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PROCEEDINGS OF THE WORKSHOP ON SEISMIC AND DYNAMIC FRAGILITY OF NUCLEAR POWER PLANT COMPONENTS

C.H. Hofmayer and K.K. Bandyopadhyay, Editors

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UNITED STATES NUCLEAR REGULATORY COMMISSION
WASHINGTON, D.C. 20555
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ABSTRACT

The Workshop on Seismic and Dynamic Fragility of Nuclear Power Plant Components was held at Brookhaven National Laboratory (BNL) on June 5-7, 1985. The purpose of the workshop was to provide a forum for exchanging concepts, information and experiences on the fragility of electrical, control and mechanical equipment used in nuclear power plants when subjected to seismic and other dynamic environments. The workshop was divided into six sessions which included discussions on definition, uses and importance of component fragility; parameters affecting component fragility; categorizing equipment and existing test results; methodology and application of fragility data to equipment assemblies; equipment requiring future fragility testing; and, use of fragility data in PRA and Seismic Margin studies. The proceedings represent the compilation of the papers presented at the workshop.

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PREFACE

The Workshop on Seismic and Dynamic Fragility of Nuclear Power Plant Components was held at Brookhaven National Laboratory (BNL) on June 5-7, 1985. The workshop was hosted by Brookhaven National Laboratory under the sponsorship of the U.S. Nuclear Regulatory Commission (NRC).

The workshop provided a forum for exchanging concepts, information and experiences on the fragility of electrical, control and mechanical equipment used in nuclear power plants when subjected to seismic and other dynamic environments. It attracted 75 participants from industry and government who exchanged views on important issues affecting fragility. Twenty-two oral presentations were made during the six workshop sessions. Each session also included extensive periods of discussions between the participants. The written contributions that correspond to each presentation are included in this report. Two presentations made at the workshop, but not included in the distributed program schedule, are included in this report as appendices.

The papers presented, the speeches delivered and the discussions followed during the workshop, covered a wide spectra of subjects related to seismic fragility of components. The NRC representatives described the component fragility research program currently being conducted by the NRC and their contractors, indicated the goal of establishing fragility levels for the overall safety evaluation of a plant, and encouraged a greater coordination between the industry and the government in achieving this common goal. Testing laboratories discussed the complex and delicate points in controlling fragility testing including nonlinearities, multi-axis vibration inputs and electronic signal saturation at a high vibration level. They also shared their experience in considering various factors which affect selection of the equipment and the vibration input for fragility testing, and presented test results identifying some electrical equipment which reached the fragility level during age-related seismic testing. By presenting existing test results for their equipment, a manufacturing company demonstrated the need to understand the intricacies of the functions of a component, and its interaction with and performance under various testing inputs and techniques. A number of authors representing utilities, reactor suppliers and A/E firms, and some seismic consultants described the role of component fragility in the Probabilistic Risk Assessment (PRA) of an entire plant and emphasized the need to establish a reliable fragility data bank in order to refine their PRA studies. Still, other speakers presented their experience in testing some equipment to the fragility level, described the effect of anchorage on component fragility and summarized the data collection program sponsored by a utility group. Several seismic consultants defined seismic fragility as the response amplitude as a function of both frequency and time, and proposed a probabilistic fragility concept useful in PRA studies.

In general, the workshop identified many past and present fragility testing programs and methods to compile, analyze and use fragility data. The importance of establishing seismic fragilty levels of safety-related equipment was upheld by the participants. The workshop also highlighted the fact that there are considerable existing data within the industry which if compiled and evaluated could yield better estimates as to how well nuclear power plant components will operate in the event of an earthquake and confirm the belief that seismic fragilities are greater than that which was previously estimated. BNL will further discuss the views and perspectives that have been gained as a result of the workshop as part of its research project report which will be issued in the Fall of 1985.

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ACKNOWLEDGEMENT

The Editors highly appreciate the guidance and technical stimulation provided by the Session Chairmen. EPRI's cooperation to make it possible for some Chairmen to attend the workshop is sincerely acknowledged. The Editors extend their appreciation to all speakers and participants, and to their organizations for making the workshop a success. Specifically the keynote speeches provided by NRC representatives Messrs. Guy Arlotto, James Richardson and James Knight are greatly appreciated. Special thanks are also due to Dr. John O'Brien of the NRC for his continuous direction since the concept of the workshop. Lastly, the Editors express their sincere appreciation to Joan Murray, Liz Gilbert and Diana Votruba for their assistance and cooperation in organizing the workshop.

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INTRODUCTORY PRESENTATIONS

THE COMPONENT FRAGILITIES PROGRAM IN THE OFFICE OF NUCLEAR REGULATORY RESEARCH

BY
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The NRC recently stated[1] that "quantitative risk assessment techniques will be used judiciously by the staff and the boards to estimate risks as an aid to decision making...Whenever probabilistic risk assessment is used there must be... a systematic evaluation of the most important uncertainties." I want to focus on these uncertainties, not only as they pertain to probabilistic risk assessments, but also as they relate to deterministic margin studies. My remarks will be applicable to electrical and mechanical components at nuclear power plants, with emphasis on electrical components since they are the major risk contributors according to present views. Mechanical components are, in general, inherently rugged since they must withstand loads such as pressure and temperature effects, and therefore, are less susceptible to earthquake damage than electrical components which normally are not designed to resist other significant internal loading situations. Also, piping, which may be considered a mechanical component, is excluded. In general, only active mechanical components will be treated, such as pumps and valves. On the other hand, both active and passive electrical components are of interest. While seismic loads will be of principal concern, other loading situations, as for example, hydrodynamic loads, will also be covered.

We have, over the last several years, developed sophisticated analytical methods, such as those employed in the Seismic Safety Margins Research Program (SSMRP), to predict the best estimate behavior of nuclear power plants subjected to large earthquakes. However, the component fragility data used in these analyses are based largely on subjective judgment or extrapolation, and thus have large uncertainties. In order to improve our estimate of seismic risks, programs within the Office of Nuclear Regulatory Research are currently underway to determine the fragility levels of key components. These programs depend on data collection and evaluation and experimentation.

Past probabilistic risk analyses have indicated that accidents initiated by large earthquakes are major contributors to public risks. However, in some quarters inside and outside the NRC, it is believed that pessimistic estimates of seismic component fragility have led to needlessly conservative estimates of the seismic threat and questionable bases for licensing decisions. This view can only be validated when sufficient evidence is assembled, analyzed, and interpreted to provide the required technical basis. Moreover, for older operating reactors where equipment qualification

1 "1985 Policy and Planning Guidance", NUREG-0885, Issue 4, February 1985.

requirements and records may be more hazy, the staff is beginning to depend on experience data to allow continued operation. This is a more or less qualitative approach. To make it more quantitative and objective requires a better foundation which can only come from controlled testing such as proposed in our newer research effort.

Our component fragility research supports the need for realistic inputs for probabilistic risk assessments and margin studies. This research seeks to test the hypothesis that electrical and mechanical components have higher failure levels than those presently assumed in seismic PRAs, and as a consequence, the significance of the earthquake threat may be diminished in licensing decision making. Additionally, it is hoped that this research will contribute to the development of simplified seismic risk methodologies that are more understandable to the decision makers, by eliminating certain branches on event trees and fault trees which do not contribute to risk. These branches can be identified when the actual component failure levels are shown to be extremely high when compared to predicted seismic responses. Realistic component fragilities are a prerequisite to validation of current seismic PRA methods.

An additional benefit which could result from this program would be the identification of component designs which afford greater reliability. This information would be valuable for replacing components in operating plants or in constructing new plants.

Our efforts are being conducted in two phases. We have selected Brookhaven National Laboratory and Lawrence Livermore National Laboratory to perform the first phase. During this first phase, we will search for existing component fragility data, develop a scheme for prioritizing and grouping components, initiate cooperation with other institutions and develop standardized procedures for component fragility testing. With respect to these objectives, we have found that a large body of component fragility data does exist and is available to us, and we have begun working harmoniously with the Electric Power Research Institute (EPRI) in collecting data. NRC and EPRI will use a common data format for collection of information from various sources and will coordinate our data acquisition efforts, for example, visiting different source organizations, and collecting and submitting test reports in order to avoid duplication. It has been agreed that EPRI will primarily collect data from the utilities and West Coast Testing Laboratories, and NRC will primarily acquire data from vendors and East Coast Testing Laboratories. Finally, NRC and EPRI will exchange data sheets and pertinent information. The prioritizing and grouping of components are important because our limited resources will not allow us to perform all the testing or data evaluations on all components. This would be impractical, very time consuming, and very costly. In the first instance, we wish to focus our attention on those components which most endanger public health and safety. By grouping components, we hope to test members from a component family and infer the behavior of the entire family without actually investigating each member of the family. This will be most difficult - everyone

will not be satisfied; we must rely on reasonable assurance and not rigorous scientific proof.

The completion of Phase I will provide assurance that any testing performed during Phase II will not duplicate any already existing and usable data. Demonstration tests also will have been conducted that will define the procedures and clarify the approaches for arriving at usable fragility data. In addition, the prioritization scheme will permit the appropriate selection of components for fragility testing during Phase II. Those components essential to the safe shutdown of the reactor in the event of an earthquake, those components essential to maintaining the integrity of the reactor coolant pressure boundary and those components needed for mitigating accidents will be given the highest priority for further testing.

Although we have received authorization, we have made no commitments for the potentially much larger and potentially more expensive second phase, whose continuance depends on the success of the first phase. The second phase will likely depend on a mixture of additional data collection and analysis coupled with some limited testing. Our preference, based on economic considerations, is to reduce to a minimum the amount of testing we will undertake - particularly to minimize large scale testing.

Component fragilities, in general, suggest a probabilistic description of failure. In the purest statistical sense, empirically developing a meaningful seismic fragility for a given component would require that a large population of identical components be subjected to successively higher levels of acceleration and the distribution of failures as a function of acceleration level recorded. Within practical constraints on time and resources, this is hardly feasible for a single component under well-defined load conditons, let alone for the great number of combinations and permutations of component type, size, mounting, loading conditions, and environment that could be identified for actual nuclear power plants. Therefore, an alternate approach is necessary to experimentally gain insight into fragility.

The present approach envisioned in this program takes advantage of the fact that, for PRA application, a limited fragility description may be adequate. This is because, in a probabilistic analysis, failure occurs only when the probability distributions of response and fragility overlap; this limits our concerns for this case to understanding the distribution only where the tails of these curves overlap. Therefore, the number of tests could be limited substantially, although a relatively large number of identical components might still have to be tested to assure statistically meaningful results.

We seek greater realism in estimating component fragilities for our margin evaluations and PRA studies. A key issue is obtaining assurances that component fragilities developed through laboratory testing are relevant for in-situ predictions, with emphasis on support conditions, anchorages,

system interactions and connections to electrical and mechanical subsystems. Among the other technical factors on components fragility are the impact of aging as it may degrade fragility, scaling effects and the impact of construction practices, vintage and manufacturer.

One of the key spinoffs of these efforts is the establishment of a component fragility data bank at one of the national laboratories. This would make the data available to all for design, operation, and safety reviews. It also gives us a convenient mechanism to add new data or correct existing data as we gain more knowledge.

To a large degree, our concerns with component fragility are driven by questions relating to East Coast seismicity, particularly the Charleston Earthquake and the New Brunswick Earthquake issues. Our work is intended to provide a rational basis for decision should these issues impose new licensing requirements on East Coast nuclear power plant operators. It is important to recognize that actual component fragility levels need not be determined to satisfy licensing needs. What is needed is documented evidence that components have higher fragilities than those presently assumed in margin studies and PRAs that have concluded the risk is acceptable. This can be achieved without testing to failure. Of course, we must be prepared to face any research outcome - including that seismic component fragilities are no greater and perhaps less than those currently used.

Component fragilities are only one aspect to seismic PRAs and margin studies. Estimations of the seismic hazard, soil-structure interaction, building response and subsystem response are also needed to complete the analyses. Each aspect has its own deficiencies and weaknesses. Jim Richardson of my staff will follow me and give an overall view of the entire procedure.

In concluding this brief presentation, I wish to encourage the cooperation of all in these endeavors. We are excited about this program, and we believe all should be. We perceive that this work will prove to be of mutual benefit to the industry, the public, and the government. There is a very real prospect that this work will lead to greater public safety, improved and more reliable reactor designs, and lower costs. Thus, the potential benefit to the industry as suppliers and to the public at large as consumers can result in a win-win outcome for the regulated and the regulatory.

SEISMIC SAFETY RESEARCH PROGRAM

J. E. RICHARDSON

USNRC OFFICE OF NUCLEAR REGULATORY RESEARCH

JUNE 5, 1985

ISSUES

- SEISMIC HAZARD
  - CHARLESTON EARTHQUAKE (1886)
  - NEW BRUNSWICK EARTHQUAKE (1982)
  - EASTERN SEISMICITY PROGRAM
- SEISMIC RISK
  - PRA'S SHOW SEISMIC RISK IS SIGNIFICANT CONTRIBUTOR TO RISK
  - NEED TO PREDICT BEHAVIOR BEYOND DESIGN BASIS
  - NEED TO VALIDATE METHODS
  - NEED IMPROVED DATA BASES
- SEISMIC MARGINS
  - NEW SEISMOLOGICAL INFORMATION MAY LEAD TO HIGHER DESIGN BASIS EARTHQUAKES
  - NEED TO DETERMINE MARGINS TO MINIMIZE LICENSING ACTIONS
  - STIFF PIPES MAY REDUCE SAFETY

