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

Task 4: The Use of Fragility in Seismic Design of Nuclear Plant Equipment

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Southwest Research Institute

Prepared for
U.S. Nuclear Regulatory
Commission

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PREFACE

This report represents one of a series which presents the results of a research program that is being conducted to evaluate methodology of equipment seismic qualification for nuclear plants. The overall program consists of the following subtasks:

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

Specifically, this document constitutes the Task 4 Summary Report.

1.0 INTRODUCTION

For purposes of nuclear plant equipment qualification, fragility has been defined [1], as "the susceptibility of equipment to malfunction as the result of structural or operational limitations, or both." In this regard, malfunction is considered the loss of capability of Class 1E 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 item 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 [1], 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 testing 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.

This report 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, vibration, etc.) that influence its operation. However, in this report emphasis will be principally on the dynamic fragility levels of equipment. The most general definition of dynamic fragility and various methods for its measurement will be explored. The state of published data on nuclear equipment fragility will be discussed, and limitations on its use delineated. From there, the concept of a standardized fragility data base and its potential uses will be considered. Various gaps in the methodology will be identified, and recommendations for further research will be outlined.

2.0 CONCEPT OF DYNAMIC FRAGILITY

2.1 General Fragility Description

A measure of dynamic fragility includes a determination of the level of specific excitation parameters (amplitude, frequency, time) at which a malfunction occurs in a specimen. Fragility and functionality are very much related, although they are basically different concepts. In effect, fragility denotes the upper limit of functionality. Thus, a measure of dynamic fragility generally includes the gradual increase of amplitude and time while maintaining frequency constant (or using some other variation of these three parameters), and simultaneously observing the appropriate indications of functionality, and finally malfunctioning of the device. In view of this approach, proof tests which demonstrate that functioning of a specimen continues to occur for some preselected set of excitation conditions, do not provide fragility information directly, but may be used as an indication of a lower bound of fragility.

One of the most general descriptions of dynamic fragility has been discussed by Roundtree and Safford [2], and is shown in Figure 1 as a fragility surface. Note that the surface can be represented as the function

$$F_{xy}(f,t) = M_F(f,t) \tag{2-1}$$

where $M_F(f,t)$ is the magnitude or amplitude of the excitation at the fragility surface. Note also, as indicated above, that the true surface may be quite complex, depending on mechanical resonances and other characteristics of the specimen, but a simpler lower bound surface can be defined conservatively acceptable for practical engineering purposes. Furthermore, this surface may be assumed to be essentially independent of time for many types of equipment, so that Equation (2-1) reduces to the fragility function:

$$F_{xy}(f) = M_F(f). \tag{2-2}$$

Herein, this type of fragility will be called threshold fragility. Fortunately, most equipment used in nuclear plants (except that which is subject to metal fatigue) essentially fall into this category. The above general description of fragility has been employed as the basis for comparisons of proof test severities in earlier reports [3,4] from this program.

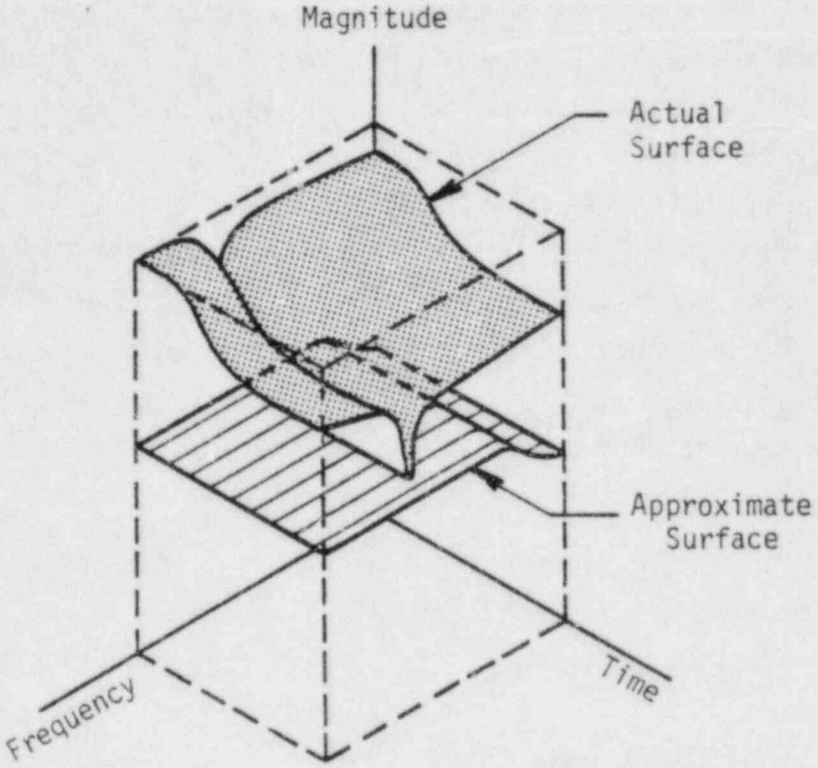

Figure 1. Definition of Actual and Approximate Dynamic Fragility Surfaces

2.2 Measurement Parameters

Fragility measurement as defined in IEEE 344 [1] includes the use of deterministic parameters to define the fragility function denoted by Equation (2-2). This approach contrasts with the statistical measurement of fragility which will be described shortly. In the deterministic case, fragility has been measured by a variety of methods, most of which are related to proof test procedures in one way or another. Herein, we will summarize these methods into two categories, those which include narrowband fragility functions, and those which include broadband fragility functions. Narrowband fragility functions include those generated by narrowband excitations such as sine dwells, slowly swept sine waves, sine beats, and narrowband (i.e., less than 5 Hz) random time histories. This form will also include floor level motions prescribed by a response spectrum where lightly-damped building resonances are present. Broadband fragility functions include those generated by excitations which include simultaneous multifrequency content. Such excitations are usually prescribed by a required response spectrum (RRS) or a power spectral density (PSD). This form is representative of ground level seismic and combined ground and floor level seismic motions, or excitations generated by operating transient events.

The nature of a fragility function is, of course, dependent on the type of malfunction mechanism involved, and the structural dynamic characteristics of the device, as well as the type of excitation used during the measurement. This will be described by several hypothetical examples. Figure 2 shows the type of fragility function that would result for a rigid threshold device under narrowband excitation. Thus, the fragility level is independent of the frequency for the narrowband excitation. The amplitude can be measured by peak value, or by root-mean-square (RMS) value. The latter is most useful for those cases where several cycles at some level are necessary before malfunction occurs (i.e., a slight dependence on time is present; but no greater than one test run duration). A narrowband fragility function for a simple flexible threshold device might look like Figure 3. A simple device is one which includes only a single effective

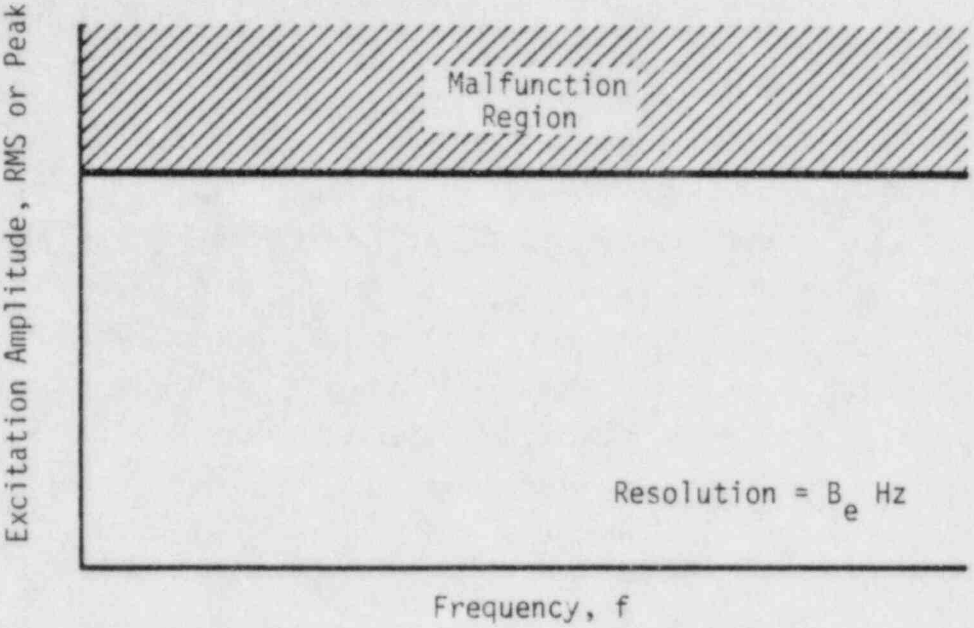

Figure 2. Narrowband Fragility Function for Rigid Threshold Device

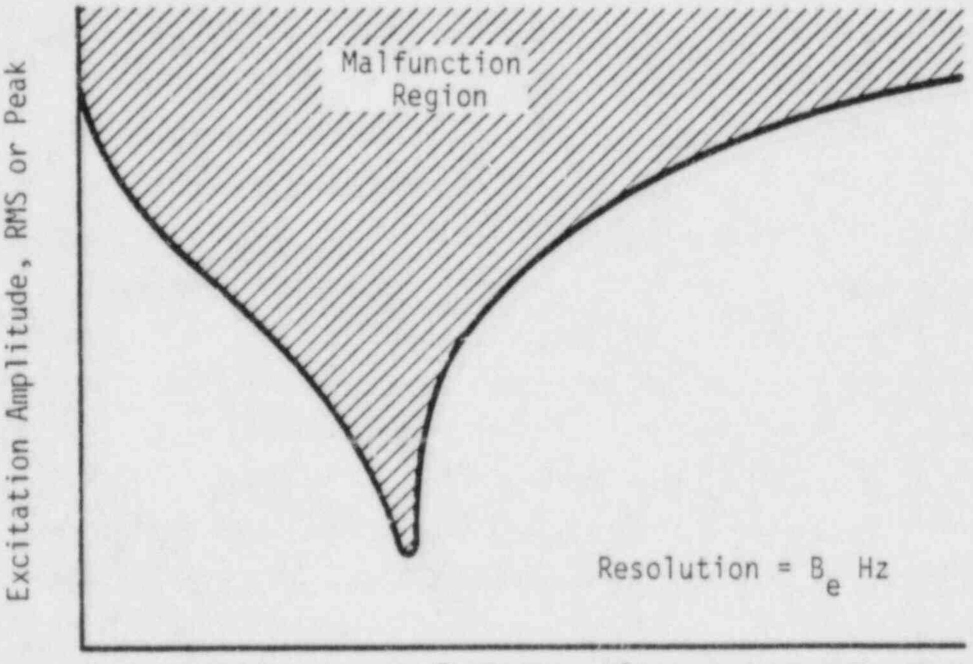

Figure 3. Narrowband Fragility Function for Simple Flexible Threshold Device

resonance, at which the fragility curve experiences a significant minimum value (the case of multiple resonances will be discussed later). Again either peak or RMS value may be appropriate for amplitude measurement.

