters.

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APPENDIX

SUMMARY OF RECOMMENDATIONS FROM TASK 3 SUMMARY REPORT

Note: Items with asterisk (*) have already been implemented in IEEE 344 Revision (Draft No. 4).

1.0 STANDARDIZATION OF PROCEDURES/INFORMATION

1.1 Equipment List and Standards

1. A standard equipment list, similar to Table 2.1 [5] should be adopted. Each piece of equipment requiring qualification should be placed in one of these categories. Justification of the selected category should be included in the qualification documents.

2. The categorization of equipment should be based on the primary function of the device or system.

3. After an equipment list has been standardized the existing regulatory guides and industrial standards applicable to each group should be defined and published as a separate document. This document list should be updated periodically as additional literature becomes available.

4. This action should be performed by the NRC with consultation from members of the industry.

1.2 Acceptance Criteria

Justification of the acceptance criteria should be included in the test and analysis specifications. This would limit the number of retests and reinterpretation of functional requirements. Anyone who writes or reviews test specifications should be responsible for this action.

1.3 Response Spectrum Margins

*During the development of the RRS to be used in a given test specification, a complete record should be maintained on all adjustments or enveloping which adds conservatism to the final RRS. This information should be included in the test specification. Part of this process should include the 10% margin specified by IEEE 323-1974. In the event that the latter adjustment is not specifically stated as having been included in the RRS, then the test organization should automatically add 10% to the given RRS curve.

2.0 DEMONSTRATION OF ADEQUATE METHODOLOGY

2.1 Dynamic Load Combinations

1. The NRC should continue to recognize the SRSS method of load combination for uncorrelated loads.

2. The direct sum of PSDs should be recognized as equivalent to the SRSS method for combination of response spectra.

2.2 Synthesis of Damping

1. The weighted energy approach should be considered when using nonuniform damping.

2. Current recommendations (Regulatory Guide 1.61) for uniform damping often produce overly conservative results. Additional test programs should be supported by the NRC to obtain more realistic values. These tests should consider as a minimum:

   a) Level of excitation.

   b) Type of excitation.

   c) Influence of boundary conditions.

   d) Methods used to calculate damping.

   e) Type of structure.

2.3 Degree of Model Complexity and Validation of Analytical Models

1. Analytical procedures based on sound engineering judgement should continue to be used in the qualification of equipment whose functionality is based on structural integrity or mechanical deflections. Furthermore, analysis combined with verification tests on subcomponents should be used on very large assemblies.

2. Justification of the appropriate boundary conditions should be included in the analytical report.

3. Some form of experimental verification should be required for all qualification by analysis unless justification for not doing so is given. This may be required only on subcomponents where the system is very large.

3.0 NEW METHODOLOGY

3.1 Response/Power Spectrum Transformation

1. The response/power spectrum transformation should be approved by the NRC as an aid to answer certain questions described above.

2. If multiple damping response spectra are specified, assurances should be made, by the specifying organization, that they are consistent.

3.2 Waveform Parameters

1. *The following parameters should be considered when generating simulations for the strong motion of earthquake signals.

   a) Frequency content

   b) Stationarity

   c) Coherence (less than 0.3 for ground level motion)

   d) Amplitude probability density (Gaussian)

2. A standardized definition of the strong motion portion of the earthquake signal should be established in a suitable NRC Regulatory Guide. The definition on page 21 [5] (or a similar definition) is appropriate.

3. *All presentation of this data should include the statistical analysis parameters used (resolution bandwidth, data samples per block, and/or statistical degrees of freedom).

3.3 Correlation of Test Methodologies

1. Test correlation procedures based on equivalent vibration concepts should be accepted by all concerned as a standard method of comparing various test procedures.

2. The weighted factor procedure should be used to account for multimode response in narrowband test results. The use of an interaction correction factor of 0.7 may result in a conservative approximation of modal interaction.

3. Consideration should be made in current qualification (proof) test programs to obtain fragility related information. It is not the intent to require additional tests for qualification but to provide necessary information (assumed critical location and failure mode, appropriate transfer functions, influence of bandwidth of excitation, etc.) in the event that subsequent requalification is required.

4. A data bank of qualification and fragility information should be established for each equipment category in a standard list.

3.4 In-Situ Test/Analysis

1. The use of in-situ testing can reduce the effort required for requalification of equipment. The MASOPT AND UMASS procedures described in Reference [2] have been shown to provide acceptable results. It is recommended that these procedures be accepted for use in in-situ qualfication procedures which include seismic excitations. Any other justifiable procedures for estimating modal participation factors may also be considered.

2. Procedures using in-situ testing should include some evidence of verification of the methodology. This need be established only once.

4.0 PROCEDURAL CLARIFICATIONS/MODIFICATIONS

4.1 Waveform Characteristics

*1. Consideration of the proper frequency content for the strong motion portion of synthesized waveforms should be demonstrated and justified. Justification need not be given if correct frequency content is shown by one of the following methods:

a) Enveloping of the RRS by the TRS within +30% or less at all frequencies, within the amplified region of the RRS. (Note that consideration of the frequency range above the start of the ZPA is handled separately.)

b) Show that the shape of the magnitude of the Fourier Spectrum of the synthesized waveform is frequency compatible with the amplified region of the RRS.

c) Show that the shape of the PSD of the synthesized waveform is compatible with the amplified region of the RRS.

d) These steps shall be performed with each new synthesized waveform development.