PROGRAM OBJECTIVES

SEISMIC HAZARDS

- IMPROVE METHODS FOR ASSESSING THE SEISMIC HAZARD OF EASTERN UNITED STATES

- REDUCE UNCERTAINTIES RELATED TO ESTIMATING SEISMIC HAZARDS AND SEISMICALLY INDUCED SOIL LIQUEFACTION AND SETTLEMENT

PROGRAM OBJECTIVES

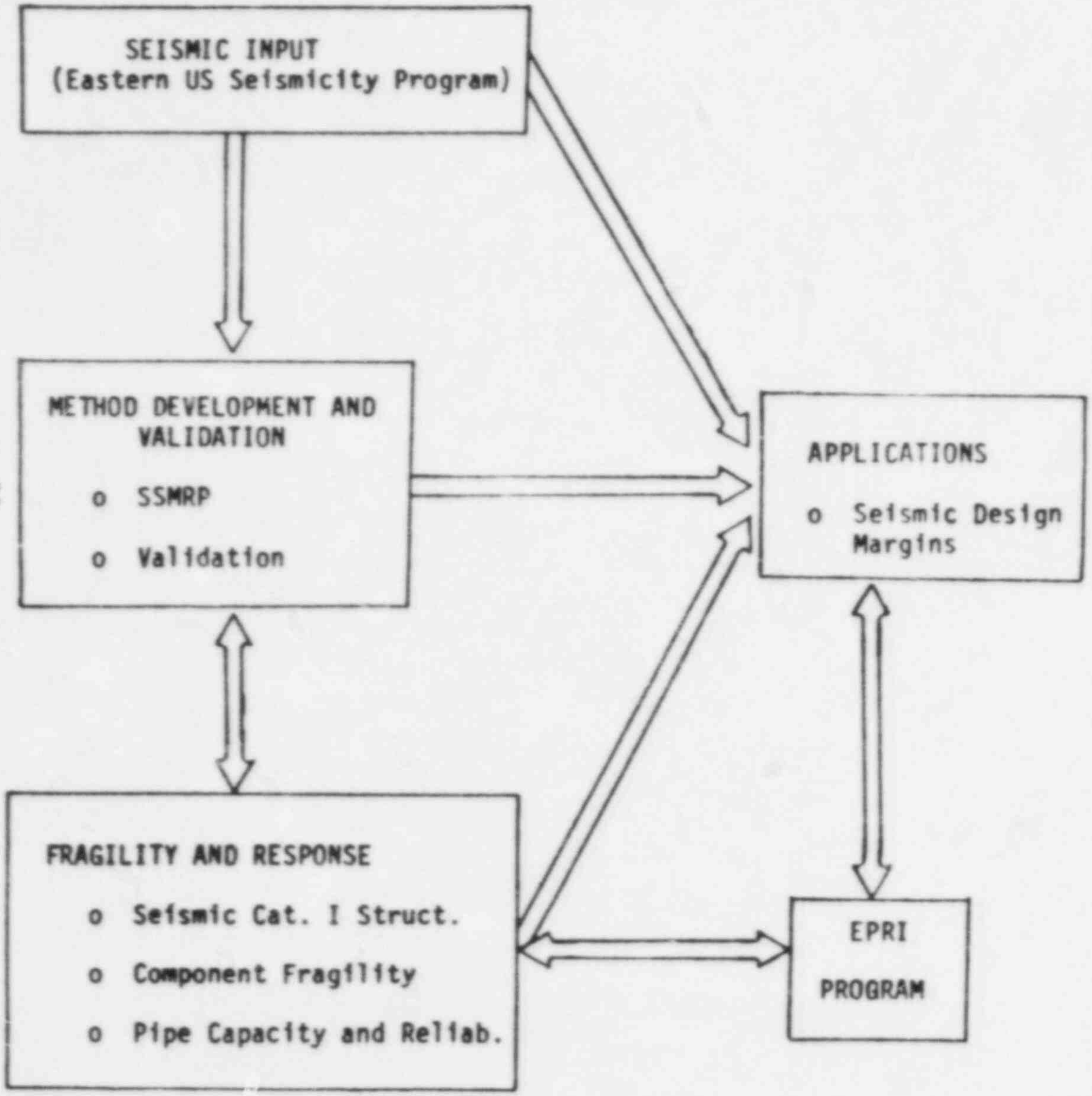
SEISMIC RISK

- o DEVELOP SIMPLIFIED SEISMIC RISK METHODS
- o VALIDATE METHODOLOGY
- o ASSESS ADEQUACY OF ASSUPTIONS USED IN PRA

PROGRAM OBJECTIVES

SEISMIC MARGINS

- o IMPROVE AND REDUCE UNCERTAINTIES IN CURRENT SEISMIC DESIGN CRITERIA
- o REDUCE UNCERTAINTIES IN DETERMINING RESPONSE AND FAILURE MODES OF STRUCTURES, COMPONENTS AND EQUIPMENT
- o DEVELOP SIMPLIFIED REVIEW METHOD AND PROCEDURES TO ESTIMATE SEISMIC DESIGN MARGINS



REGULATORY USES

- Charleston Earthquake
- New Brunswick Earthquake
- NTOL Seismic Issues
- ISAP
- RMEIP
- Pipe Damping (RG 1.61)
- Floor Spectra (RG 1.122)
- ASME Code-Piping
- Licensee PRAs
- Equipment Qualification
- Structural Damping (RG 1.61)

PROGRAM INTERACTIONS

- SEISMIC HAZARD
  - EPRI AND INDUSTRY SEISMIC HAZARD PROGRAM
  - USGS GROUND MOTION STUDIES
  - NATIONAL EARTHQUAKE HAZARD REDUCTION PROGRAM
- VALIDATION OF SEISMIC METHODS
  - GERMANY - KFK HDR EXPERIMENTS
  - EPRI - TAIWAN SSI EXPERIMENTS
  - JAPAN - MITI/NUPEC SEISMIC EXPERIMENTS
- FRAGILITIES
  - EPRI PIPING PROGRAM
  - EPRI EQUIPMENT QUALIFICATION PROGRAM
  - NRC AGING PROGRAM
  - SQUG
- SEISMIC MARGINS
  - EPRI SEISMIC MARGINS RESEARCH PROGRAM
  - INDUSTRY PRAS

SEISMIC DESIGN MARGINS RESEARCH PROGRAM

	FY 1985	FY 1986
o VALIDATION OF SEISMIC METHODS	1092K	1850K
o COMPONENT FRAGILITIES	755K	1100K
o CATEGORY I STRUCTURES	800K	1200K
o PIPING PROGRAM	680K	1100K
o MARGINS STUDIES	650K	600K
	3977K	5850K

VALIDATION OF SEISMIC METHODS

OBJECTIVE

- DEVELOP AN EXPERIMENTAL BASIS FOR ASSESSING THE ACCURACY AND ADEQUACY OF METHODS USED TO ESTIMATE SEISMIC RISK

ELEMENTS

- DEVELOP PLAN - 1985
- COOPERATION WITH KFK AT HDR - 1985-1986
- COOPERATION WITH NUPEC AT TADOTSU - 1985-1986
- COOPERATION WITH EPRI IN TAIWAN - 1985-1987

COMPONENT FRAGILITIES

OBJECTIVE

- DEVELOP FRAGILITY DATA BASE FOR IMPORTANT COMPONENTS TO SUPPORT MARGINS STUDIES AND RISK ANALYSES

ELEMENTS

- IDENTIFY IMPORTANT COMPONENTS - 1985
- DEVELOP TEST PROCEDURES - 1985
- ASSEMBLE AND ANALYZE EXISTING DATA - 1985
- PERFORM FRAGILITY TESTS - 1986-1987

CATEGORY I STRUCTURES

OBJECTIVE

- o PROVIDE ANALYTICAL AND EXPERIMENTAL DATA ASSESSING HOW PARAMETERS USED IN DESIGN OF EQUIPMENT AND STRUCTURES ARE AFFECTED BY EARTHQUAKE LOADS ABOVE DESIGN LEVEL

ELEMENTS

- o PERFORM EXPERIEMENTS ON 3-DIMENSIONAL STRUCTURES
  - COMPLETED 15 EXPERIMENTS ON 1 INCH WALL MODELS
  - COMPLETED 3 EXPERIMENTS ON 3 INCH WALL MODELS
  - TEST TWO 4 INCH WALL MODELS - 1985-1986
  - BASED ON RESULTS DETERMINE REMAINING TESTS - 1986-1987
- o VALIDATE PREDICTIVE ELASTIC-INELASTIC METHODS - 1985-1987
- o INVESTIGATE ANALYTICAL-EXPERIMENTAL DIFFERENCE - 1985-1986
- o MAINTAIN REVIEW GROUP OF NATIONAL EXPERTS

PIPING PROGRAM

OBJECTIVE

- DETERMINE FAILURE MODE AND LEVEL
- PROVIDE MORE BALANCE IN SAFETY BETWEEN OPERATION AND ACCIDENT CONDITIONS

ELEMENTS

- PIPE CAPACITY TESTS (WITH EPRI) 1985-1987
- LOAD COMBINATION PROGRAM - 1985 (COMPLETED)
- DAMPING STUDIES - 1986 (COMPLETE)
- SEISMIC SPECTRA STUDIES - 1986
- SEISMIC DESIGN ANALYSES - 1986
- INELASTIC RESPONSE - 1986-1987

MARGINS STUDIES

OBJECTIVE: PROVIDE TECHNICAL RECOMMENDATIONS, DATA AND PROCEDURES TO QUANTIFY SEISMIC DESIGN MARGINS

ELEMENTS

- o DEVELOP PLAN (COMPLETED)
- o REVIEW AND ASSESS RECENT PRA'S, MARGIN STUDIES, EARTHQUAKE EXPERIENCE DATA AND FRAGILITY TESTS - 1985
- o DEVELOP PRELIMINARY CONCLUSIONS ON ADEQUACY OF SEISMIC MARGINS - 1985
- o DEVELOP SCREENING GUIDELINES - 1985-1986
- o CONDUCT TRIAL PLANT REVIEWS - 1986
- o MAINTAIN PANEL OF EXPERT CONSULTANTS

NRC SEISMIC DESIGN MARGINS WORKING GROUP

- o J. KNIGHT - NRR (CO-CHAIRMAN)
- o J. RICHARDSON - RES (CO-CHAIRMAN)
- o A. THADANI - NRR
- o C. GRIMES - NRR
- o G. LEAR - NRR
- o L. REITER - NRR
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- o D. GUZY - RES
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REFERENCE: LETTER FROM W. DIRCKS TO J. EBERSOLE 4/12/84

SUBJECT: QUANTIFICATION OF SEISMIC DESIGN MARGINS

SEISMIC DESIGN MARGINS EXPERT CONSULTANTS

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CONTRACTOR - LAWRENCE LIVERMORE NATIONAL LABORATORY (R. MURRY)

SESSION I

DEFINITION, USES AND IMPORTANCE OF COMPONENT FRAGILITY

COMMENTS ON SEISMIC FRAGILITY OF NUCLEAR POWER PLANT COMPONENTS

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ABSTRACT

Recent advances in the prediction of seismic hazard have resulted in concern that some nuclear power plant sites could experience seismic events in excess of their design bases. This concern, along with the considerable interest that his arisen from interpretations of probabilistic risk assessments, has resulted in significant professional activity in the prediction of fragilities of structures and equipment. Several programs sponsored by utilities, regulators and EPRI are addressing many of the aspects of seismic fragility.

This paper discusses the current state-of-the-art in fragility prediction, fragility data sources, relative seismic ruggedness of power plant components, problem areas in fragility prediction, and suggested future work in fragility testing.

INTRODUCTION

The prediction of seismic fragility of nuclear power plant structures and equipment is a technical issue that has received much recent attention. The interest in seismic fragility arises from three separate but related issues:

- Earthquakes greater than the design bases are postulated to be credible, though highly unlikely.
- Structures and equipment in earlier plants had either very limited or no seismic design basis.
- Probabilistic Risk Assessments (PRAs) have indicated that seismic events are a non-trivial contributor to overall plant induced risk to the public.

The technical community realizes that current analytical design and test qualification requirements for nuclear power plant components contain explicit built-in margins in the governing codes and standards plus numerous conservatisms in each of the seismic response parameters that are introduced in the design process. The questions are then, how much conservatism really exists, what are the uncertainties in those conservatisms, and how much real

margin remains to accommodate a greater-than-designed-for seismic event? Several ongoing programs sponsored by utility groups, regulatory agencies and EPRI are addressing these issues. This paper discusses observations-to-date from PRAs, seismic margin studies and research programs.

Before discussing seismic fragilities, the definition of fragility is first clarified. The seismic fragility of a structure or component is the threshold of response at which it ceases to perform its intended function. Fragility can either be referenced to a ground motion input or to a local in-structure input. Some damage may result at response levels below the defined fragility, but function might not be impaired at the onset of damage. Fragility is most appropriately defined as a conditional probability of failure versus an input or response parameter. For convenience, a lognormal distribution is commonly assumed and a median value, $\check{A}$, and two variables, β_R and β_U, are used to describe randomness and uncertainty about the median (Kennedy, 1980), where β_R and β_U are logarithmic standard deviations about the median. Figure 1 shows a family of fragility curves for a component. The slope of each curve represents the randomness, β_R, in the prediction of capacity and the family of curves represents the distribution of uncertainty, β_U, in where the true curve lies. The terminology "high confidence of low probability of failures" (HCLPF) has come into use and is typically defined as about 95% confidence of less than approximately 5% probability of failure. HCLPF is also shown in Figure 1. Expressed mathematically, the HCLPF is:

$$\text{HCLPF} = A \exp\left[(-1.65)(\beta_R + \beta_U)\right] \quad (1)$$

If one can show that the HCLPF value for each plant component is greater than a specified earthquake level, then there should be little concern regarding public safety for earthquakes below this specified level.

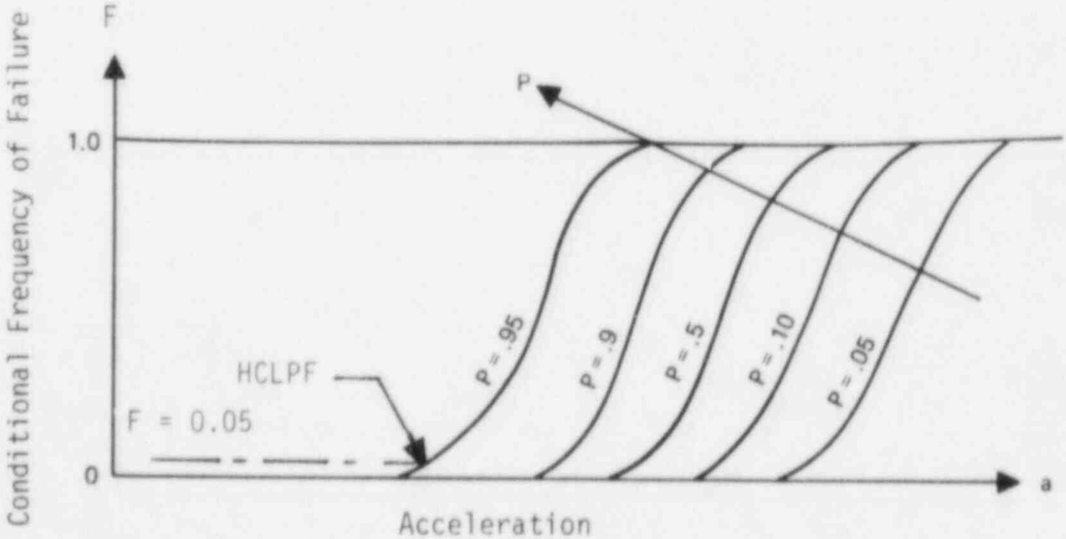

Figure 1. Fragility Curves

Although Equation (1) might indicate that the HCLPF should be calculated from $\breve{A}$, β_R, and β_U, it has been our experience that an engineer can most often estimate HCLPF more accurately than any of these other parameters. As a result, in developing fragility curve estimates, the emphasis should be on estimating HCLPF, and $\breve{A}$. Then β_R and β_U are estimated to maintain the predetermined relationship between HCLPF and $\breve{A}$. Secondly, one should not place undue emphasis on the lognormal distribution. This distribution is simply used for convenience. Within our experience with seismic PRA studies, the fragility curve probability range of interest is from about 5% to 50%. So long as HCLPF and $\breve{A}$ are held constant, the specific shape of the fragility curve (lognormal, extreme value, Weibel, normal, etc.) is unimportant in the tails (probabilities much less than 5%). This tail of the fragility curve cannot be defined with any accuracy and PRA studies whose results depend on the shape of this lower tail are highly suspect.