Example fragility functions for broadband excitations are shown in Figures 4 and 5. The nonuniqueness of fragility functions is emphasized in these figures. For example, a rigid threshold device which is sensitive to peak excitation will malfunction at that fragility level (i.e., the zero period acceleration or ZPA) of the excitation signal, no matter what the frequency content of the signal. Likewise, if RMS level is the sensitive parameter, then that level can be generated by many different signals, each with a different PSD. These statements are true for both narrowband and broadband excitations, so long as the specimen is a rigid threshold type device. However, the nonuniqueness characteristic is even more complex for a broadband fragility function generated for a simple flexible threshold device, as indicated in Figure 5. The envelope of a narrowband fragility function, measured either by test response spectrum (TRS) or PSD, is shown first. Three significantly different test response spectra, each representing a broadband excitation of different frequency content also are shown, where each touches the narrowband function envelope at a different point. Thus, each of the significantly different response spectra represents a lower bound fragility function for the device. The importance of frequency content of the excitation on the definition of fragility level is very apparent from this figure. This result is even more pronounced for specimens that include multiple resonances, as will be discussed later.

2.3 Relationships Among Parameters

In the above discussion four parameters have been included for measurement of the fragility function magnitude. Any one of these parameters may be used for a given specimen, depending on the physical nature of the specimen, and its observed tendencies for malfunction. It is useful to summarize the relationships among these parameters.

Zero Period Acceleration or ZPA is the peak value of the excitation time history. It is also the high frequency asymptote of the response

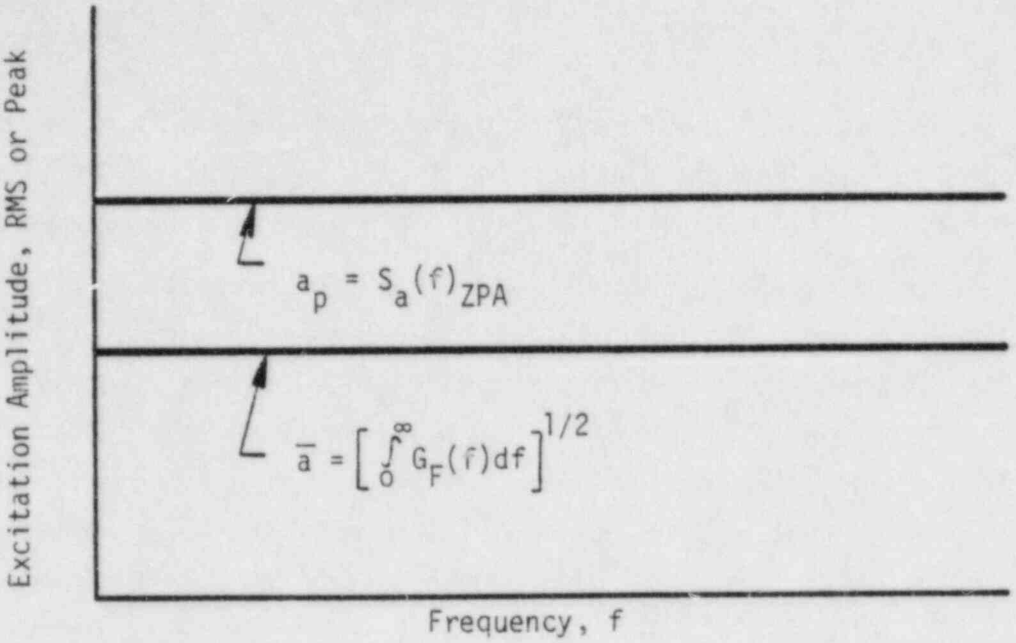

Figure 4. Nonuniqueness of Fragility Function for Rigid Threshold Device

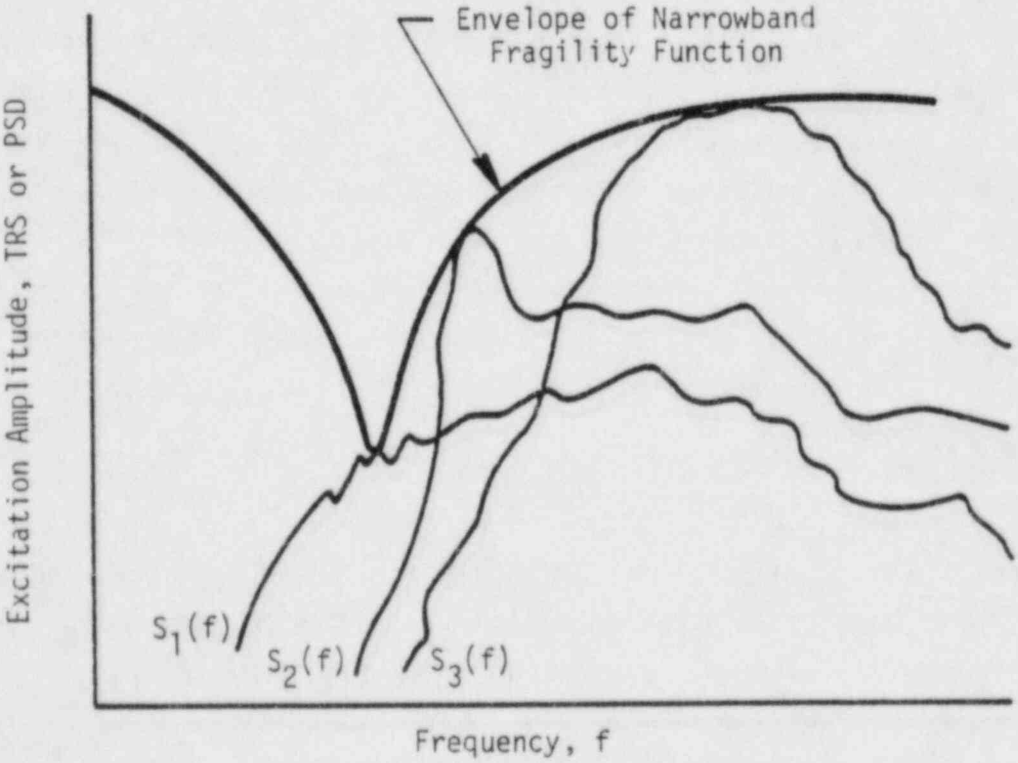

Figure 5. Nonuniqueness of Broadband Fragility Function for Simple Flexible Threshold Device

spectrum computed for that time history. Thus

$$a_p = S_a(f)_{ZPA} \tag{2-3}$$

Root Mean Square or RMS is the acceleration computed from

$$\bar{a} = \left[\frac{1}{T} \int_0^T a^2(t)dt \right]^{1/2} \tag{2-4}$$

or

$$\bar{a} = \left[\int_0^\infty G(f)df \right]^{1/2} \tag{2-5}$$

where $G(f)$ is the PSD of the acceleration. For most seismic ground motion

$$3\,\bar{a} < a_p < 6\,\bar{a} \tag{2-6}$$

the exact value depends on whether the averaging period T is for strong motion only or for the entire event [5].

Response Spectrum is the usual seismic acceleration parameter computed at some resolution bandwidth and damping. Herein we use spectral acceleration $S_a(f)$.

Power Spectral Density or PSD is that computed at some resolution bandwidth and is understood to be computed over the averaging period T. Usually the PSD for the strong motion is of more concern than that for the entire event. Note that a transformation from response spectrum to PSD and its inverse is available from earlier work [6]. This transformation is very useful in solving various equipment qualification problems.

There are other parameters such as Housner intensity, Arias intensity, and damage severity factor that have been considered for fragility or seismic severity measurement [3]. However, the above four are considered to be the most practical.

2.4 Statistical Fragility Description

The forms of fragility functions defined above are particularly useful for direct measure of fragility from experiments on equipment. However, they are not sufficient for incorporation into risk studies for various postulated accidents of a plant. For this, the above types of fragility functions must be supplemented with several uncertainty factors, and transformed to probability fragility curves, which can be used in the overall probability risk analysis (PRA). Azarm, et al [7] have summarized this process. Figure 6 shows a block diagram of the sequence of computations included in such an analysis. Equipment and other fragility functions which serve as inputs to this analysis must be obtained by transforming the above forms of fragility functions to probability fragility curves as shown in Figures 7 and 8.

The probability fragility curve shown in Figure 8 is obtained from the response spectrum fragility function for a given equipment item by considering the uncertainty distribution about the mean response spectrum at a given frequency, as shown in Figure 7. The frequency is usually chosen to be that considered to be the fundamental critical resonance frequency (or frequency range) for the given item. The probability density function of Figure 7 is integrated over the spectral amplitude $S_a(f)$ to form the frequency of failure curve as a function of spectral acceleration A, given in Figure 8. In addition, other distributions about this median curve are considered. The median acceleration capacity $\hat{A}$ is subject to a randomness with standard deviation β_R, and an uncertainty with standard deviation β_U. Compilation of such median fragility data and its associated uncertainty factors for a variety of nuclear plant equipment was originally provided by Kennedy, et al [8]. More discussion of these seismic risk fragility parameters will be given herein in a later section. For now, an understanding of the relationship between the above deterministic fragility functions (Figures 1-5), and the probabilistic fragility curves (Figures 7, 8) is sufficient for our discussion.