*2. Consideration of the proper frequency stationarity for the strong motion portion of the synthesized waveform should be demonstrated and justified. Justification need not be given if correct frequency stationarity is shown by the following methods:

a) A time history of the excitation must be recorded and included in the data.

b) To demonstrate the validity of the synthesis process, time interval PSD or TRS calculations should be performed and the results shown to be within accceptable limits for one typical case. These calculations need be performed only once and filed to establish the nature of the synthesis process. They need not be performed for subsequent tests that are based on the same procedures.

*3. Other waveform characteristics such as coherence and amplitude probability density, or distribution should be considered for those cases where known to be important.

*4. In all cases where statistical parameters such as PSD, coherence, etc. are generated, the number of statistical samples and resolution bandwidth used for the calculations should be noted.

4.2 Response Spectrum Envelope Accuracy

*1. Response spectra calculations for testing purposes should be computed for 1/6 octave or higher resolution.

*2. For TRS envelope of the RRS, a point of the TRS may fall below the RRS by 10% or less, provided that the adjacent 1/6 octave points are at least equal to the RRS, and the adjacent 1/3 octave points are at least 10% above the RRS.

*3. A maximum of 5 of the 1/6 octave analysis points may be below the RRS, provided that they are least 1 octave apart.

*4. Line segments which are used to connect the TRS calculated points are used only for convenience, and are not considered as calculated points of the TRS. Thus, whether they fall above or below the RRS is immaterial.

4.3 Mounting/Shaker Table Interactions

A process to address potential dynamic interaction between the test specimen and the shaker table shall be developed and justified. The following steps are appropriate.

a) If it is obvious that a given specimen will produce a large dynamic overturning moment on the shaker table, or if potential interaction may be expected from experience with similar specimens, the amount of interaction should be established by determining the resonance frequency shifts under free and blocked, off-axis conditions. Performance of a resonance search in a simulated floor-mounted condition is also permissible for this purpose.

b) When interaction is shown to be present, broadening of the response spectrum should be performed in order to account for the frequency shift error.

c) Details of the entire process should be documented in the test report. Justification for disregarding equipment/table interaction in a specific case should also be recorded.

4.4 Measurement of ZPA

*1. The amplified region ZPA should be used as the basis for meeting ZPA requirements for a test. It can be measured by filtering the excitation signal with a high slope filter (24 dB/octave or greater) above the start of the ZPA on the RRS.

*2. This procedure is not to be applied where the rattling of loose parts occurs within the equipment itself. In this case the nonlinear generation of higher frequency content is a genuine part of the test.

4.5 Nonlinearities in Resonance Searches

*When significant equipment nonlinearity is evident from resonance search results, and the use of these data is a requirement in the qualification process, excitation levels of the resonance search should be adjusted so that the response levels are as near as practical to what they will be during the simulated seismic portion (SSE) of the qualification test, without risking fatigue damage. This will assure that damping levels and resonance amplification are approximately appropriate for the SSE excitation levels.

4.6 Nonlinearities in Elevated Reponse

*When significant equipment nonlinearity is evident from resonance search data, generation of elevated response information should be performed with excitation levels corresponding to the maximum response for the excitation amplitude range considered, without risking fatigue damage.

4.7 Line Mounted Equipment

In addition to the present discrete sine beat test specified by IEEE Standard 382 for line mounted equipment, an alternate swept narrow band random test should be allowed. The bandwidth should be no greater than 2 Hz, and the RMS level should be set at 70% of that specified for sine beat tests. The total test time should be set equal to the aggregate of the total individual 1/3-octave sine beat dwells that are prescribed in IEEE 382. The sweep rate should be set so that only sweep up in frequency results (rather than sweeping up and down in frequency). Actuation of the equipment for functional purposes should be performed to coincide with any observed resonance conditions, as indicated by an initial resonance search. Furthermore, if the most conservative conditions are desired, multiple functional operations can be made to coincide with times for large excitation bursts for the narrow band random motion.

4.8 Resonance Search With Random Excitation

*Resonance searches conducted with random or transient excitation should be performed with special care. In particular, all data and computations include statistical philosphy, and therefore the number of statistical samples in developing such information should be noted. Likewise, the resolution bandwidth should be such that about four bandwidths are present for the narrowest resonance peak to be resolved. Hence the data should be computed with statistical parameters that are commensurate with the accuracy desired.

5.0 RECOMMENDED FURTHER STUDIES

5.1 Extension of Response/Power Spectrum Transformation

Response/power spectrum transformation methodology should be studied in more detail to consolidate its use for earthquake response prediction problems, and to determine its potential for use in response prediction to other types of loading. Two immediate parameters that enter the transformation should be explored--the time duration of the assumed stationary motion and the peak/RMS ratio, which inherently is related to the instantaneous amplitude probability density (or amplitude distribution). An understanding of their influence on the transformation is essential to potential application to non-earthquake type waveforms. At the same time, an even better understanding of its limits for use in earthquake problems will also result. This issue is of Priority 1, since its benefits are of immediate use in many existing practical problems.