FRAGILITY PREDICTION

There is generally a dearth of real fragility data for seismic and dynamic loads. For the most part, fragility predictions in support of probabilistic risk assessment and seismic margin issues have been derived analytically, from qualification test data, and from earthquake experience data, supplemented by limited fragility data from military-sponsored shock tests and limited seismic fragility tests (Kennedy, 1984a). Actual dynamic capacities are considered by many to be much greater, but a lack of data precludes confirmation of these insights. Reasonable lower bounds on HCLPF fragility can be estimated from recent and ongoing documentation of seismic experience and of qualification testing. These lower bounds are very useful in justifying the continued use of unqualified equipment in older plants, screening of components for seismic margin studies and conservatively defining the HCLPF values of component fragility curves used in PRAs.

Considerable evidence is present to demonstrate ruggedness in certain classes of equipment as long as the equipment is adequately anchored, whereas, some types of equipment tend to be more susceptible to seismic loading. Ranking of equipment ruggedness based on past PRA derivations and earthquake experience has been a recent NRC-sponsored activity in support of seismic margin issues.

For the most part, prediction of structural fragilities is at a more advanced stage than for equipment, especially active equipment. While each structure is unique, the lateral load-carrying mechanisms are limited to standard practice (shear walls, braced frames, moment frames, etc.). Much research has gone into predicting the capacity of structural elements under cyclic loading. Lateral load-carrying provision of codes and standards have evolved from experience in structural behavior in seismic events and from ongoing research on structural response to dynamic loads. Even when seismic is a governing design factor, structures typically have median capacities at least three to four times the specified safe shutdown earthquake. Exceptions to this may result for brittle structures such as unreinforced masonry walls or for structures with brittle connection detail. For

the most part, reasonably good predictions of median structural capacity and the uncertainties in capacity can be made by analysis or by extrapolation of design analyses.

For passive equipment, similar conclusions can be drawn although the equipment design process places less emphasis on seismic design and more on the functional requirements of the equipment. Codes and standards for pressure vessels and piping have evolved throughout the years with emphasis on pressure retention, with seismic being an add-on load condition for which a stress check is required. Codes and standards for equipment design have not differentiated between dynamic and static load energy content. As such, ductile equipment tends to have very large seismic margins. Fragility predictions for passive equipment concentrate more on the non-ductile failure modes that might occur in the equipment supports or the anchorage to the supporting structure. Fragility prediction for passive equipment are typically derived by extrapolating design data, just as for major structures. Often times, redundancies exist which cannot be directly accounted for by extrapolating linear elastic analyses and the predictions are biased on the low side. This bias is acceptable only if the predicted capacity is very high relative to the specified earthquake hazard. Otherwise, the prediction distorts the truth and is better off not being made. Conservatism in design is acceptable design practice but conservatism in fragility predictions is not an acceptable practice. Usually, with some diligent effort to eliminate conservatisms in design analysis, passive component fragilities can be realistically predicted.

Active components present a much more difficult problem to the fragility analyst. When components are qualified by analysis, there are usually some rather arbitrary limits placed on deflections and stresses to assure function. External piping reactions are also very conservatively specified and without resorting back to results of final piping analyses, the fragility analyst has no direct means of removing conservatisms in design loads imposed on the equipment vendor. Real functional limits are very difficult to predict analytically and extrapolation of design analysis, which includes conservative external loading, often results in low capacity predictions. These predictions when coupled with the uncertainties in capacity, equipment response predictions and structural response predictions, result in unrealistically low HCLPF values. In these cases, earthquake experience data for similar equipment are utilized to truncate the lower fragility tails but the data do not affect the predicted median values. The resulting fragility prediction is then somewhat distorted in that the uncertainty is small due to the artificially low median fragility prediction coupled with a realistic lower tail. Since actual fragility data do not exist nor do data from high test levels exist, adjustment in the predicted median capacity is a very judgmental situation and subject to controversy.

When active components are qualified by test, the achieved test level, though statistically insignificant, is often considered to be a lower bound or HCLPF value for fragility. In the absence of fragility test data, the

median capacities are speculative and are often considered to be some arbitrary factor above the achieved test level. This is acceptable if the achieved test level was high relative to the SSE but may be very unrealistic if the achieved test level barely exceeded the SSE. In these cases, other generic sources of data must be applied to develop realistic fragility predictions. The principal concern with using generic data is the similarity between components.

For active electrical equipment, two or three fragility values are typically given. One value is provided for relay chatter if the equipment contains relays. Chatter is not a permanent failure of the device but the consequences of chatter must be determined by the systems analyst. If the equipment contains breakers which can trip from inertial effects, a fragility for trip is provided. Trip may also be caused by protective relay chatter as well as inertial effects and the limited test data usually do not pinpoint the actual cause of trip. Trip is also not a permanent failure but, again, the systems analyst must determine the consequences.

A third fragility prediction is provided for a permanent (unrecoverable) failure mode which may be dislodgement of the device from its supporting cabinet or failure of cabinet anchorage. Historical data would indicate that anchorage is the more likely failure mode, thus the fragility prediction is usually based upon anchorage failure. Design analysis of anchorage can be extrapolated to predict the capacity but if the anchorage was qualified by test then generic arguments must be made, just as for the device function fragility.

It is particularly important for all equipment and especially active equipment, that a thorough walkdown be conducted to observe anchorage, attachment of devices to cabinets and attachment of electrical cables, instrument lines, cooling lines, etc. Most of the equipment is inherently rugged but on rare occasions, conditions will be observed where loads or deflections significantly greater than the SSE might result in functional failure. Examples that have been found besides poor or no anchorage are threaded cooling lines entering HVAC equipment mounted on spring vibration isolators, insufficient flexibility in instrument lines to accommodate large piping motion, brittle support details and potential systems interactions resulting from non-qualified equipment failures impacting safety equipment.

DATA SOURCES

Recent efforts by utility groups, NRC and EPRI are increasing the sources of data from which fragility predictions can be estimated. Actual fragility data are usually limited to testing of electrical devices to their malfunction limit and this limit is usually a recoverable failure mode such as relay chatter, contactor chatter or breaker trip. Some manufacturers have conducted fragility tests on standard product lines. A centralized data bank of these data does not exist, however, and in developing

fragility predictions a more generic approach is usually taken, assuming the component under consideration is similar to one for which limited fragility data are available.

In using device fragilities, the transmissibility of the cabinet in which the device is mounted must be factored into the fragility prediction. Care must be taken to use realistic transmissibilities compatible with the acceleration levels at which the device would malfunction. Transmissibility tests are often run at very low input motion levels for which the resulting damping is very low and the resulting transmissibility is very high.

During the SAFEGUARDS program, a series of fragility tests were conducted on electrial and mechanical components and subsystems (USACE, 1975). In most instances, actual failure levels were never achieved on mechanical components due to table input motion limits. Tests of electrical devices mounted in cabinets were conducted up to the malfunction limits. Damage to electrical cabinets was observed but not to the extent that a functional failure was noted.

These tests were characterized by short duration superimposed sine beats. The input motion was defined for zero percent damped required response spectra and, for the time history input used, typical 5% damped spectra would be about 2/3 of the spectral acceleration amplitude of the zero damped spectra.

These tests are felt to provide valuable fragility data for components whose failure was functional while the subsystems were responding essentially elastically. For these cases, the input motion duration is not a dominant factor. For subsystems and components whose failure mode is characterized by cyclic inelastic response, the short duration input motion contained much less energy than longer duration earthquake motions and use of the data would result in an overprediction of capacity for seismic events. Many mechanical systems consisting of passive and active components survived 30g undamped spectral acceleration with little or no apparent damage. Failures that did occur were restricted to anchorage, failure of threaded pipe joints at vessel connections, one check valve seizure, and miscellaneous cosmetic damage. It is felt that a longer duration input would have produced more damage. Consequently, these data are suspect for fragility predictions of ductile failure modes.

The Seismic Qualification Utility Group (SQUG) has documented historical performance of specific classes of components in earthquakes (EQE, 1983). It has been shown that, with proper anchorage, the component types studied will perform their intended function after the seismic event. A USNRC-sponsored Senior Seismic Review and Advisory Committee (SSRAP) has independently reviewed the data and has recommended conservative "experience spectra" for which equipment would not require qualification (SSRAP, 1984). These spectra represent a factor of safety of about 1.5

from the actual ground motion spectra which the equipment has experienced. The SQUG data and SSRAP recommendations are often currently used to establish HCLPF values for component fragilities.

In an EPRI-sponsored program, Generic Equipment Ruggedness Spectra (GERS) are being established for certain classes of equipment (ANCO, 1985). The GERS are based upon qualification of test data and represent the highest achieved test levels without malfunction. The GERS are defined in terms of local input motion rather than ground motion and are currently being used to establish HCLPF values in terms of local acceleration levels. These values are then translated to ground motion input using transfer functions for the specific structure in which the equipment are mounted. THe GERS program is in early stages and data to date are limited. No organized effort has been made to date to correlate GERS to experience spectra from the SQUG program. A correlation would require transfer functions to represent building response at various elevations.

In support of the Systematic Evaluation Program for older plants, utility groups have sponsored generic fragility tests of cable raceway systems typical of those in existing power plants (URS/JAB, 1983). Data are presented as fatique curves of ductility demand versus number of cycles to failure. These data are very useful in developing generic raceway system fragilities.

Piping system test data (ANCO, 1984) and documentation of piping experience data (USNRC, 1985) confirms the very high piping system capacities that have been developed analytically in prior PRAs. Further work on piping fragility is not considered a high priority item.

The USNRC is currently sponsoring through LLNL, the tabulation of fragility data from completed PRAs in a computerized data base. These data have been developed predominantly from vendor analysis or test reports and most of the derivations have been conducted prior to availability of SQUG experience data and GERS data. The net result is that when uncertainties on each of the variables contributing to the fragility description are consolidated, many of the analytically predicted HCLPF values fall below those that can be currently substantiated by SQUG and GERS data. Many of the lower tails of fragility curves from the earlier studies are felt to be too conservative. These apparent conservatisms have not, however, been the dominant contributors to calculated risk as each plant tends to have a few unique seismic-induced failure modes that overshadow other contributors. In some PRA studies, a second pass has been conducted on fragilities for dominant contributors and usually, a more in-depth evaluation will decrease the uncertainty and, in many instances, raise the median. Decreasing the uncertainty has a particularly beneficial effect in that the predicted risk is often dominated by the portion of the fragility curves from 5% to 20% that correspond to lower level earthquakes of more frequent occurrence (Kennedy, 1984b, 1985).

From the experience gained to date, it is concluded that a second pass on selected fragility derivation is mandatory in order to achieve a more reasonable estimate of the real risk and to reduce the uncertainty bounds on the predicted risk.

RUGGEDNESS RANKING

From experience gained in PRAs and from documentation of historical experience and test data, relative ruggedness of structures and components can be estimated. There are, of course, conditions that apply to the relative ruggedness that must be verified by site inspections, drawing reviews and reviews of design analyses. A panel of experts has prepared a draft seismic margins report in which some relative ruggedness rankings have been made (LLNL, 1985). The rankings are presented in terms of the threshold of earthquake for which a seismic margin evaluation is required. As examples, for earthquakes up to 0.5g peak ground acceleration, the panel recommends that the following types of structures and components need no seismic reevaluation for earthquakes greater than the SSE.

Prestressed and Reinforced Concrete Containment
Piping
Valves
HVAC Ducting

There are some conditions placed on the above recommendations. These recommendations result from both analytical studies and historical data. At the other end of the spectrum, recommendations are made that evaluations should be performed for earthquakes greater than the SSE for the following structures and components even for earthquakes below 0.3g:

Steel Containment (lack of sufficient data available to panel)
Reactor Internals (lack of sufficient data available to panel)
Unreinforced or Lightly Reinforced Block Walls
Heat Exchangers (anchorage and support)
Tanks
Batteries and Racks (anchorage and support)
Soil Liquefaction Potential
HVAC Fan and Cooler Units mounted on Vibration Isolators
Electrical Device Function (relay chatter, breaker trip, and anchorage)

There are provisions by which some of the above may not require detailed evaluations, i.e., a walkdown may suffice. Some of the recommendations for reevaluation stem from a lack of data where other recommendations are made based upon reviews of existing analytical and experience data.

Other components and types of structures fall between these two ground acceleration levels and conditions and restrictions also apply. The rankings are intended in this case to define what types of structures and equipment need to be considered in a seismic margin review and what are the

specific areas of the items upon which the review should concentrate. The concept in providing these guidelines is that the minimum threshold for which a review is required is a HCLPF value of the fragility description.

The above discussions on fragility prediction methods, supporting data base and resulting ruggedness ranking highlight some of the problem areas in developing fragility descriptions and provide some insight as to what future work would be fruitful to better define fragility.

RECOMMENDED FUTURE WORK

From the previous discussions, it is apparent that most ongoing activity is concentrated toward demonstrating minimum capacities of generic classes of components via documentation of seismic experience and qualification data. This activity is most directly applicable to seismic margin issues resulting from postulated earthquakes beyond the design basis or for older plants with no seismic qualification of equipment. In these cases, a single value of hazard is specified and compared to a minimum survival threshold. These data are also extremely useful to define lower tails of fragility curves. A complete fragility curve, however, requires that some fragility testing be conducted. Fragility testing is, however, a very costly procedure and the tests that are conducted must be well-planned to optimize available resources. A fragility test program is being initiated by the NRC and LLNL (Holman, 1985) which should fill in many of the gaps in the current data base. Our own recommendations for a program of this type are provided herein.

Fragility tests should concentrate on active components. Passive components and subsystems are much more amenable to analysis than active components. There are three broad categories of active components to be considered:

- Electrical power distribution components
- Instrumentation and control components
- Mechanical fluid system components

For electrical power distribution components, there are two fragility parameters of interest, the functional capacity of devices and the structural capacity of the cabinets, cabinet anchorage, device attachments or the devices themselves. Evidence to date would indicate that the prime areas of concern are anchorage failures which are non-recoverable failure modes and device function failure modes which are ususally recoverable, with or without operator action. Device functional failure modes are not readily predictable by analysis and testing is the only viable means of developing fragility relationships. Devices may be tested individually or in their supporting cabinets or panels.