2.5 Effects of Modal Interaction and Cross-Axis Coupling

In the above descriptions of fragility nothing is said about the potential of multimode interaction and spatial orientation of the excitation axes relative to the specimen. These are issues that are very much at the state-of-the-art for dynamic fragility measurement. If the specimen includes multiple modes such that failure by modal interactions is possible,

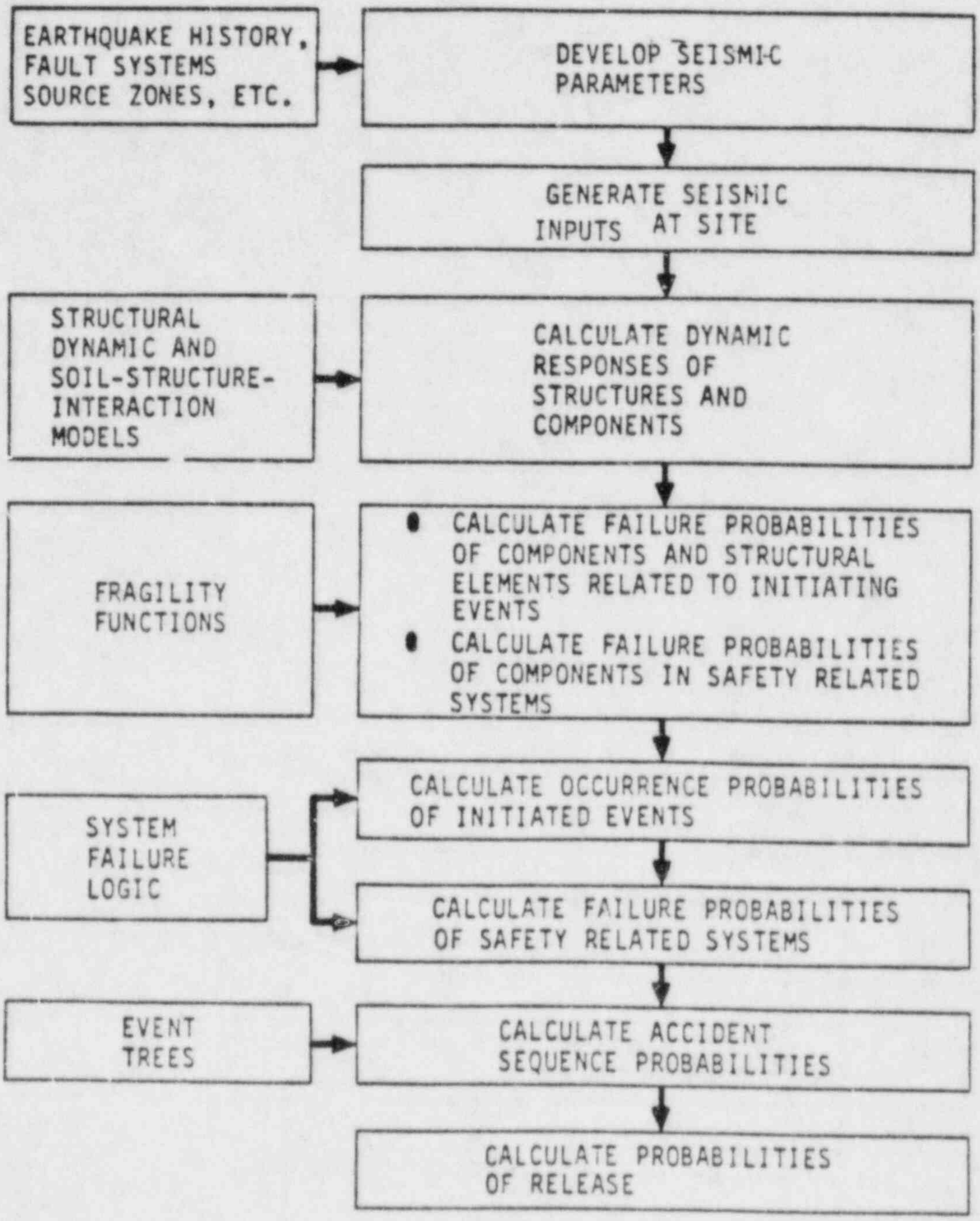

Figure 6. The Sequence of Computations Necessary to Compute Probabilities of Release Due to Earthquake Impact on a Nuclear Power Plant (From Reference 7)

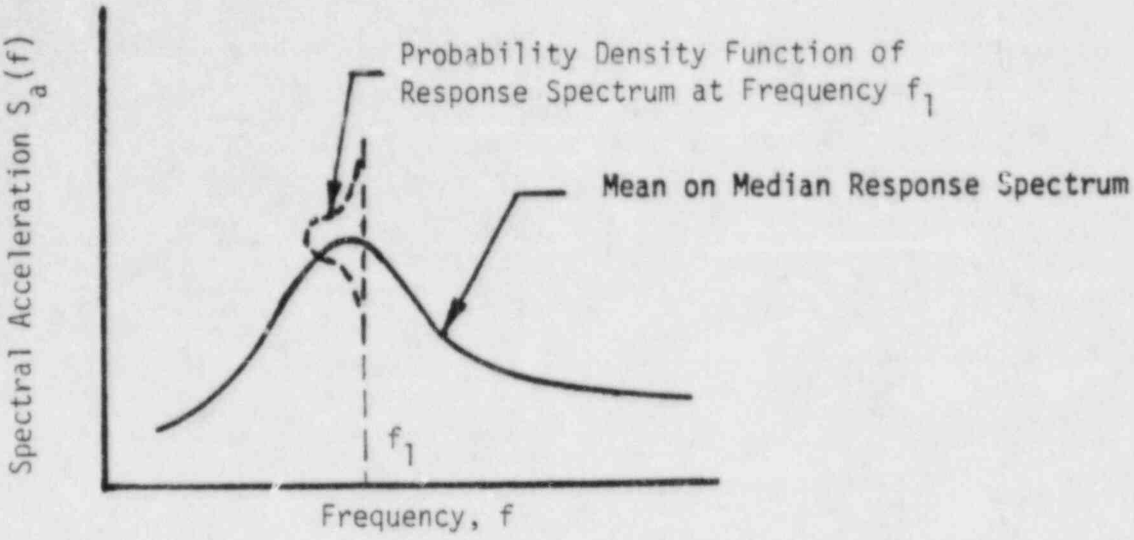

Figure 7. Uncertainty of Response Spectrum Fragility Function

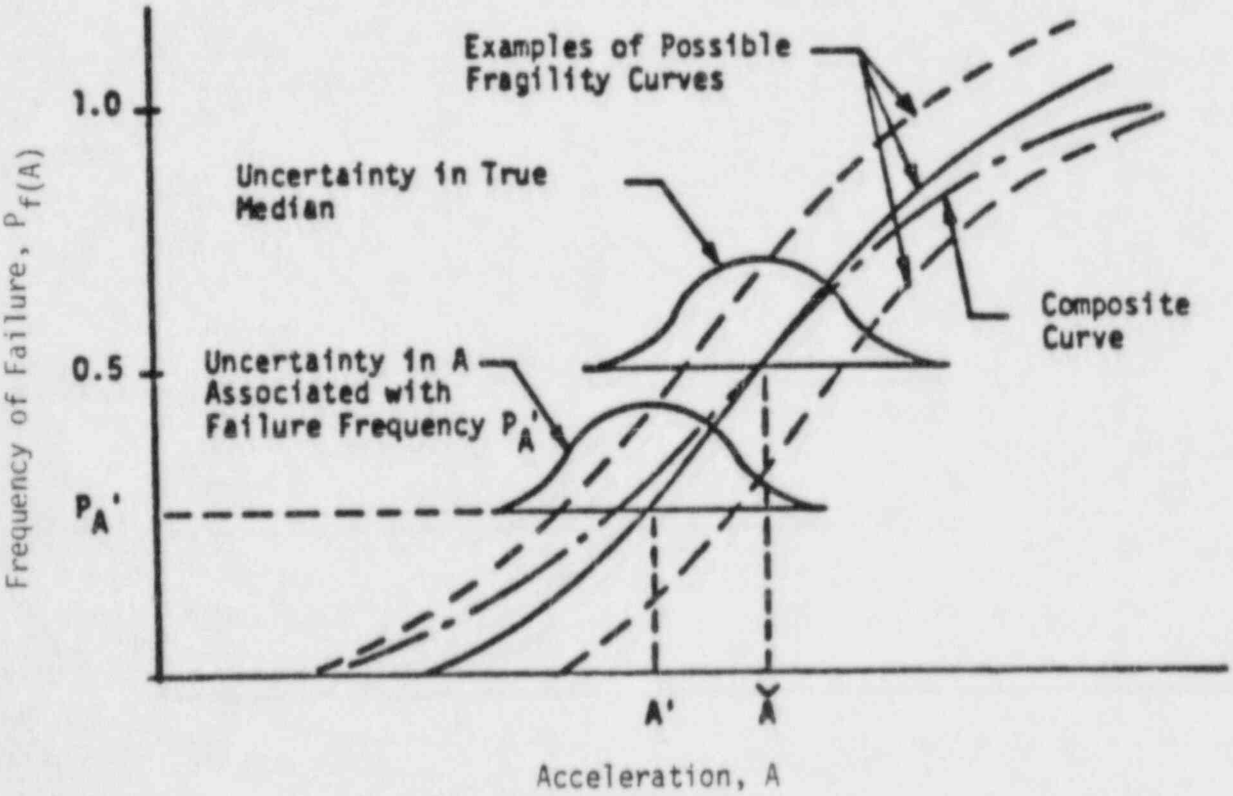

Figure 8. Probability Fragility Curve with Associated Uncertainties (From Reference 8)

then it is referred to as a complex system, and generally the fragility must be measured with a broadband excitation which is capable of exciting all significant modes simultaneously. A spread in the fragility function can occur, depending on the degree to which each mode is excited. Thus, the frequency content of the excitation is very important. For such a specimen, a fragility curve obtained with a narrowband excitation will be higher than that for a broadband excitation, since modal interaction cannot occur in the former case. A similar situation may occur for a specimen that is normally subject to cross-axis coupling. The orientation of the device relative to the dynamic excitation axes may be very important in the measurement of a fragility function. At the very least, a different fragility function may exist for each orthogonal axis of excitation.