5.2 Cross Coupling Effects

Further investigation of the cross coupling problem should be conducted. It would be most efficient to include the use of the electrical rack, which has already been studied in Task 1 of this program. A finite element model of the rack is already available, and in fact preliminary analytical studies have already been conducted. It would be most informative to alter the characteristics of the rack by adding additional off-center masses, so that coupled modes were lowered even further into the earthquake range. The analytical model should be modified to include these effects. Then, experiments on the actual specimen should be conducted for both biaxial and triaxial excitation. The results should be used to develop the differences expected under each type of excitation, and correction factors applied to assure conservatism in all cases. Furthermore, the potential effects of specimen/shaker table coupling due to table compliance should be explored in all cases. Also, the consequences of ignoring the high coherence of coupled floor motions should be included. If it turns out to be important, then methodology for its inclusion in qualification tests should be developed. This issue is considered Priority 2. This means it can be started somewhat later than the Priority 1 tasks, but it is imperative that it be accomplished in any long term extended program.

5.3 Fragility

A general program of research on the potential use of fragility in equipment qualification should be pursued. This program should include several approaches.

1. A review of the various aspects of equipment qualification where fragility is most urgently needed (such as to aid in the decision to restart a a plant that has been subject to an earthquake). In addition to its use as lower bound fragility data, further potential use of existing qualification proof test data for fragility purposes should be investigated.

2. Development of a standardized set of parameters for measure of fragility that is applicable to all practical uses. For example,

acceleration response spectral amplitude for ground level frequency content may be appropriate for seismic qualification.

3. Compilation of a best known set of standardized fragility data for the generic equipment list previously described. An initial attempt at this task has been reported by some researchers. However, this approach includes data acquired under a variety of methodology that must be standardized to ground level data.

4. Development of methodology for conversion to standardized ground level data for fragility data that may have been acquired by other methodology.

5. Conduct of an experimental program for verification of fragility measured on a selected set of equipment specimens.

6. Development of methodology for transfer of standardized fragility data to specific floor level locations, to allow prediction of fragility under all practical uses. The methodology should include format for input to seismic risk analysis.

7. Recommendations for change of qualification guidelines should be made to include more general use of the standardized fragility data and methodology developed.

This task is considered Priority 1 because of its relationship to test correlations, and for application in risk analyses. It will require a more fundamental and long term effort, since the state of development and use of the fragility concept lags all other areas discussed in this report.

5.4 In-Situ Testing/Analysis

1. An improved numerical algorithm should be developed to improve the reliability and reduce the computational effort in the current digital program. This can be accomplished by including the mass smoothing effects into the optimization approach by merging the present MASOPT and UMASS programs. Specifically one can form the functional

$$F(m_i) = (\tilde{m}_{11}-1)^2 + \sum_{p=1}^{R} \sum_{q=p+1}^{R} (\tilde{m}_{pq})^2 + \gamma\sigma^2(m_i)$$

where γ is a parameter that is a measure of the smoothness of the mass distribution, $\gamma = [0.0, 0.2]$.

2. Develop an algorithm for checking the quality of the measured data in order to weed out poorly defined mode shapes of higher order. Such modes are known to degrade the results rather than improve them.

3. Apply the improved methodology to several typical examples of equipment where companion analytical models are also developed by an independent approach. Compare results from both models to verify the accuracy of the in-situ approach for equipment having a wide range of physical characteristics.

4. Acquire other existing in-situ test/analysis methodology and compare predictions to above results.

This task should be considered Priority 2. It can also be started somewhat later, but is essential to the total program.

5.5 Test Correlation Correction Factor Limits

1. Conduct an analytical investigation to establish a lower limit for the test correlation correction factors α_1 and α_2. Outline details for use of these fators in comparing various single frequency and multiple frequency test criteria. This task is Priority 1 as it is of immediate use in resolving the Task A46 Unresolved Safety Issue.

5.6 Aging and Synergistic Effects

1. Results of the NRC program at Sandia Laboratories should be summarized and the influence of aging on seismic qualification specifically addressed.

2. Fragility data should be standardized so that they represent the functionality of equipment in an aged state.

3. Aging and synergistic effects should be categorized according to a standardized equipment list.

Present information indicates that the influence of aging on seismic qualification may not be as significant as other parameters described above. Furthermore, other ongoing programs are currently addressing this problem. Therefore, this task is considered Priority 3 within the context of this program.

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The program has spanned a period of three years and resulted in seven technical summary reports, eachof which covered in detail the findings of different tasks and subtasks, and have been combined into five NUREG/CR volumes. This volume is to summarize the entire program from an overall philosophical point of view.

Volume 1 includes Task 1 Summary Reports parts 1, 2, and 3, which describe evaluations of various aspects of equipment qualifications methodology. Volumes 2, 3, and 4 includes the summary reports for Tasks 2, 3, and 4, which are concerned with correlations of methodologies, recommendations for improvements, and evaluation of fragility methodology.

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