Structural failure modes may be predicted by analysis but should be benchmarked by confirmatory tests. As an example, if 4160 volt switchgear is a component of interest, one might test the protective relays and the

switchgear truck individually to determine their failure levels and failure modes, whether recoverable or non-recoverable. The cabinets are somewhat standard and could be analyzed to determine transmissibility and the expected level of anchorage failure or other structural failures. A complete assembly test could then be conducted as a cross-check and confirmation on fragilities derived from the component tests and analyses. This provides information to guide further testing and to modify future fragility analysis methods.

Instrument and control panel fragility tests could be conducted along the same line as for electrical power equipment. A concerted effort should be made prior to conducting device tests to solicit fragility or qualification test data from manufacturers. Many manufacturers may have qualified their devices for very high acceleration levels, in which case, fragility tests are not warranted.

Mechanical fluid system components such as pumps and valves are quite rugged and are usually qualified by analysis. Analysis is not, however, a good indicator of real capacity as, in most cases, usually very conservative limits are arbitrarily defined as failure. Examples are shaft deflection causing rubbing of pump wear rings, yielding of a valve operator support, yielding of a pump casing, etc. Fragility tests of mechanical fluid system components are extremely expensive and, due to the large variety of such components, tests must be carefully thought out. A very valuable guide to determining what types of components should be tested would be to conduct a thorough review of the SAFEGUARDS fragility test data to rank component capacities, or, as was usually the case, determine what levels the components would survive. As described previously, the SAFEGUARDS tests were of short duration with less energy content than an earthquake time history that would result in an equivalent response spectrum. By considering energy content of the SAFEGUARDS input motion and energy content of earthquake motions, scale factors for ductile components could be developed to estimate the fragility level or the achieved test level for an equivalent earthquake motion. This exercise could eliminate many types of components from fragility testing by demonstrating that capacities are above any credible level of concern. Then, a manageable number of fragility tests could be planned and conducted with confidence of obtaining meaningful data.

In conducting fragility tests, it is not necessary to test to the extent that precise fragility curves are defined. It is necessary though to develop sufficient data to make reasonable estimates of median capacity and to establish lower bounds on capacity. Well-planned test programs can aid in establishing approximate capacities and failure modes for selected classes of equipment. The continuing effort on gathering earthquake experience and qualification test data can define the lower tails of the fragility curves. From these data, sufficient information should be present to greatly increase the credibility of PRAs and seismic margin studies as well as support the continued use of unqualified equipment in older plants.

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SAFETY CAPACITY CONCEPTS FOR NUCLEAR PLANT EQUIPMENT QUALIFICATION

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ABSTRACT

Safety capacity concepts are considered for use in generalization of nuclear plant equipment qualification procedures. The objective is an eventual increase of efficiency and reduction of cost for the equipment qualification process. A general definition of fragility is given and its relationship with several currently considered safety capacity concepts is described. These include equipment fragility as defined in Standard IEEE 344, probabilistic fragility, generic equipment ruggedness, and safety margin. Typical parameters for determination of the respective safety capacities are included. The general fragility definition is recognized to be applicable to all types of environments. However, herein emphasis is on dynamic, and particularly on seismic effects on equipment. Recommendations for further research and development of these concepts are discussed.

INTRODUCTION

Methods for seismic qualification of nuclear plant equipment have progressed over the last fifteen years, and much equipment has been qualified to various design levels. Most of the efforts have included proof test methodology [1], whereby equipment operation is verified for given site specific excitation spectra. Efforts to update this methodology have also been in progress [2]. More recently, there has developed an increasing trend to include the use of previous qualification data and actual earthquake experience data to reduce duplication of efforts and to seek more generic qualifications. These efforts have invariably led to a desire to determine the ultimate performance levels of equipment to demonstrate the degree of conservatism present in previous qualifications.

The trend toward use of existing data has been especially evident in attempts to verify previous equipment qualifications under newer criteria, although the approach is equally as useful for newer equipment. General guidelines for qualification by use of existing data have been available since 1975 [1]. They rely on establishment of similarity of the specified excitations and in many cases on the equipment dynamic characteristics as well. However, detail procedures for using this approach have only been evolving more recently. Some of these procedures are based on what for the purpose of this paper, will be called safety capacity concepts.

Safety capacity may be defined as a measure of the ultimate natural or operational environmental challenge level under which an operating unit can

perform its safety function. It may be expressed directly in terms of the challenge level itself, or by a comparison of the ultimate level with a lower design working level. It is useful for describing the capability of a single device, a multi device component, or even the entire nuclear plant. It may further include the influence of various typical environments. The need for estimating such safety capacities is obvious. However, methodology for their measurement and interpretation of the relationships between overall plant and equipment capacities is currently very much in a state of development, and details are being studied by various organizations. The purpose of this paper is to concentrate on a review of several developing concepts for determining safety capacity of equipment under seismic environments, and to explore the relationships among them. However, much of the discussion can be further related to overall plant seismic safety capacity as well.

GENERAL FRAGILITY DEFINITION

Currently some confusion exists over the definition of fragility and no uniform agreement exists on how it is to be measured. A general definition of fragility may be used in several measures of safety capacity, and it is therefore appropriate to attempt to resolve some of the confusion. One of the most general descriptions of dynamic fragility has been discussed by Roundtree and Safford [3], and is shown in Figure 1 as a fragility surface. Note that the surface can be represented as the function

$$F_{xy}(f,t) = M_F(f,t) \qquad (1)$$

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

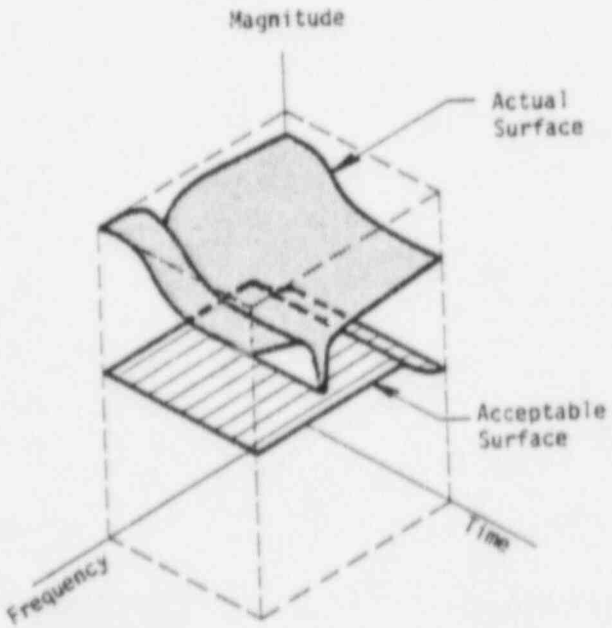

FIGURE 1. GENERALIZED DYNAMIC FRAGILITY SURFACE

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.

In accordance with Equation (1), 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. 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 distribution 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.

For some systems the fragility mechanisms are independent of time, so that the surface given by Equation (1) reduces to a fragility function given by

$$F_{xy}(f) = M_F(f) \qquad (2)$$

This type of dynamic fragility can be called a nonaging process. Fortunately, much equipment used in nuclear plants (except that which is subject to metal fatigue) essentially falls into this category. Note however, that consideration of thermal, radiational, and operational environments will not generally allow this simplification. The above general description of fragility has been employed as the basis for comparisons of proof test severities in earlier work [4], and a review of the role of fragility in equipment qualification and design [5].

EQUIPMENT FRAGILITY

Definition

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 of a specific motion 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 level of the motion. 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 equipment 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 test 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, and for providing a methodology for more efficient equipment qualification. Therefore, a review of all aspects of equipment fragility and its use in nuclear plant design and qualification is in order.

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). 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 cwells, slowly swept sine waves, sine beats, and narrowband (i.e., less than 5 Hz) random time histories. Amplitude for this type excitation is usually measured in terms of peak or RMS values. This form of excitation 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.

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 acceleration excitation time history. It is also the high frequency asymptote of the

response spectrum computed for that time history. Thus

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

Root Mean Square or RMS is the acceleration computed from

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

or

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

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

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

the exact value depends on whether the averaging period T is for strong motion only or for the entire event [6].

Response Spectrum is the usual seismic acceleration parameter computed at some resolution bandwidth and damping. Herein we use spectral acceleration $S_a(f)$. Thus, the particular test response spectrum (TRS) at malfunction becomes the fragility response spectrum.

Power Spectral Density or PSD is the mean square acceleration density 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 that that for the entire event. Note that a transformation from response spectrum to PSD and its inverse is available from earlier work [7]. 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 [4]. However, the above four are considered to be most practical. Because of the confidentiality of qualification data, it is difficult to establish which of these four parameters has been most utilized for measurement of equipment fragility. It is probably safe to guess that the response spectrum associated with equipment qualification is the most likely. For this case it is important to remember that most such required response spectra are site specific. Therefore, use of such fragility response spectra at other site or floor locations must be done with considerable care. That is, the frequency content of the spectrum is extremely important for flexible equipment, as will be described hereafter.

Typical Fragility Functions

The nature of a fragility function is, or course, dependent on the type of malfunction mechanism involved, the structural dynamic characteristics of the device, and the type of excitation used during the measurement. It appears that for our purposes, equipment of concern can be considered one of three types:

1) Rigid Threshold
2) Simple Flexible
3) Complex Flexible

Fragility functions for each of these 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 device would look like Figure 3. A simple flexible device is one which includes only a single effective resonance (at which the fragility function experiences a significant minimum value), or if multiple resonances are present (i.e., multiple minima occur) no modal interaction takes place. For this case the narrowband fragility function amplitude can also be measured either by peak or RMS value. Note also that the shape of the curve in Figure 3 would be similar to that for the envelope of the peak spectral value, if spectral amplitude of the narrowband input were used for the measurement.

Example fragility functions for broadband excitation of rigid threshold and simple flexible devices are shown in Figures 4 and 5, respectively. The non-uniqueness of such fragility functions is emphasized in these figures. For example, a rigid threshold device which is sensitive to peak excitation will malfunction at its peak fragility level (i.e., the ZPA of the excitation signal), no matter what the frequency content, as shown in Figure 4. Note also for this case that the device would not be responding to a constant RMS at the same time, for each of the three response spectra have a different amount of amplification above the ZPA (for the same damping). This indicates that the RMS values for each of the excitations is correspondingly different even though the peak values are identical.

The above comments about non-uniqueness are actually true for both narrowband and broadband excitations, so long as the specimen is a rigid threshold type device. However, the non-uniqueness characteristic is even more acute for a broadband fragility function generated for a simple flexible device, as indicated in Figure 5. The envelope of a narrowband