3.0 EXPERIENCE WITH AVAILABLE DATA

3.1 Typical Forms of Data

In the past limited amounts of fragility data have been generated for nuclear plant equipment from additional tests associated with qualification proof test programs. However, this information has usually been retained as company proprietary by the particular manufacturer. We will present several examples for such typical data that were generated earlier in this research program [3]. As pointed out earlier, the data fall into the category of narrowband and broadband fragility functions. Other fragility data in the form of parameters for probability seismic risk curves will be discussed separately in Section 3.3.

Figures 9 and 10 show several forms of narrowband fragility functions generated for a Yarway liquid level indicator. These data were acquired by exciting the device with a given type of narrowband excitation which was centered at a given frequency, and the amplitude slowly increased until malfunction was observed. Some statistical variation of the data occurred for different runs, and the results show some dependence on the form of excitation. Similar narrowband data are shown in Figures 11 and 12, where the results are displayed as a PSD function, rather than peak or RMS acceleration. In these cases examples of approximate acceptable fragility functions are also indicated. These were drawn purely by judgment, with the basis for the judgment different for each.

Examples of broadband fragility functions for the same device are shown in Figures 13 and 14. These resulted from broadband excitation of the device while mounted on an electrical equipment rack. Time histories for simulated earthquake runs were measured directly at the mounting location of the Yarway instrument on the rack. The PSD and response spectra were computed from these time histories. It should be noted that the broadband PSD of Figure 13 should fall within the narrowband PSD of Figures 11 or 12 at all corresponding frequencies. If significant multimode interaction had occurred in this instrument, then the broadband data should be significantly lower than the narrowband data.