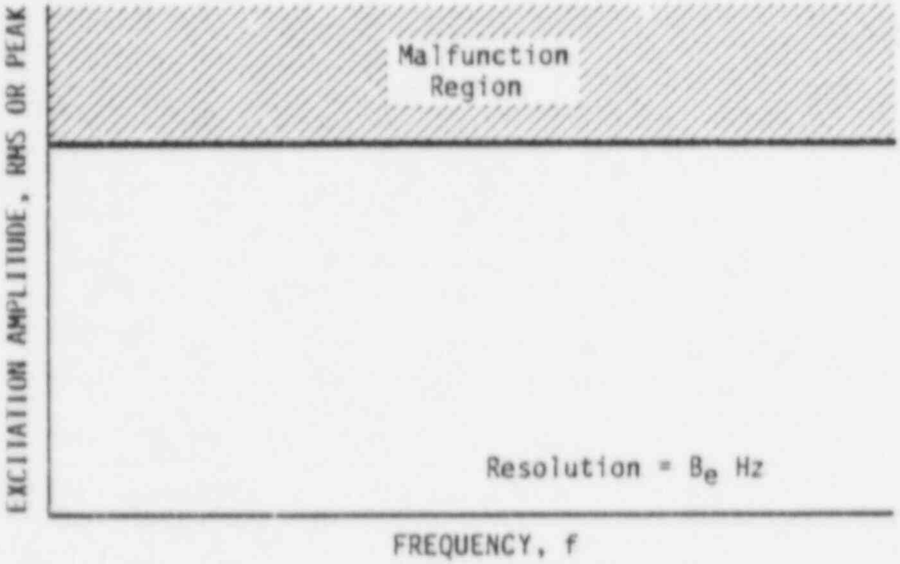

FIGURE 2. NARROWBAND FRAGILITY FUNCTION FOR RIGID THRESHOLD DEVICE

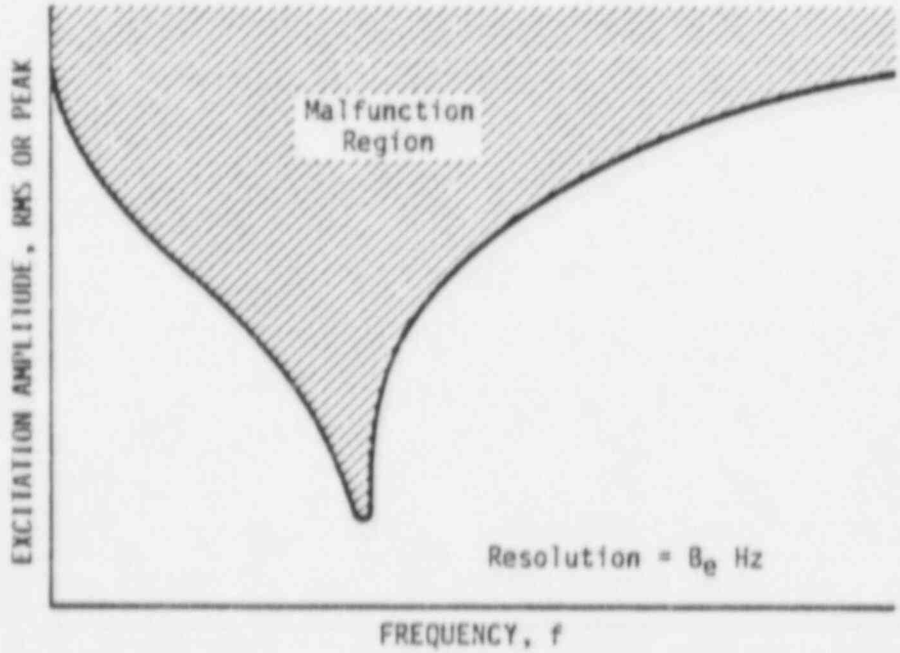

FIGURE 3. NARROWBAND FRAGILITY FUNCTION FOR SIMPLE FLEXIBLE DEVICE

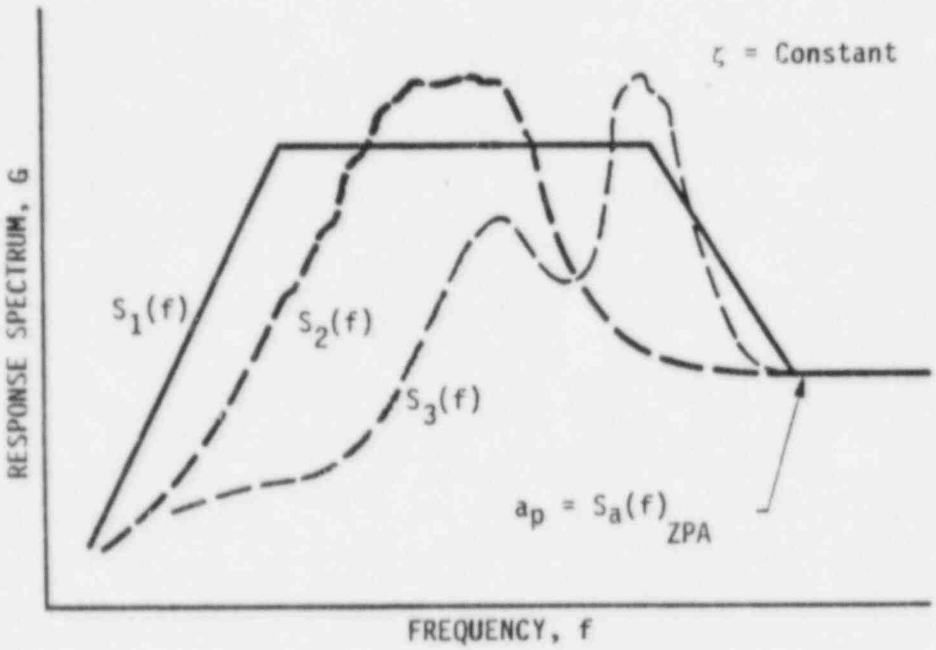

FIGURE 4 BROADBAND FRAGILITY FUNCTIONS FOR RIGID THRESHOLD DEVICE

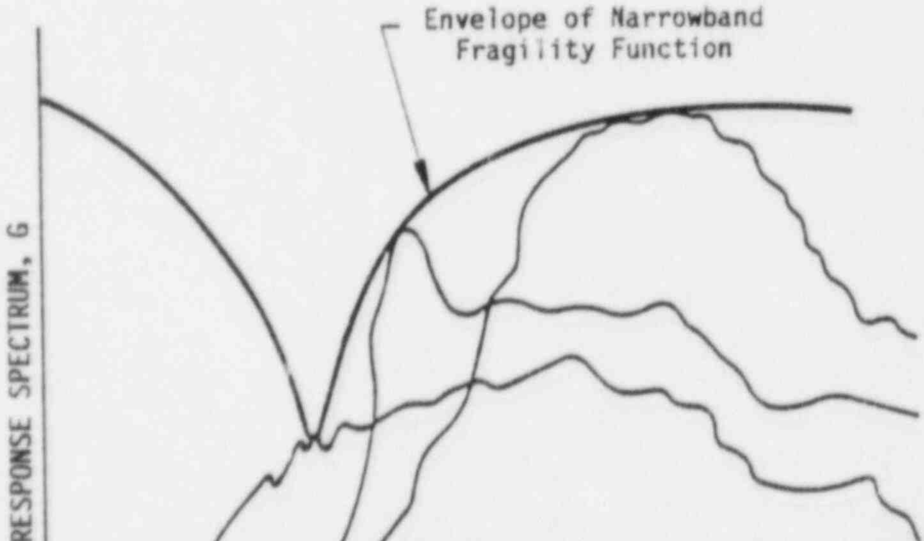

FIGURE 5 BROADBAND FRAGILITY FUNCTIONS FOR SIMPLE FLEXIBLE DEVICE

fragility function, which is measured as a TRS, is shown first. Then three significantly different test response spectra, each representing a broadband excitation of different frequency content and RMS amplitude are also shown. Note that each spectrum touches the narrowband fragility function envelope at a different frequency. Thus, each of the significantly different response spectra represents a broadband fragility function for the device. The importance of frequency content, its role in site and floor specific spectra, and its influence on the definition of fragility level is very apparent from this figure. This behavior is even more pronounced for devices in which multimode interaction occurs.

In the above discussion both multimode interaction and potential effects of spatial orientation of the excitation relative to the axes of the specimen have not been included. If the specimen includes multiple modes and failure by modal interactions occurs, then it is referred to as a complex flexible device. For such a device, 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, so that the most practical approach to fragility measurement for this type device is to use an excitation whose spectral shape is proportional to the site specific response spectrum at the mounting location. 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. This is shown conceptually in Figure 6. 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 othogonal axis of excitation.

PROBABILISTIC FRAGILITY

The forms of fragility functions described 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 probabilistic fragility curves, which can be used in the overall probability risk analysis (PRA). Azarm, et al [8] have performed a recent review of this concept. Equipment and other fragility functions which serve as inputs to this analysis must be obtained by transforming the above forms of fragility functions to probabilistic fragility distribution as shown in Figures 7 and 8.

The probabilistic fragility distribution 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 as

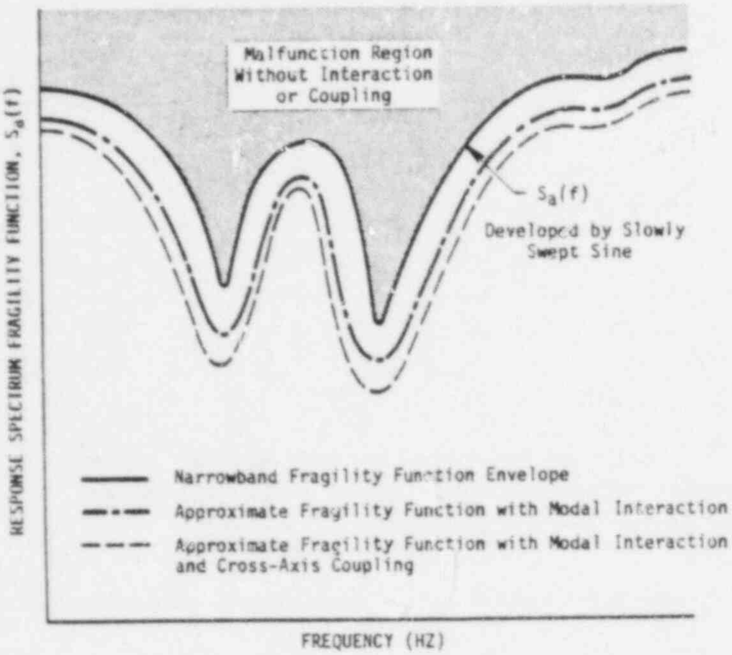

FIGURE 6. FRAGILITY FUNCTIONS FOR A COMPLEX FLEXIBLE DEVICE

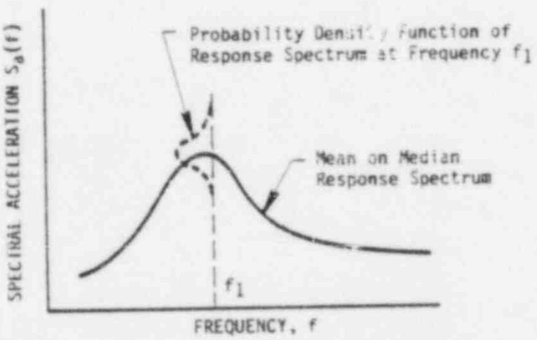

FIGURE 7. UNCERTAINTY OF FRAGILITY RESPONSE SPECTRUM

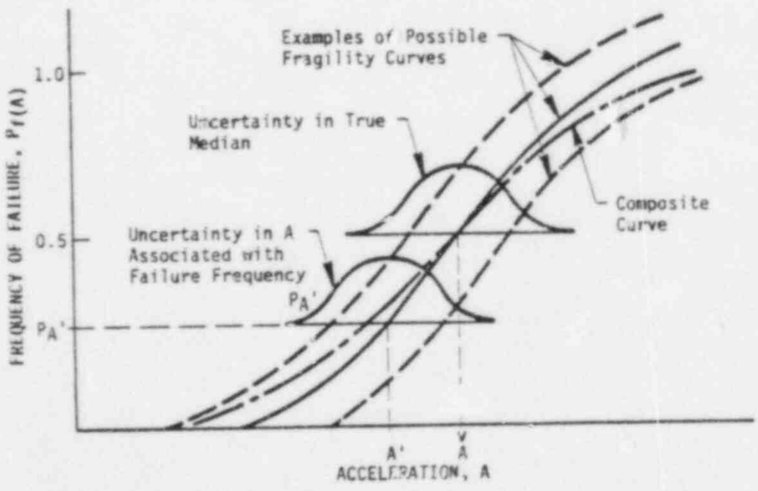

FIGURE 8. PROBABILISTIC FRAGILITY AND ASSOCIATED UNCERTAINTIES

that considered to be the fundamental critical resonance frequency (or frequency range) for the given item. The probability density function of Figure 7 is then 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 [9]. These uncertainty factors were established by judgment from review of test, analysis, and other available data for a variety of equipment. They can be used to draw probabilistic fragility curves, such as shown in Figure 8 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

$$P_{f(A)} = \Phi[(1/\beta_c) \ln (\hat{A}/A)] \quad (7)$$

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

$$\beta_c = [\beta_R{}^2 + \beta_u{}^2]^{1/2} \quad (8)$$

The median acceleration capacity $\hat{A}$, and the random factor β_R and uncertainty factor β_u are all given in tables of Reference [9]. 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.

It is important to recognize that the assumption of the existence of a fundamental critical resonance, as described above, is equivalent to saying that the item of concern is a simple flexible device; that is, the existence of multimode interaction is incompatible with this concept. Furthermore, the critical frequency f_1, in Figure 7 is therefore comparable to the frequency of minimum excitation amplitude for the fragility function shown in Figure 3. Generally, the assumption of non-interaction of multiple modes is contrary to the requirements of IEEE 344 [1], unless otherwise justified.

GENERIC EQUIPMENT RUGGEDNESS

Since relatively little fragility data has been acquired for equipment in the past, it is appropriate to consider to what extent existing qualification or actual earthquake experience data can be used as a measure

of safety capacity. To this end, by referring back to Figure 1, this question can be answered by letting the most severe experience data available become an approximate acceptable lower bound fragility function. This approach has been used for comparing severities of different type tests in the past [4]. A somewhat similar approximate concept has recently been developed into what are called Generic Equipment Ruggedness Spectra [10].

An example of such an approximate approach is given in Figure 9. Suppose that a device has previously been qualified by the TRS given as $S_1(f)$, and on another occasion by $S_2(f)$. A question is, under what conditions can this information be used to argue that the device is therefore already qualified to the new spectrum $S_3(f)$, which falls within the envelope of $S_1(f)$ and $S_2(f)$? This envelope may be referred to as the generic equipment ruggedness spectrum. In view of the previous discussion, it becomes apparent that qualification to $S_3(f)$ is valid providing that the device can be argued to be one of the rigid threshold, or at least the simple flexible type. It may also apply to a complex flexible device, if the lowest resonance present is above the cut off frequency of $S_3(f)$. Furthermore, the envelope of $S_1(f)$ and $S_2(f)$ may be assumed to be a lower bound fragility function under these conditions.

The next step is to consider a case for which $S_1(f)$ represents a TRS for one device and $S_2(f)$ a TRS for a second, but similar device. Can the envelope of $S_1(f)$ and $S_2(f)$ be used to constitute qualification for a third device that is similar to the first two? According to the similarity approach defined generally in IEEE 344 [1], the answer is yes! However, the pertinent question is what constitutes similarity? In view of the previous discussion, similarity essentially means similarity of dynamic response characteristics and malfunction mechanisms. In other words, similarity means approximately similar fragility functions. The use of the lower bound approximate fragility function appears to be a means whereby the similarity argument can be used effectively.

SAFETY MARGIN

Equipment safety margin may be defined as the difference between equipment fragility and some proposed design level, such as that for the safe shutdown earthquake (SSE). Therefore, as shown in Figure 10 for a simple flexible device, safety margin is a function of frequency, if it is measured in terms of <u>spectral</u> acceleration. However, it is more convenient to measure it in peak acceleration (ZPA) level, and represents the amount (in peak g's) that the excitation must be increased before the proposed spectrum equals the fragility function spectrum at any frequency. This definition is therefore dependent on the site specific response spectrum at the mounting location of the device. Nevertheless, this approach is consistent with typical equipment qualification procedures. Thus, it is understood that quotation of safety margin in terms of peak g alone is inadequate, unless it is for a rigid threshold device. Furthermore, as shown for a simple flexible device in Figure 10, the frequency content of the proposed spectrum $S_1(f)$ is extremely important, so that the frequency f_c

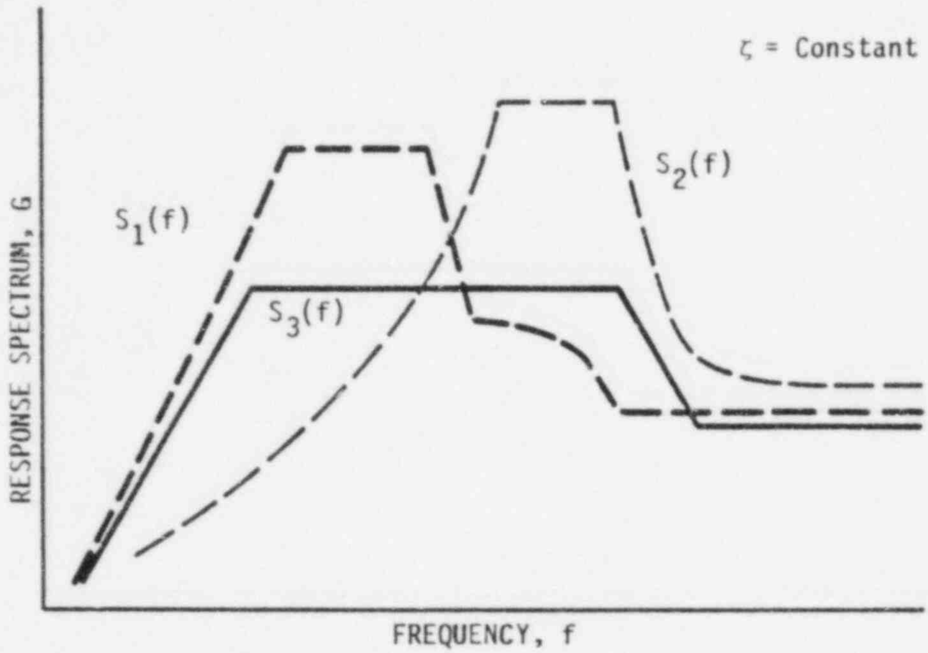

FIGURE 9. DEVELOPMENT OF GENERIC EQUIPMENT RESPONSE SPECTRA

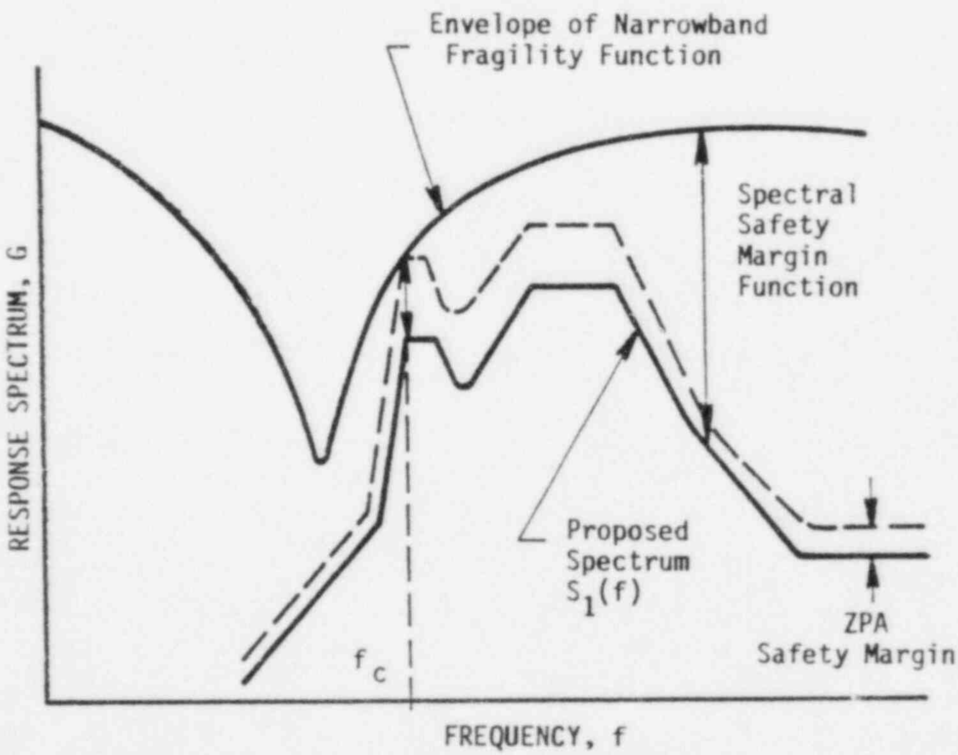

FIGURE 10. SAFETY MARGIN FOR SIMPLE FLEXIBLE DEVICE

of intersection of $S_1(f)$ with the fragility function may not be at the frequency for the minimum point of the fragility function.

For complex flexible equipment the approach to measurement of safety margin requires particular care. If the broadband fragility response spectrum is based on an excitation whose spectral shape is proportional to the site specific RRS, then determination of safety margin is simple. It is the difference between the fragility function ZPA and the SSE ZPA. However, it is rarely possible to produce a TRS that is exactly proportional to a given RRS at all frequencies, so some judgment must be exercised. If the broadband fragility response spectrum does not have the site specific shape as described above, then additional judgment must be exercised. At this point there is some thought to use a standard shape, such as that of R.G. 1.60 ground motion, to make such fragility measurements.

DISCUSSION

Four types of equipment safety capacity concepts have been described, each of which relates seismic excitation level to the ultimate equipment safety function level. All are related to the general definition of dynamic fragility in one form or another. All are also site specific in one form or another, because of dependence on frequency content and peak excitation amplitude. All are also in a very early stage of development, so that much needs to be done to validate their application to equipment qualification and design. Furthermore, in some cases, general agreement in the engineering community does not exist for their definition or use at this time.

Classification of equipment into one of these categories: rigid threshold, simple flexible, or complex flexible, appears to be central to an understanding of any of the safety capacity concepts. Once this is done, the nature of measurement parameters and relationships between safety capacities for groups of equipment can be determined.

This paper has concentrated on safety capacities applied to equipment. However, for any one of the four concepts, a similar overall plant safety capacity is made up of the aggregate of those for the equipment and subsystems. Therefore, the procedures for combining equipment safety capacities into a subsystem, and ultimately to that for the total plant are of great interest. For this methodology, perhaps, the most important factor to bear in mind throughout is the limitations and assumptions associated with each type of description for safety capacity and realize that the final value computed for the entire plant is no better than the weakest assumption associated with any individual item of equipment.

It is recommended that virtually all areas of the concepts discussed herein and their relationships to overall plant safety capacity be studied with vigor, as they show promise for eventual simplification of the equipment qualification process. It is especially pertinent to evaluate the limitations of each of the concepts, so that the degree of consistency among

them can be established.

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THE ELEMENTS OF FRAGILITY MODELS

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ABSTRACT

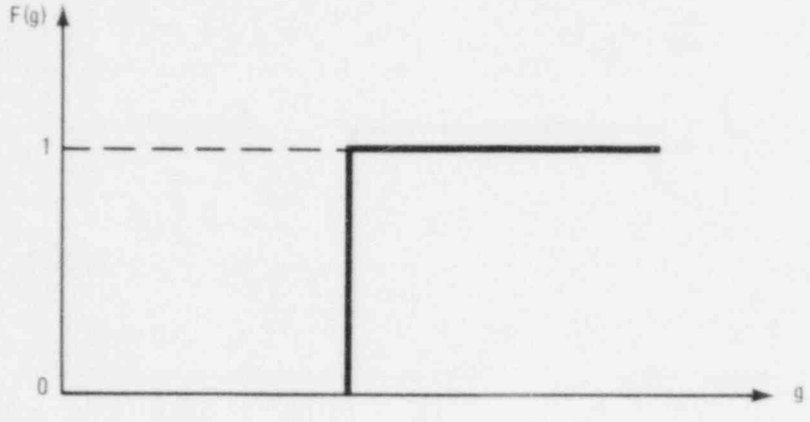
In order to provide a common basis for conducting uniform fragility analyses, the following five basic elements of fragility models are identified and discussed: risk presentation, failure modes, analytical form of the fragility curve, evaluation of fragility curve parameters and assembly of component fragilities into a system or a plant fragility. The importance of every element of the fragility model is demonstrated and its impact on core melt probability for a generic nuclear power plant is discussed.

INTRODUCTION

Seismic Probabilistic Risk Analysis (SPRA) could prove to be important to the assessment of the overall safety of nuclear power plants considering the potential ability of earthquakes to incapacitate simultaneously several safety graded systems. The evaluation of component fragilities and their assembly into the plant fragility is a significant part of the SPRA. Therefore, providing a common basis for conducting a fragility analysis will be beneficial for future SPRA's.

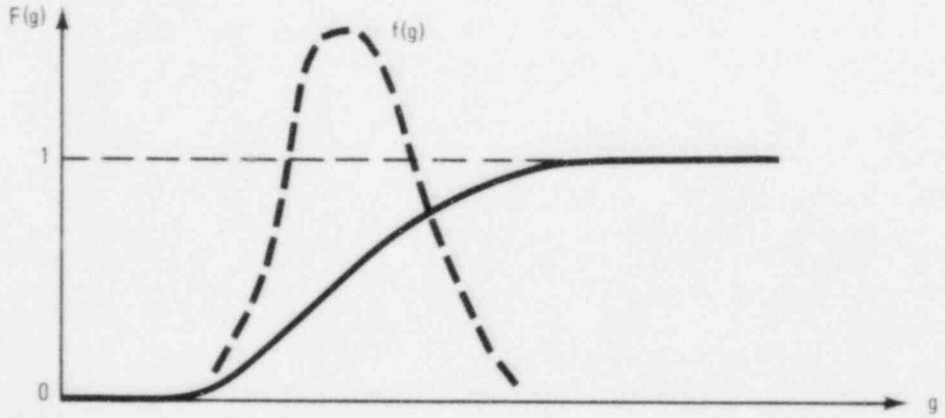
In current PRA analyses every component can exist only in two states: success or failure states. The failure of a component means a failure to perform its function. The use of the two-state approach is dictated by Boolean Algebra and the fault tree analysis technique. In reality, it is not always easy to separate success and failure states, for example, reduced rated flow, and some attempts to broaden the methodology by using multiple states technique are underway [1]-[3]. However, all these methods are in a too early developmental stage to consider them seriously at the present. Therefore, we will base our present discussion on the two-state approach.

The failure of a component may occur at some value g of the failure indicator G which is a parameter associated with a loss of function. The cumulative probability of failure F(g), called a fragility curve, is presented in Fig. 1a. This curve presumes that for identical components failure always occurs at the same value of the failure indicator. However, in actual tests, even so-called "identical" components would fail at different values of the failure indicator g. Therefore, the value of the failure indicator g at which a component fails is random with a density function $f_R(g;\theta)$ where θ is a set of parameters like mean, standard



a)

FAILURE INDICATOR VALUE AT WHICH
FAILURE OF A COMPONENT OCCURS IS EXACT



b)

FAILURE INDICATOR VALUE AT WHICH
FAILURE OF A COMPONENT OCCURS IS RANDOM

Figure 1
FRAGILITY CURVES

deviation, skewness, etc. This function and a corresponding cumulative function $F(g)$ are presented in Fig. 1b. The variability of the failure indicator value at which a failure occurs is referred to as randomness.

Parameters θ could be found from test data. Because of the finite size of the existing data base, there is some uncertainty in parameters θ. If we measure a failure indicator indirectly or base it on expert judgement, then additional uncertainty exists due to the vagueness of the relationship between a measured variable and a failure indicator. We may quantify this uncertainty with a distribution density function $f_U(\theta)$. The set of fragility curves with a different likelihood due to uncertainty is shown in Fig. 2.

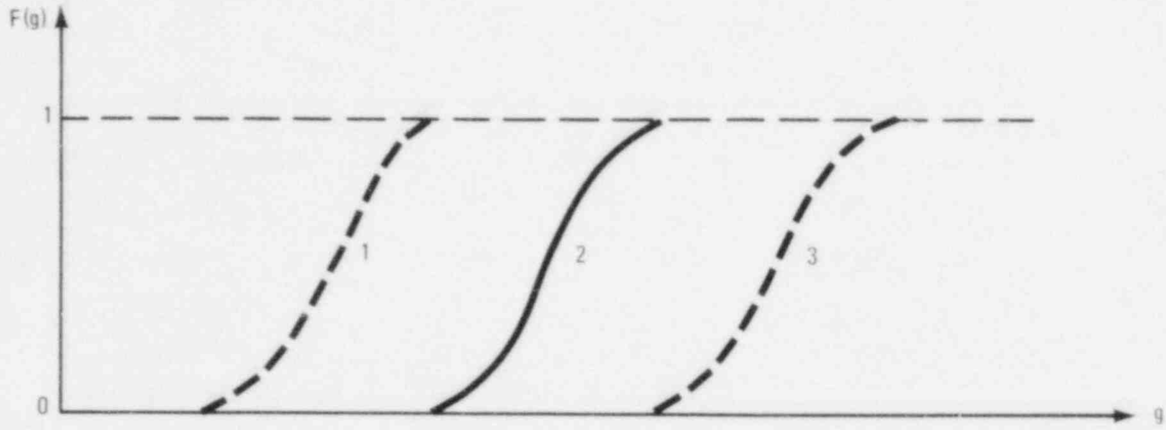
The set of rules and methods for calculation of component fragilities with randomness and uncertainty and assembling them into a plant fragility is called a fragility model. The five basic elements of the fragility model are discussed below.

Fragility curves are then convolved with the seismic hazard curves to determine probabilities of damage states. This convolution can be accomplished if both the hazard and fragilities are mapped to the same parameter. The choice of the peak ground acceleration as this common parameter assumes that the fragilities of components include the effects of the transfer functions of the supporting systems and structures. The choice of the peak support acceleration as the common parameter assumes that the hazard curves include the transfer function of the supporting system and structures.

RISK FORMATS AND FRAGILITY PRESENTATION

Different ways of risk presentation with randomness and uncertainty are called risk formats [4]. If the risk probability is presented as a mixed distribution reflecting both randomness and uncertainty, the presentation is called an M-format. If we estimate an expectation of all uncertainty parameters with a corresponding distribution (a U-distribution), the final risk probability will be a distribution of randomness (an R-distribution). We call this presentation an R-format. If we estimate an expectation of all random parameters with an R-distribution, the final risk probability will be a U-distribution. We call this distribution a U-format. It is also known as a probability-of-frequency format [5]. If we estimate an expectation of all random and uncertainty parameters, the final risk probability will be the total expectation and we call it a T-format.

Handling of fragilities is different for different risk formats. In the M-format we have to know the M-distribution $f_M(g)$ of the failure indicator. In case this is not readily available, it can be easily derived from distributions $f_R(g;\theta)$ and $f_U(\theta)$. The distribution $f_M(g)$ is a maximum variability distribution reflecting both randomness and uncertainty. This type of the format for SPRA was used in [6]-[7].



1 = LOWER CONFIDENCE FRAGILITY
2 = MEDIAN CONFIDENCE FRAGILITY
3 = UPPER CONFIDENCE FRAGILITY

g = FAILURE INDICATOR
F(g) = FRAGILITY FUNCTION

Figure 2
FRAGILITY CURVE FAMILY

In the U-format we use cumulative probabilities $F_R(g;\theta)$ to calculate the expectation of the risk given parameters θ (and corresponding parameters for the hazard curve) and then we present the distribution of risk expectation induced by function $f_U(\theta)$ and its counterpart for the hazard curve. This format is used in most current SPRAs [8]-[13].

In the R-format we have to know the function $f_R(g;\bar{\theta})$ for the best fitted parameters $\bar{\theta}$. Otherwise, the procedure of the risk calculation is similar to that for the M-format. In both cases we use a hazard density function for generations of the risk distribution. Additionally, in the M-format we use the U-distribution of parameters of fragility and hazard curves.

In the T-format we use functions $f_R(g;\theta)$ and $f_U(\theta)$ (or $f_M(g)$, or $f_R(g;\bar{\theta})$) for the calculation of the total expectation of risk.

The relationship between different formats is shown in Fig. 3. If the risk distribution presented in the M-format is integrated over all uncertainty parameters (best fit of parameters) then it will result in the R-format. If the M-format risk distribution is integrated over all random variables (conditional expectation), then it will result in the U-format. Accordingly, the integration of the R-format risk distribution over uncertainty parameters or the U-format risk distribution over random variables will result in T-format (total expectation).

The choice of the format depends on the objectives of the analysis and available data. If we need just a number for risk comparison, then the T-format will be appropriate. If our decision-making process takes into account explicit distribution of uncertainties, then the U-format is needed. If we are looking at the actual variability of the risk at the specific plant site (assuming a large and perfect data base), then the R-format will provide the answer. However, if we are looking at the potential variability of the risk at the plant site due to randomness of natural phenomena and uncertainty in data, then we have to use an M-format risk presentation. Since in practice only sparse fragility data are available, a separation of variability into randomness and uncertainty becomes somewhat artificial and presents some difficulties in using both the R and U-formats. A forced use of these formats in such circumstances might lead to some misinterpretation of results.

FAILURE MODES

Usually, there are several mechanisms which can lead to the loss of function of a component. Each mechanism may result in one or several damage scenarios resulting in different damage states. Every damage state may or may not result in the loss of function, or component failure. Sometimes, it depends on the system function goal within a specified accident scenario. Therefore, there are many different ways of the loss of function for a component. A failure mode is considered to be a characteristic pattern of behavior or sequence of events which result in the loss of function.