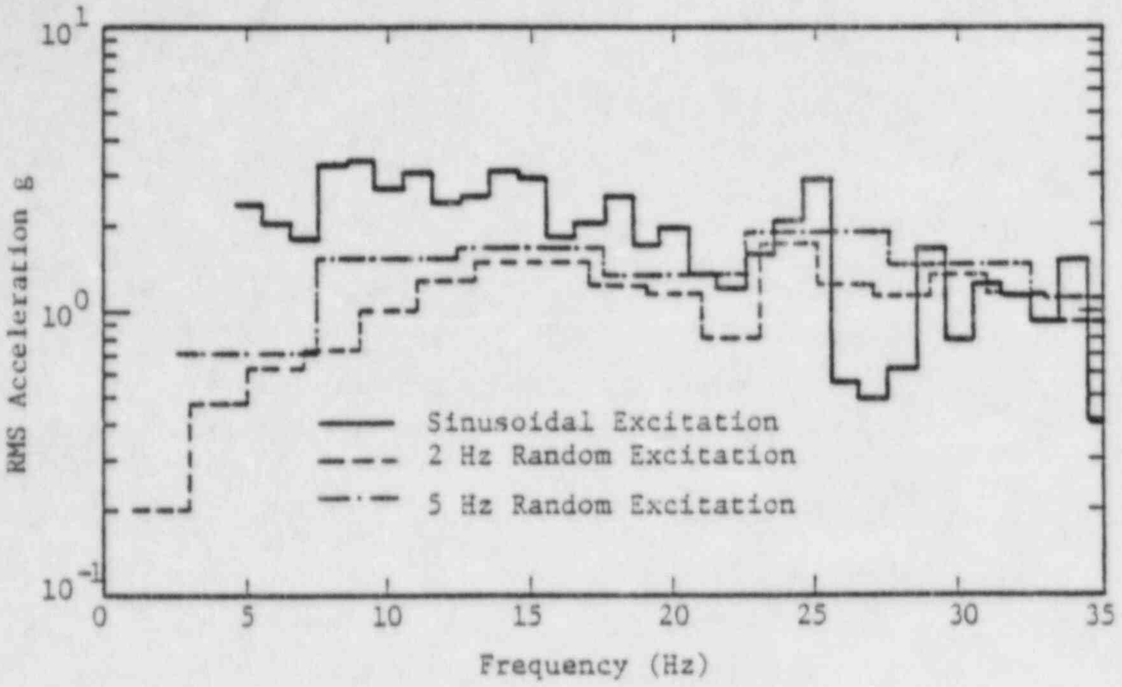

Figure 9. RMS Acceleration Fragility Function For Yarway, X-Axis

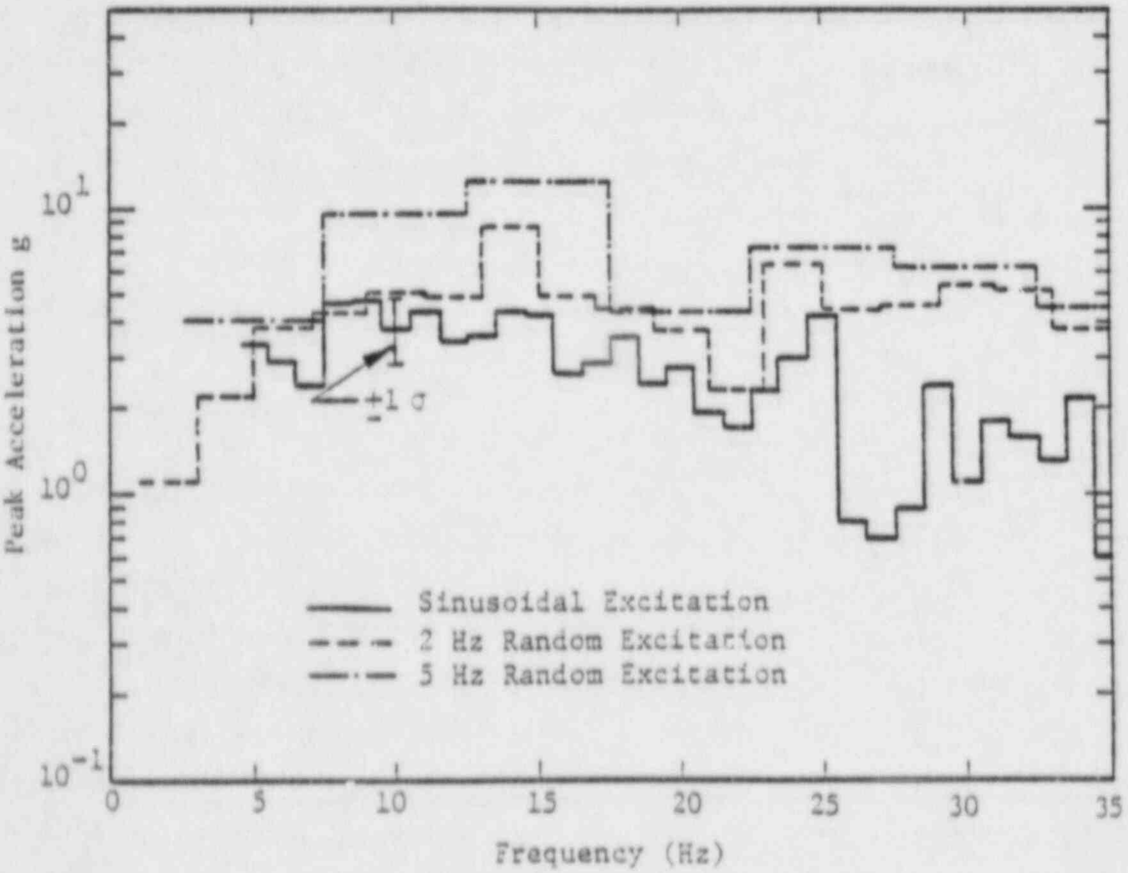

Figure 10. Peak Acceleration Fragility Function for Yarway, X-Axis

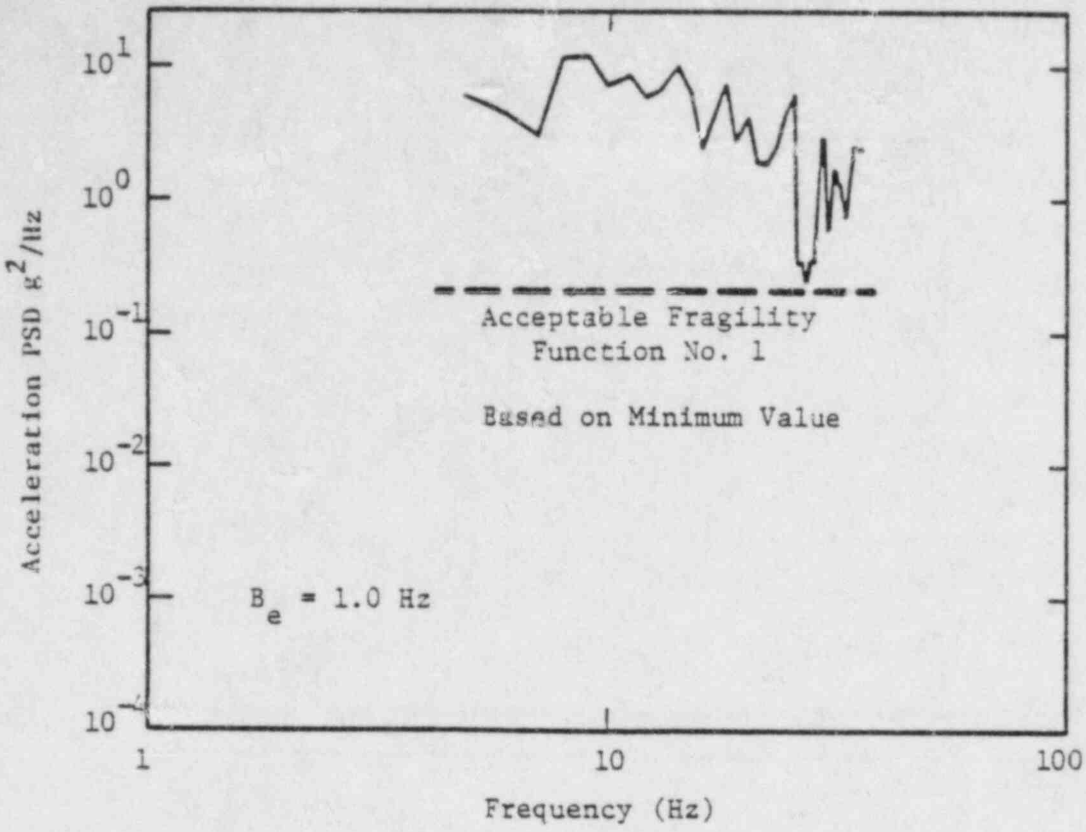

Figure 11. Sinusoidal Excitation PSD Fragility Function for Yarway, X-Axis

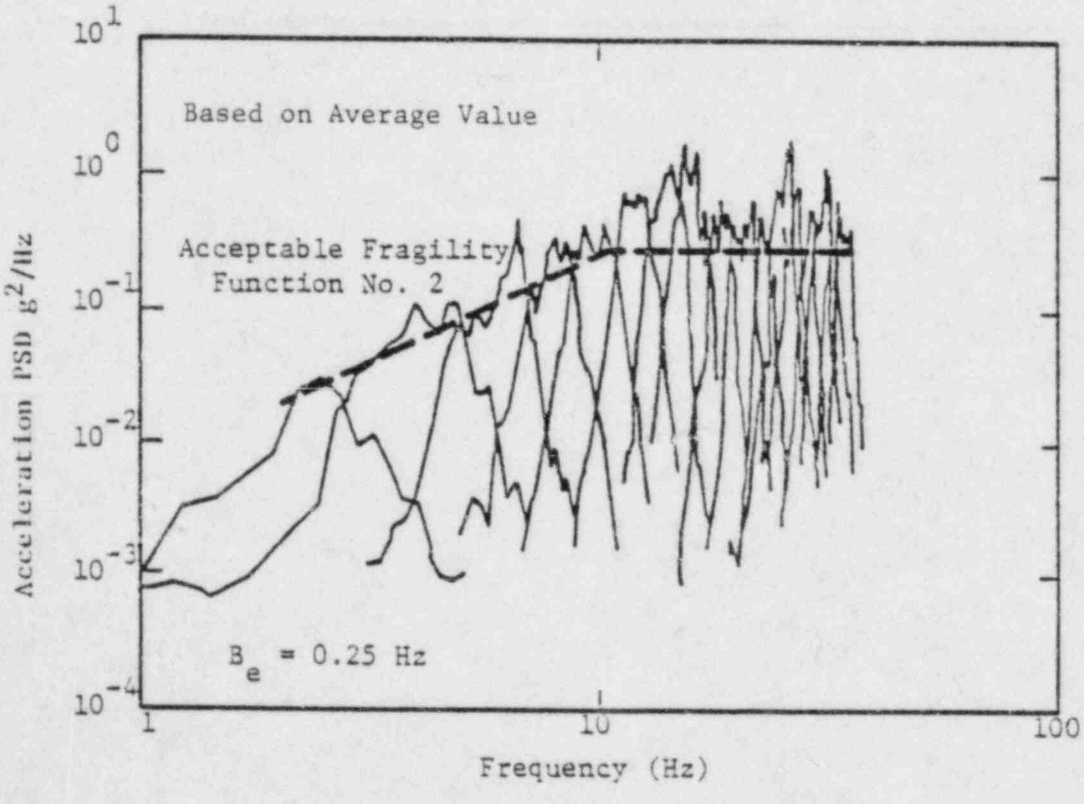

Figure 12. 2 Hz Bandwidth Random Excitation PSD Fragility Function for Yarway, X-Axis

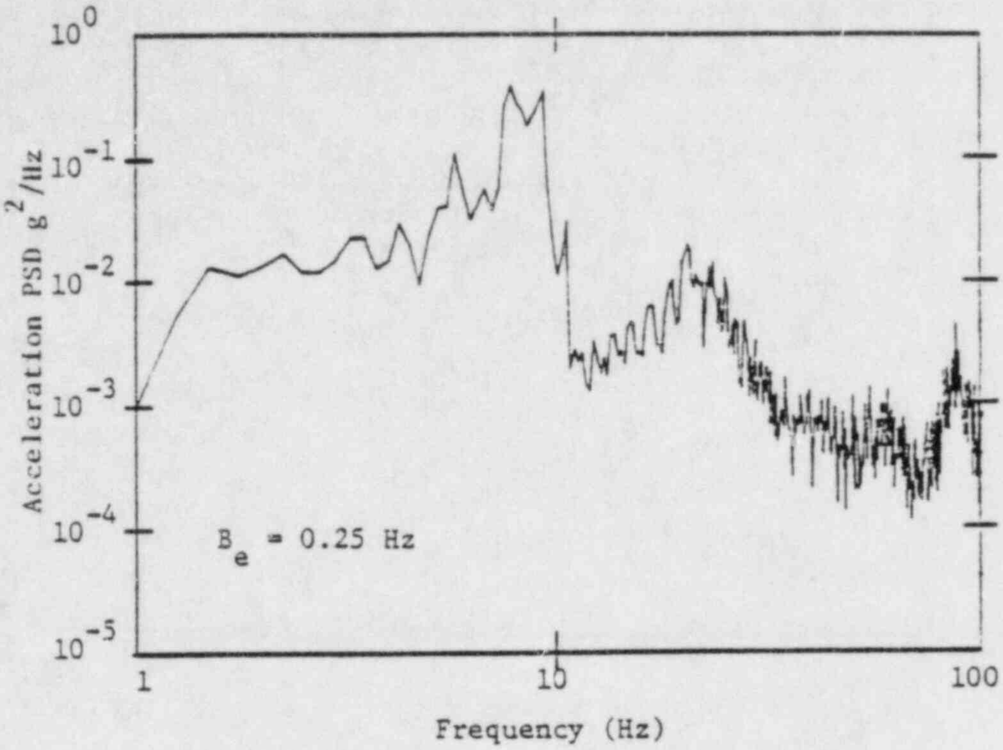

Figure 13. Broadband PSD Fragility Function for Yarway Instrument

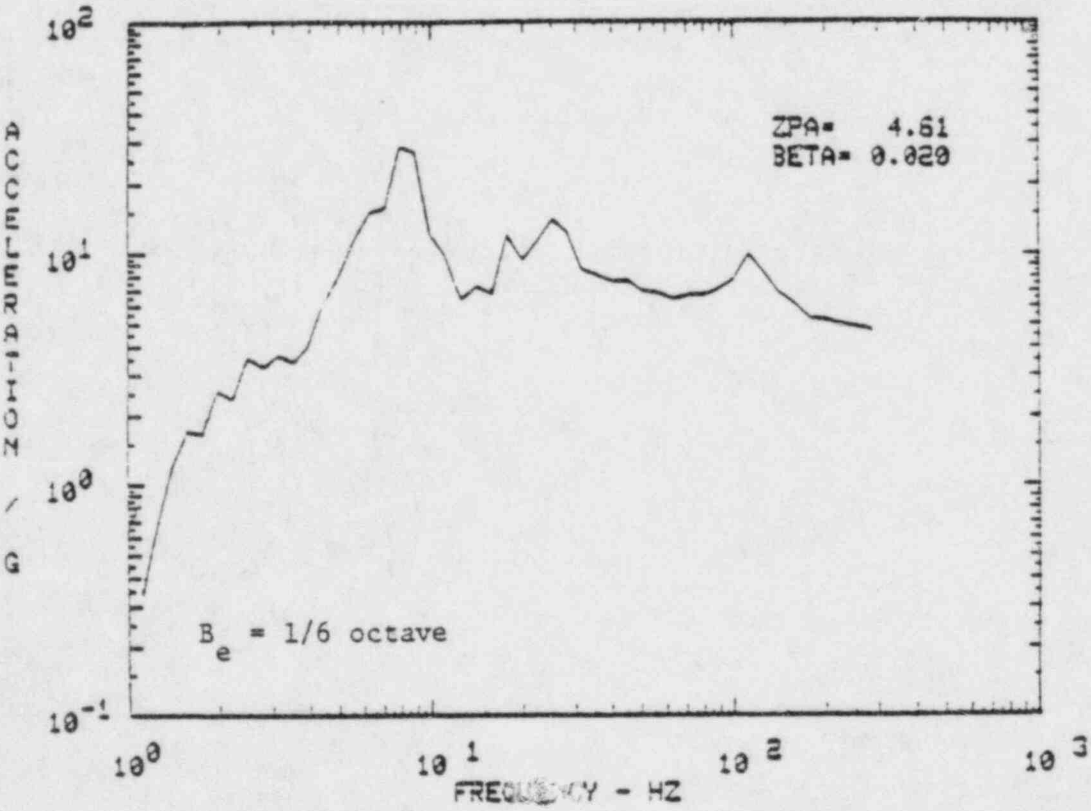

Figure 14. Broadband TRS Fragility Function for Yarway Instrument

3.2 Approximate Transformation of Data

In view of the fact that much of the earlier qualification test methodology included the use of uniaxial narrowband excitation of one form or another, it is a moot question as to whether fragility data acquired by such methods can be transformed to include potential multimode interaction and cross-axis coupling by some approximate approach. Methodology for this transformation has already been proposed for correlation of qualification test severities [3,4], and can also be applied to the actual fragility function. This is shown conceptually in Figure 15, where a narrowband fragility function response spectrum envelope was first generated by a slowly swept sinewave. It is obvious that two resonances occurred, but the effects of modal interaction or cross-axis coupling are not likely to be present in the original fragility function. Corrected fragility functions for each effect can be obtained by multiplying the original curve by a factor $\alpha_1 < 1$ for the modal interaction and $\alpha_2 < 1$ for the cross-axis coupling. Details of how the values for these correction factors are developed are somewhat uncertain yet at this time. However, some suggestions are given in Reference [4].

3.3 Seismic Risk Fragility Parameters

The use of fragility data in the form of seismic risk parameters has been mentioned in Section 2.4. This form of fragility description requires a compilation of parameters which represent probability fragility curves of the type shown in Figure 8. A list of such parameters for most equipment used in nuclear plants has been compiled by Kennedy and others [8,9], while a more recent review of the work has been given by Azarm, et al [7]. In the compilation of these data a variety of opinion and judgment was used where data were lacking. Much of the data for electrical equipment was based on earlier results of fragility experiments performed on similar equipment while subject to blast type ground shock [10,11]. Relatively high uncertainties inherent in these data are recognized; and are subjectively quantified in the appropriate parameters. Nevertheless they are accepted as the best published data available. Limitations and potential improvements for the data will be discussed in later sections.

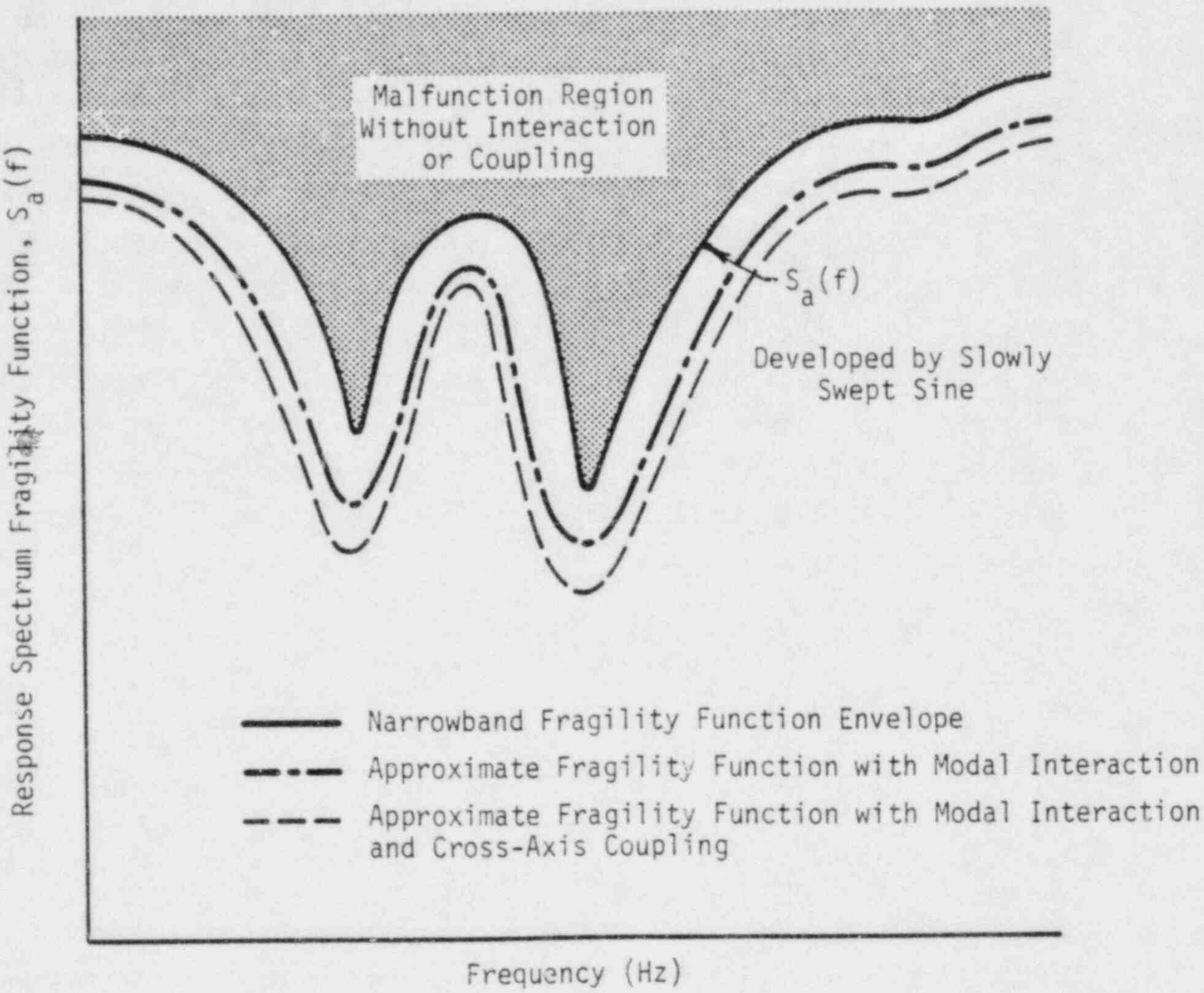

Figure 15. Approximate Fragility Function for Complex System

Table 1 shows a sample of fragility parameters for some components that have been studied. Much more extensive lists appear in References [7,8]. Briefly, the uncertainty parameters of such lists are used to draw probability fragility curves by means of the following equations. For a given component, a composite curve for the frequency of failure $p_{f(A)}$ for a given acceleration level A is given by

$$p_{f(A)} = \Phi[(1/\beta_c) \ln (\hat{A}/A)] \tag{3-1}$$

where (Φ) is the value for the cumulative standard normal probability distribution function, and

$$\beta_c = [\beta_R^2 + \beta_u^2]^{1/2} \tag{3-2}$$

Furthermore, the median acceleration capacity $\hat{A}$, and the random factor β_R and uncertainty factor β_u are all given in tables such as Table 1. It should be noted that for some equipment the median capacity $\hat{A}$ is given in terms of peak ground acceleration (ZPA), and for others it is given as spectral acceleration. Furthermore, a fundamental natural frequency (or range for it) is given for each item of equipment. Therefore, data given in the form of a fragility response spectrum are reduced to that described above, by means of assuming the existence of a lognormal distribution about the mean spectral acceleration in the indicated frequency range.

3.4 Characteristics of Ground Shock Data

It has been mentioned that some of the fragility parameters given in References [7,8] were reduced from blast ground shock data. The excitation waveforms for these tests were synthesized [10,11] as the sum of several short duration sinebeat components of the type described in Table 2. Generally, the longest duration component was about two seconds, and the center frequencies for each sinebeat component was spread from 1 to above 500 Hz. Only about half the components occurred within the seismic range of up to 33 Hz. A typical acceleration response spectrum for this type of excitation transient is shown in Figure 16.

TABLE 1. SAMPLE FRAGILITY PARAMETERS
(From Reference 8)

GENERIC CATETORY	SPECIFIC COMPONENT	FAILURE MODE	FUNDAMENTAL FREQUENCY Hz	FRAGILITY PARAMETER	MEDIAN DAMPING, % OF CRITICAL	MEDIAN CAPACITY	LOGARITHMIC STD. DEVIATION			RANK OF SOURCE
							COMPOSITE β_C	RANDOM β_R	UNCERTAINTY β_U	
Emergency A.C. Power Units	Engine & Generator Components	Structural	Rigid	Zero Period Acceleration	NA	>6.5 g	0.5	0.3	0.4	4
Emergency D.C. Power Units	Battery Rack	Anchor Bolts	8	Spectral Acceleration	5	12.5 g	0.3	0.21	0.24	5
Emergency D.C. Power Units	Batteries	Case Cracking & Plate Failure	8	Spectral Acceleration	5	4.2 g	0.16	0.1	0.12	6
Switch Gear	4160 & 480 Volt Units	Relay Chatter	5-10	Spectral Acceleration	5	2.07 g	1.46	0.5	1.37	6
Switch Gear	4160 & 480 Volt Units	Breaker Trip	5-10	Spectral Acceleration	5	7.7 g	0.73	0.4	0.61	6
Switch Gear	4260 & 480 Volt Units	Structural	5-10	Spectral Acceleration	5	14.6 g	0.8	0.4	0.69	6
Transformers	Generic	Structural	5-10	Spectral Acceleration	5	10.7 g	0.21	0.1	0.18	2
Local Instruments & Transmitters	Generic	Electrical Function	Rigid	Zero Period Acceleration	NA	37.8 g	0.32	0.2	0.25	6
Instrument Panels & Racks	Generic	Relay Chatter	5-10	Spectral Acceleration	5	2.07 g	1.46	0.5	1.37	6
Instrument Panels & Racks	Generic	Breaker Trip	5-10	Spectral Acceleration	5	7.7 g	0.73	0.4	0.61	6
Instrument Panels & Racks	Generic	Structural	5-10	Spectral Acceleration	5	14.6 g	0.8	0.4	0.69	6
Control Panels and Racks	Reactor Protection System	Functional-Electrical Manfunction	5-10	Spectral Acceleration	5	16 g	0.35	0.2	0.29	6
Control Panels and Racks	Generic	Relay Chatter	5-10	Spectral Acceleration	5	2.07 g	1.46	0.5	1.37	6

TABLE 2. SYNTHESIZED WAVEFORM FOR NOMINAL UNDAMPED SHOCK SPECTRA - SAFEGUARD WEAPONS SYSTEM MOTOR CONTROL CENTER (TEST LEVEL 10)