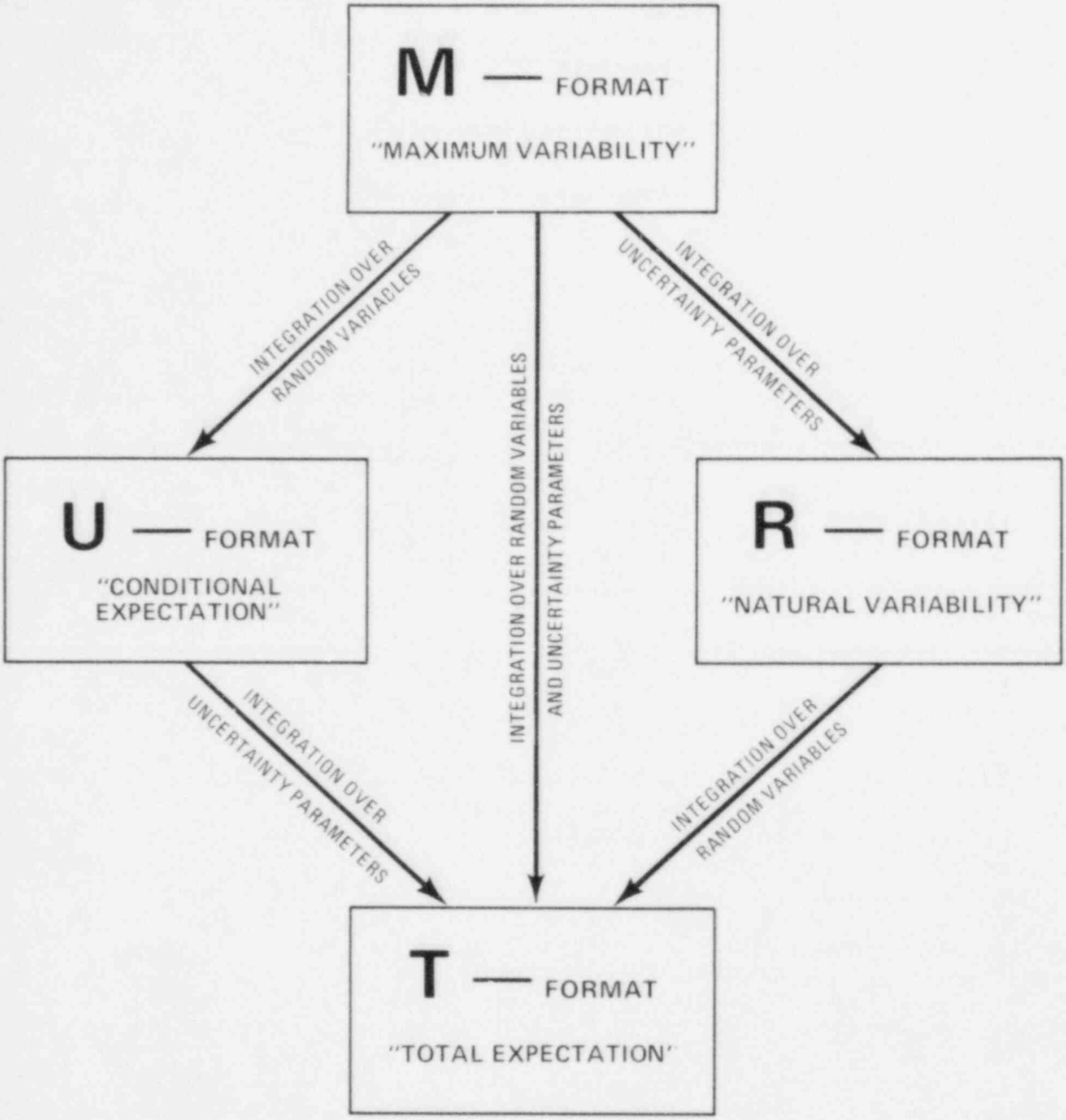


Figure 3
RELATIONSHIP BETWEEN RISK FORMATS

Different types of failure modes for nuclear power plant components are discussed in [14]. For example, for a motor actuated valve, Kennedy and Ravindra considered the following failure modes:

(1) Failure of power or controls to the valve

(2) Failure of the motor

(3) Binding of the valve due to distortion and thus failure to operate

(4) Rupture of the pressure boundary

When concrete failure data are not available, the failure mode analysis becomes very important. The purpose of such analysis is to identify all potential failure modes and then the one which is not likely to be caused by the seismic event. If we overlook the leading failure mode, it may lead to the overestimation of component serviceability and, in some instances, to the risk assessment error. Therefore, the failure mode analysis requires high qualification and knowledge of equipment and clear understanding of which failure mode is relevant to the final failure of the top event.

In some cases, there is a finite probability that a component might survive one failure mode and fail at the next one. In these situations the fragility curve takes a rather peculiar form which cannot be treated with a conventional fragility model. Some possibility for the two-failure mode model is presented in Fig. 4. This type of fragility curve cannot be described with a simple functional form.

Another complication appears when we have several failure modes described with multidimensional failure indicators. In this case, instead of a fragility curve, we will have a fragility surface. For a two-dimensional case, a fragility surface is shown in Fig. 5. If two failure modes have one failure indicator in common, then a rank of these modes will depend on values of other indicators and, therefore, may change depending on environmental conditions (for example, failure modes associated with fatigue and creep).

ANALYTICAL FORMS OF THE FRAGILITY CURVE

Discussions of analytical forms of fragility curves are important because they affect the sensitivity of seismic risk calculations.

Fragility F(g) can be presented through a fragility density function f(g) according to the formula:

$$F(g) = \int_{g_{min}}^{g} f(g')dg' \qquad (1)$$

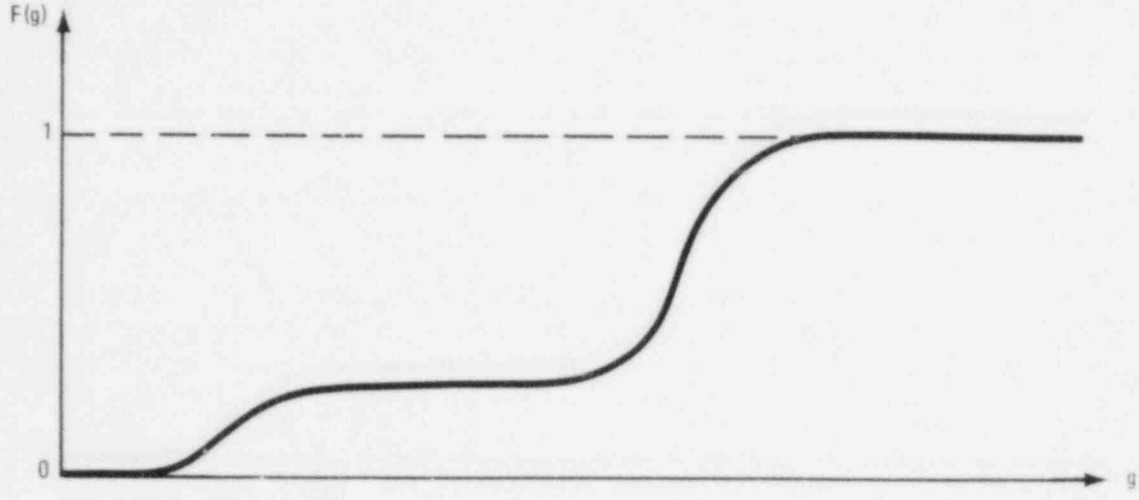


Figure 4
TWO-MODE FRAGILITY CURVE

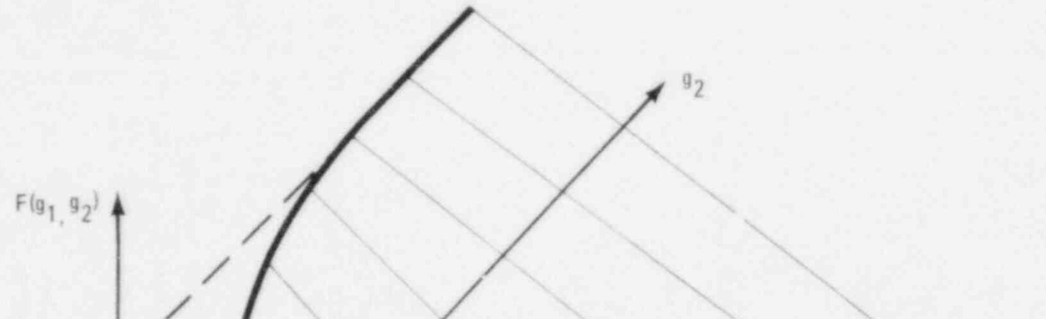


Figure 5
TWO-DIMENSIONAL FRAGILITY SURFACE

The earliest "statistical" approach (see discussion in [15]) assumed that the failure indicator value g corresponding to the component failure is a random number characterized with mean μ and standard deviation σ and, therefore, should comply with the normal distribution:

$$f(g) = \frac{1}{\sqrt{2\pi}\,\sigma} \exp\left\{-\frac{1}{2}\left(\frac{g-\mu}{\sigma}\right)^2\right\} \tag{2}$$

However, an "engineering common sense" cannot accept nonzero probability for the negative value of the failure indicator g which is positive in most cases (for example, peak ground acceleration a). This problem becomes urgent because of the large standard deviation due to uncertainty of data.

In recent SPRA studies [8]-[14] this problem was circumvented by using the lognormal distribution with logarithmic mean u and standard deviation σ:

$$f(g) = \frac{1}{\sqrt{2\pi}\,\sigma\, g} \exp\left\{-\frac{1}{2}\left(\frac{\ln g-\mu}{\sigma}\right)^2\right\} \tag{3}$$

Mathematically the lognormal form is very convenient and conforms well with the method of data analysis employed in [14]. However, in our opinion, the tails of the lognormal distribution are inappropriate because the failure of a component cannot occur below some lower limit g_{min} and always occurs above some upper limit g_{max}. Supporters of the lognormal distribution recognize this fact and have proposed the use of a truncated lognormal distribution [14].

Another approach to the selection of the fragility analytical form was developed in [16]. According to this approach the analytical form of fragility should provide maximum entropy (or uncertainty) given our present knowledge. If only the mean and standard deviation of the random failure indicator g are known, then the distribution which maximizes entropy is the normal distribution. If the additional knowledge is included that the failure indicator g is essentially a positive number, then the lognormal distribution maximizes the entropy. However, if our knowledge is enough to state that the failure indicator is confined within finite limits g_{min} and g_{max}, then the corresponding distribution for the fragility curve which maximize entropy is a Johnson [17] distribution:

$$f(g) = \frac{g_{max} - g}{\sqrt{2\pi}\,\sigma(g-g_{min})\,(g_{max}-g)} \exp\left\{-\frac{1}{2}\left[\frac{\ln\left(\frac{g-g_{min}}{g_{max}-g}\right)-\mu}{\sigma}\right]^2\right\}, \tag{4}$$

where $g_{min} \leq g \leq g_{max}$

This distribution satisfies simultaneously "statistical" and "engineering common sense" approaches. Engineers are comfortable with a finite interval of the failure indicator where component failure may occur and statistically are satisfied with the fact that the Johnson distribution is the generalization of the normal distribution for a finite interval.

EVALUATION OF FRAGILITY CURVE PARAMETERS

Data for evaluation of fragility curve parameters are vague and sparse and, therefore, the classical statistical approach for parameter estimation is not applicable. The only method practically employed in current SPRAs is a safety factor method developed in [12], [14]. This method heavily relies on design-analysis data, shock-test results by the U.S. Army Corps of Engineers and expert opinion.

The failure indicator chosen in current SPRAs is a peak ground or peak floor acceleration, a, which considers with global or local hazard variable. The relationship between safety factor F and failure indicator a is given by Equation 5:

$$F = \frac{a}{SSE} \tag{5}$$

where SSE stands for the safe-shutdown-earthquake of each acceleration.

According to the safety factor model, the random value F for the safety factor is the product of several random variables:

$$F = \prod_{i=1}^{K} F_i \tag{6}$$

For example, for structures these factors include the strength factor F_S, inelastic-energy-absorption factor F_μ, and structure-response conservation factor F_{RS}. For equipment it is also necessary to add several more factors.

Because the multiplication of many random variables tends to be asymptotically lognormal, it is logical to assume that every factor is a lognormal random variable. Based on available information, three parameters - median F_i and two logarithmic standard deviations $\beta_R^{(i)}$ and $\beta_U^{(i)}$ responsible for randomness and uncertainty - have to be determined. Combining all factors together according to formula (6) and using the definition (5), the parameters for a family of fragility curves for a component - A, β_R, β_U - are found.

In spite of the success and advantages of the above method, some current criticism has been expressed [18], [19]. The major point of this criticism is that parameters β_R and β_U heavily depend on expert opinion. We can add

to this that breakdown of total variability of the safety factor into randomness and uncertainty is somewhat artificial because there are no real test data for many cases.

Recently some alternative approaches were discussed. The method of quantification of expert opinion was considered in [20]. The method of likelihood density function for evaluation of parameters of fragility curves for sparse data was proposed in [21].

ASSEMBLING OF COMPONENT FRAGILITY

To assemble component fragilities into a system or a plant fragility we have to develop a corresponding fault free and to find all minimum cut sets. Then a top event T corresponding to failure of a system or a plant can be presented through basic events $C_j^{(i)}$ corresponding to the failure of a component as:

$$T = \sum_{i=1}^{n} \prod_{j=1}^{k_i} C_j^{(i)} \tag{7}$$

where $C_j^{(i)}$ is a j^{th} event belonging to a i^{th} minimum cut set, k_i is the number of events in i^{th} minimum cut sets, n is a number of minimum cut sets.

The fragility of the top event $F_T(g)$ can be expressed through fragilities $F_i(g)$ of minimum cut sets as:

$$F_T(g) = 1 - \prod_{i=1}^{n} \left[1 - F_i(g)\right] \tag{8}$$

In the case of independent events, the minimum cut set fragility $F_i(g)$ $(i = 1, 2, \ldots n)$ can be presented as multiplication of component fragilities:

$$F_i(g) = \prod_{j=1}^{k_i} F_{ij}(g) \tag{9}$$

In the case of dependent events, we have to substitute $F_{ij}(g)$ with conditional probability of failure given failure of all proceeding components:

$$F_i(g) = F_{i1}(g) \cdot F_{i2,\,1}(g) \cdot F_{i3,\,12} \;\cdots\; F_{ik_i,\,12\,\ldots\,k_i-1}(g) \quad (10)$$

where $F_{is,\,1,2\ldots s-1}(g)$ is a conditional probability of failure of an s^{th} component given failure of proceeding s-1 components.