(From Reference 11)

ACCELERATION: $A(t) = \sum_{m=1}^{M} A_m \sin 2\pi b_m t \cdot \sin 2\pi N b_m t, \quad 0 \leq t \leq T_m$

$A(t) = 0 \qquad , \quad 0 \geq t \geq T_m$

m	b_m (Hz)	Nb_m (Hz)	T_m (sec)	N	A_m (G_p)	f (Hz)
1	.560	1.680	1.786	3	.114	2.00
2	.513	2.565	1.949	5	.142	2.70
3	.617	4.319	1.621	7	.218	4.32
4	.696	6.264	1.437	9	.353	6.264
5	1.009	9.081	.991	9	.508	9.089
6	1.463	13.167	.684	9	.482	13.17
7	2.122	19.089	.471	9	.462	19.096
8	3.076	27.684	.325	9	.467	27.689
9	4.461	40.149	.224	9	.471	40.149
10	6.468	58.212	.155	9	.476	58.216
11	9.379	84.411	.107	9	.469	84.413
12	13.600	122.400	.074	9	.462	122.399
13	19.720	177.480	.051	9	.460	177.478
14	28.593	257.337	.035	9	.457	257.343
15	41.461	373.149	.024	9	.456	373.147
16	60.118	541.062	.017	9	.454	541.063

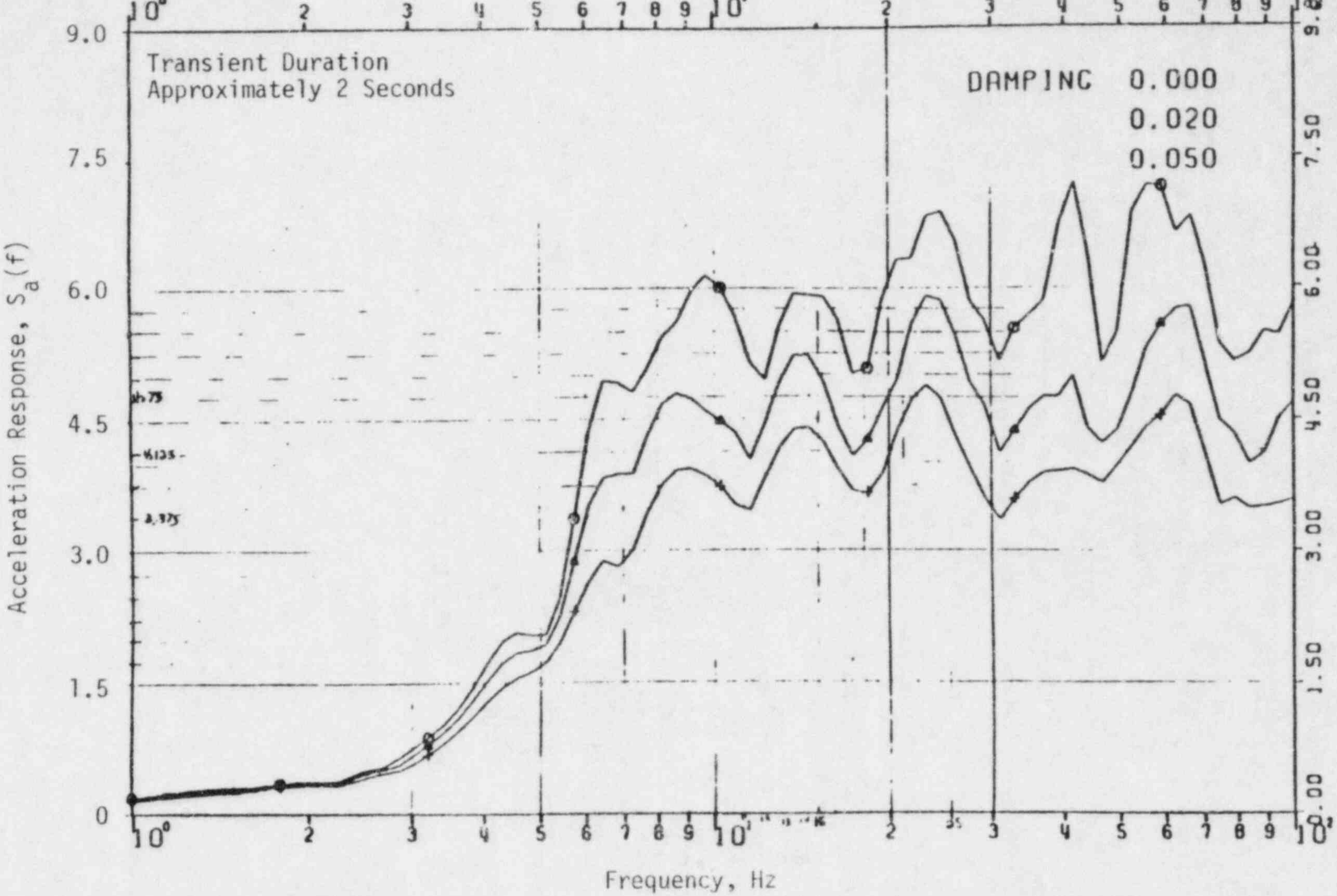

Figure 16. Synthesized Shock Waveform Responses for Varied Damping Under Simulated Blast Ground Shock (Reference 12)

The nonseismic character of the above described ground shock transients was recognized by Kennedy, et al [8], but the data were accepted as the best available at the time of that study. It was also surmised that the data may even be quite accurate for that equipment which malfunctions due to peak acceleration (i.e., a threshold type failure for a simple flexible device as described herein this report). However, a closer look at some of the waveforms and comparison with those of earthquakes suggest that some correction of the data may be in order.

Intuitively, one might suspect that a short duration transient of two seconds would not produce the same modal response in an item of equipment as a much longer duration seismic event, even when the frequency content of the two signals is similar. In order to provide some comparison of response to the two type transients, a quick analysis was performed with software which is typically used to generate seismic test waveforms [5]. A thirty-second time history which represents ground motion was generated by means of 34 narrowband random signals, each centered at 1/6-octave frequencies between 1 and 50 Hz. The resulting time history appears in Figure 17 and its computed response spectrum is shown in Figure 19 to match the RG 1.60 response spectrum very closely. We then multiplied this time history with a half-sine pulse of unity amplitude and 2 seconds duration. This was done at 8, 12, and 16 seconds into the seismic time history. The resulting filtered time history at 12 seconds is shown in Figure 18. The response spectra of the three shortened seismic events were then computed, and are compared with the RG 1.60 criteria in Figure 20. It is obvious from this figure that modal response for the shorter transients is indeed significantly less for most of the seismic frequency range. These results strongly support the suspicion that the ground shock median fragility capacities given in Reference [7] may need to be reduced by some appropriate factor as large as perhaps 2.0. In effect, this evaluation indicates that, within the 2 to 30-second range, a dependence on time exists for the fragility in this case. Therefore, time independence can only be assumed if excitations with typical seismic time durations (i.e., 30-second) are understood.

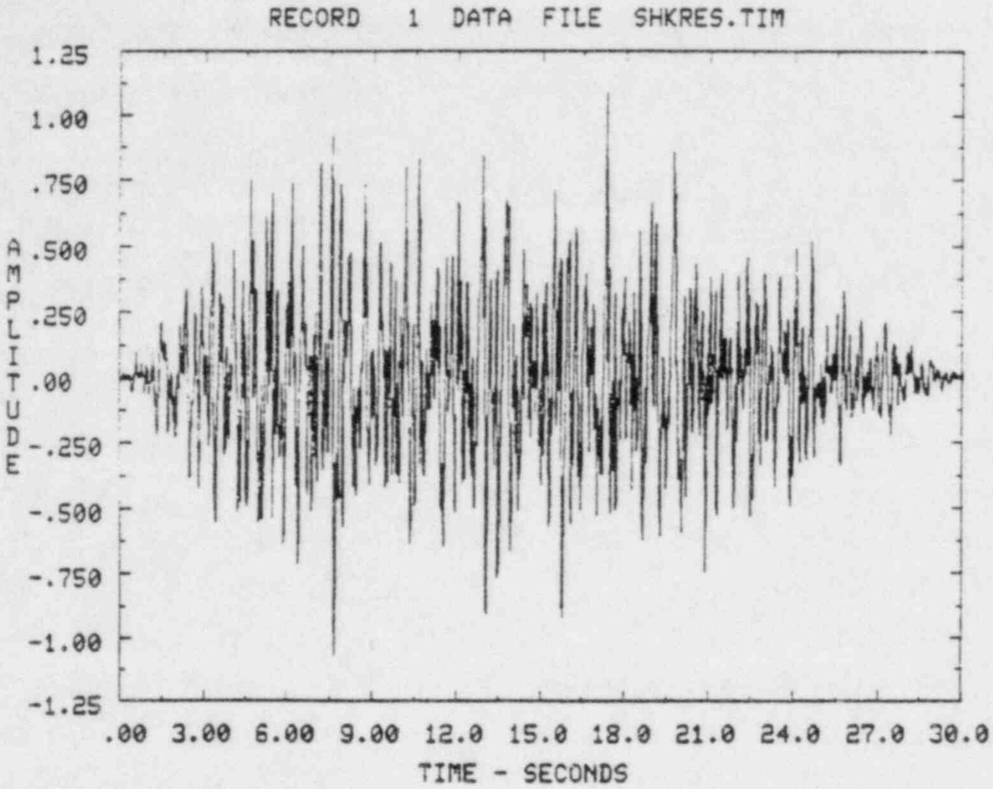

Figure 17. Time History for Typical Ground Level Motion

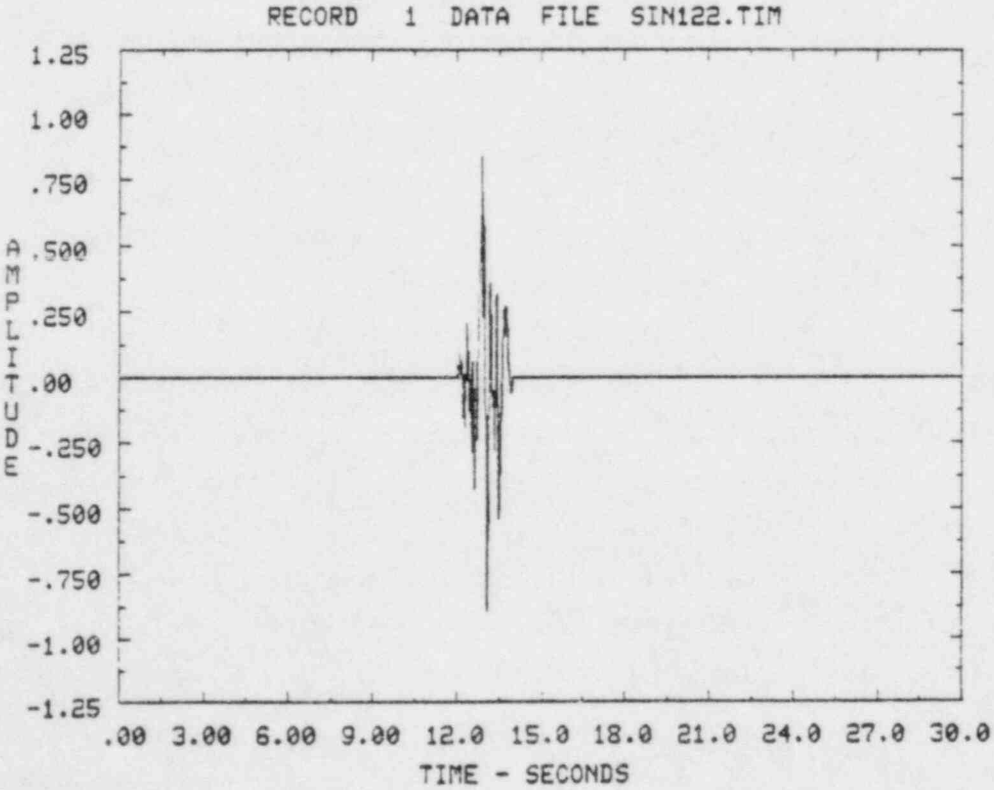

Figure 18. Two-Second Segment of Ground Level Motion

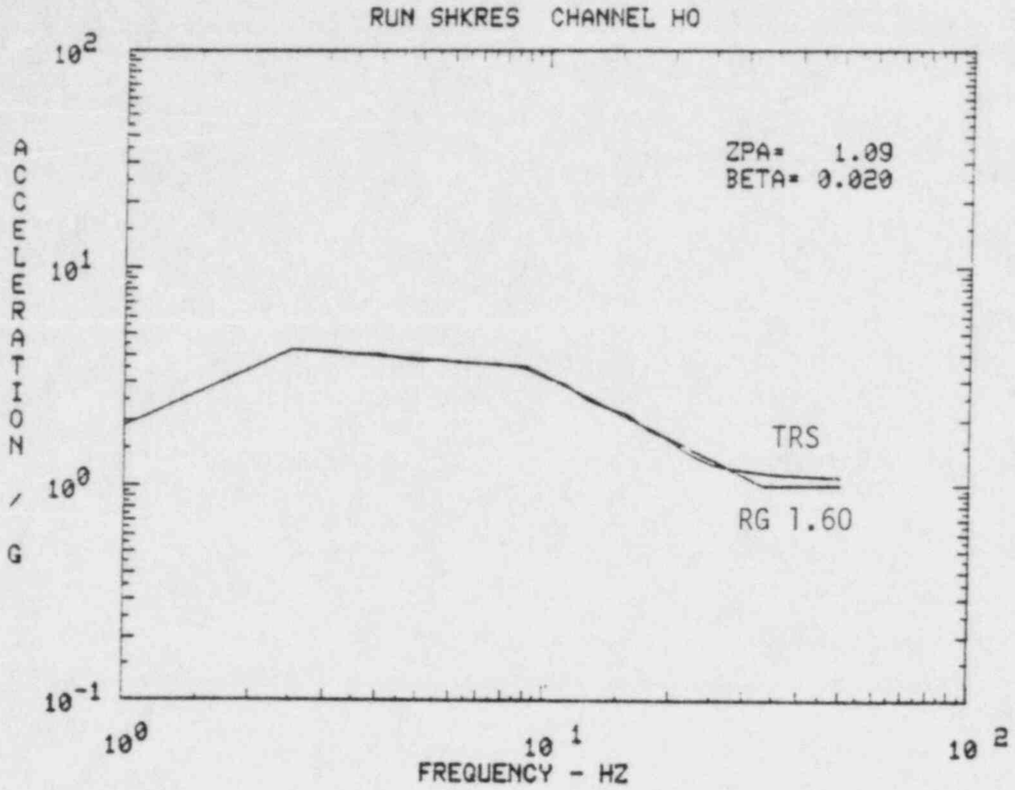

Figure 19. Matching of TRS to RG 1.60 Criterion

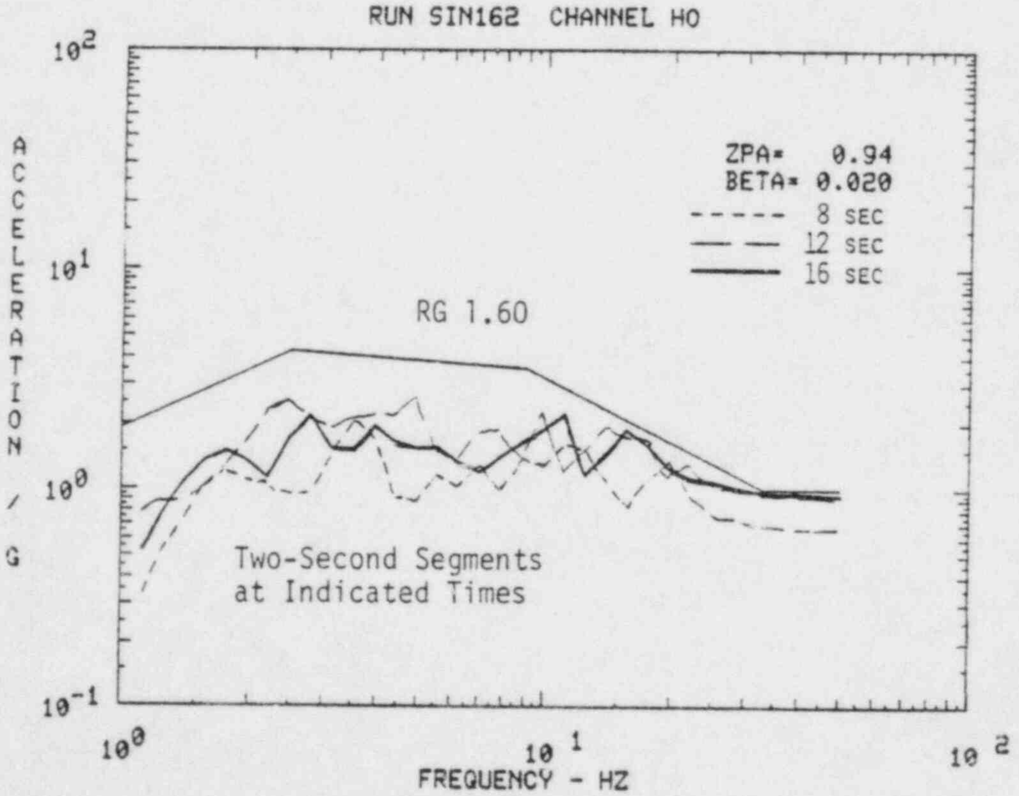

Figure 20. Comparison of Full Duration and Short Segment Spectra

4.0 DISCUSSION OF FRAGILITY IN EQUIPMENT DESIGN

This section includes a discussion of what appears to be some potential uses of fragility data at this point in time. As such, most of the concepts to be discussed need to be further developed by future research before confidence in them can be achieved. The present use of fragility in equipment design is still virtually in its infancy. This discussion presents ideas on how it can become a more practical design concept.

It appears 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 alternate waveform might be a flat random excitation to 33 Hz or higher.) If a device is suspected of having a rigid threshold fragility level, this can be checked 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 [6]. 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 can one do with currently available fragility data, much of which may have been acquired with narrowband excitation waveforms? It would appear that the approximate techniques outlined in Section 3.2 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. Techniques for this type of transformation have been given in References [3,4]. Thus, any narrowband qualification data (i.e., sine dwell, sine sweep, sine beat, etc.) become a potential source of development of fragility data.

It is conceivable that in the future, fragility testing could gradually replace the current methodology for equipment qualification by proof testing. The already existing trend toward the use of more generic qualification response spectra in proof testing has set the stage for this change. In the past, this approach has been somewhat more expensive. However, use of a standard ground level excitation would simplify the setup to where the costs may equalize.

5.0 RECOMMENDATIONS FOR ADDITIONAL WORK

The previous section has presented some ideas on how fragility methodology can be significantly further implemented to enhance the equipment qualification process. It is appropriate to consider several specific recommendations for immediate steps to help bring this about.

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 include:

1) 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 (such as those given in Table 1) from standard fragility data that has been obtained from equipment qualification procedures (response spectra).

2) Perform a series of experiments which provide data to verify the methodology developed for use of fragility in the design of equipment and facilities. This should include fragility measurement on 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.

3) Develop a risk ranking for 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.

4) Develop correction factors α_1 for multimode interaction, and α_2 for cross-axis coupling, for transfer of narrowband data to broadband data. Specifically, the corrections described in Figure 15 must be achieved.

5) Perform an analysis of existing ground shock data to develop a correction factor for nonseismic characteristics. The approach initiated in Section 3.4 must be expanded to provide an appropriate correction factor.

6) 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.

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