In R- and T-formats, all fragilities are calculated at mean (or "best") values of uncertainty parameters and, therefore, formulas (8) and (9) solve the problem of assembling of component fragilities. In M- and U-formats, all component fragilities and thus the system or the plant fragility are function of uncertainty parameters with given distributions. Therefore, we have an additional problem of propagating uncertainties in component fragilities to resultant uncertainty of the system or the plant.

There are several methods to propagate uncertainty. The exact analytical method can be applied only in several simple cases. Generally, some approximate methods - Monte Carlo, Latin Hypercube, moments, etc. are applied. Every method has some propagation error which usually is underestimated [22]. Total computational error consists of error response analysis approximation and propagation error. Therefore, efforts for both types of calculations should be coordinated to minimize total error given total cost of calculations.

In constructing the uncertainty distribution some state-of-knowledge dependency should be taken into account [23]. For identical redundant components uncertainty parameters and their distribution function are the same and, therefore, it should be presented only once in the final uncertainty distribution function. There is correlation between different components also because some types of uncertainty might shift in parallel with failure indicators of several components.

CONCLUSION

The elements of fragility models have been described. It is concluded that a careful handling of every element of fragility models is very important for the credibility of the seismic risk evaluation. A sensitivity analysis of the core melt probability [24] for a generic nuclear power plant demonstrated, despite common perception [25], that uncertainty of the fragility curve is no less a contributor than the uncertainty of the hazard curve to core melt probability.

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SESSION II

PARAMETERS AFFECTING COMPONENT FRAGILITY

OBTAINING RELIABLE QUALITY DATA FROM FRAGILITY TESTS

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ABSTRACT

The parameters discussed in this paper are the same as those present in normal seismic qualification testing. These parameters behave differently in high level acceleration tests and their contribution in providing unreliable data is of major concern since there is a significant difference. These parameters need to be considered in developing methodology guidelines for future fragility standards.

In seismic qualification testing, a predefined series of tests are performed and measured against a set of acceptance criteria. The response spectra generally has a peak acceleration of between 3-10 g's at a 2% damping value for the Design Basis Event (Safe Shutdown Earthquake). Fragility level testing has a minimum starting point of 10 g's at 2% damping and is generally 20 g's at 2% damping.

The dynamic characteristics of the simulated earthquake and the corresponding simulator hardware interfaces will be the parameters discussed.

There are two major parameter contributions in obtaining unreliable data. The first parameter is test specimen system hardware nonlinearities. These nonlinearities create impacts in the acceleration time history in all three directions and result in extreme acceleration amplitudes. These impacts can occur numerous times throughout the test program potentially decreasing 30 seconds of usable data to 10 seconds or less. The second major variable is electronic signal saturations. This attenuates the random noise earthquake raw data. The identification of these variables and the proper data adjustment are of primary importance in the presentation of fragility data.

Additional variables presented are: duration of the testing events and the impact of final amplitude response determination; multi-axis excitation and the approximated correction factors for different test axis excitation; the changing characteristics of the fragility spectra at different calculation intervals; and the natural frequency determination technique for fragility level testing.

INTRODUCTION

The parameters that affect reliable quality data from fragility testing

are the same parameters that are present in normal seismic qualification. These parameters can contribute significantly to the quality of the fragility data because their changing characteristics are more profound at high acceleration levels. These need to be considered in developing methodologies for future fragility testing standards.

In a seismic qualification test, a series of predefined events occur and are measured against a set of predefined acceptance criteria. The major emphasis prior to 1980 was on the concept of enveloping. This concept is the Test Response Spectra (TRS) enveloping the Nuclear Power Plant Site Specific Required Response Spectra (RRS) accounting for the uncertain test tolerances by the addition of a 10% margin.

The industry standard IEEE-344 defines fragility as, "susceptibility of equipment to malfunction as the result of structural or operating limitations or both when subjected to dynamic excitation". Additionally, the fragility level is defined as, "the highest level of excitation parameters that equipment can withstand and still perform the required class 1E function".

It should be noted that many historical fragility tests were not qualification programs, but design studies. To be considered a qualification program, the concept of seismic aging must be introduced into the program.

In recent years, manufacturers have conducted combined fragility programs that incorporate the qualification process. The equipments fragility level is determined by design operational malfunctions or the acceleration limitation of the seismic simulator. Within these programs, the final acceleration fragility test level, where the equipment met all performance specifications, has been preceded by five acceleration levels at 50% of the final acceleration level. Therein, a term has evolved called the Fragility Response Spectra (FRS). The FRS is the TRS obtained from these test programs that defined the equipment fragility level. The FRS has incorporated in its use the 10% margin that is applicable to specific applications.

For discussion purposes, we will define fragility levels as those greater than 10 g's at a 2% damping value.

The dynamic parameters discussed are dynamic impacts, signal saturation, ZPA application, test duration, shock response calculation, multi-axis test and determination of natural frequencies.

Since the early 1980's, we have conducted approximately 100 test programs to levels greater than 10 g's at 2%. The result of these programs have lead to a very good understanding of how parameters change at these high acceleration levels. We are presenting this information in order that (1) the industry can account for these events in future fragility programs, and (2) to provide input for the establishment of standards for fragility testing.

Dynamic Impacts

Dynamic impacting occurring between the seismic simulator and the test specimen is a variable that is very easy to overlook in a fragility program. While these variables show up in some qualification programs, the'r main contribution is during high acceleration testing. Impacts occur for many reasons and typical examples are cabinet doors banging, fan blade impacts on its housing, simulator hydraulic rod impacting on the end of the cylinders, and test specimen electrical phenomenon such as a D.C. contactor field collapse causing magnetic fields which affect the internal amplifier in some types of accelerometers. These events result in a calculation of higher acceleration levels beyond those which actually occurred.

The best approach to evaluate dynamic impacts is to review the raw accelerometer time signal. Generally, all three directions will show the presence of impact. The results of these phenomena do not resemble the remaining time history.

Figure 1 shows a sharp impact record by the shake table control accelerometer which could occur from a door or a fan blade impact. Figure 2 shows an impact on the top of a cabinet which could occur from a test specimen D.C. field collapse or from over ranging of an accelerometer, requiring extensive recovery time.

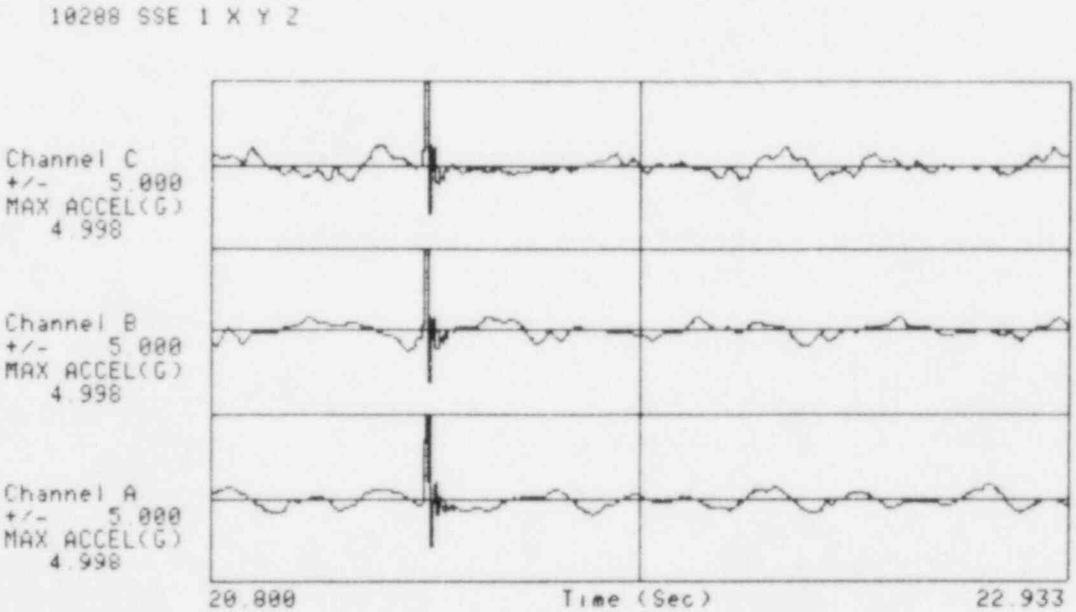


Figure 1
Sharp Impact

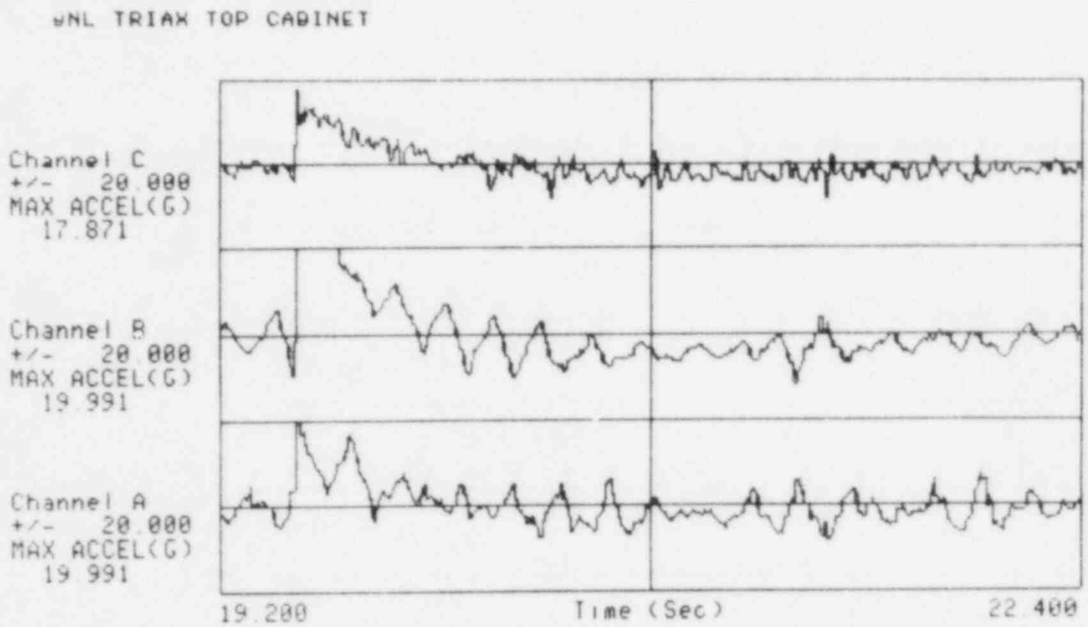
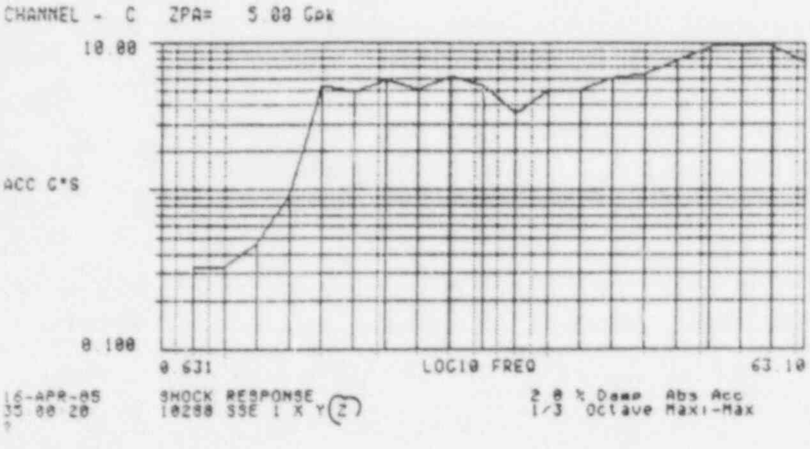


Figure 2
Impact Simular to D.C. Field Collaspe or
Over Ranging of an Accelerometer

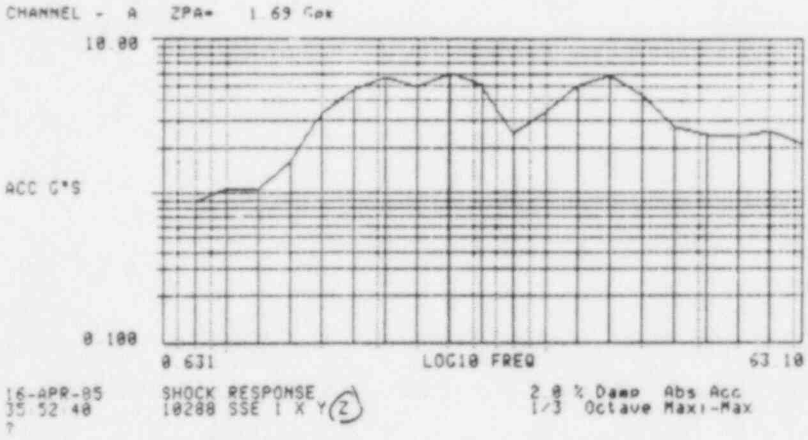
The duration in Figure 1 is a fraction of a second. By "surgically" removing the bad data, the qualification fragility test can remain valid. If the test program is conducted for a 36 second duration, that being a 3 second acceleration ramp to a maximum acceleration level for 30 seconds followed by a 3 second reduction ramp, the removal of a few seconds will not significantly affect the results when using a Gaussian random noise source. The effect would be to reduce the maximum fragility level. Figure 2 shows a minimum three second recovery time, therein reducing the maximum acceleration portion to approximately 25 seconds if only one event occurred.

Figure 3 shows the TRS with the impact present. Figure 4 shows the TRS with the impact removed. Please note the significant differences from 7.94 Hz through 63.10 Hz varying from a few percent to hundreds of a percent over actual acceleration level results.



Freq	Ampl	Freq	Ampl	Freq	Ampl
0.79	0.33	3.98	4.95	19.95	6.25
1.00	0.33	5.01	6.16	25.12	7.68
1.26	0.46	6.31	5.26	31.62	9.45
1.58	0.94	7.94	3.50	39.81	9.84
2.00	5.30	10.00	4.99	50.12	9.54
2.51	4.77	12.59	5.00	63.10	7.46
3.16	5.65	15.85	5.92		

Figure 3
RRS With Impact



Freq	Ampl	Freq	Ampl	Freq	Ampl
0.79	0.88	3.98	4.80	19.95	4.29
1.00	1.06	5.01	5.89	25.12	2.68
1.26	1.06	6.31	4.90	31.62	2.34
1.58	1.60	7.94	2.41	39.81	2.30
2.00	3.31	10.00	3.36	50.12	2.40
2.51	4.59	12.59	4.87	63.10	2.06
3.16	5.51	15.85	5.72		

Figure 4
RRS Without Impact

Please note that Figure 4 has a problem that occurred in the data removal process. This problem was a DC offset. A DC offset occurs in accelerometer amplifiers, tape recorders and filters. Additional data processing attempts can be made to remove this offset, or a technical explanation can be presented such as (1) the original values in Figure 3 are values for frequencies below 2 Hz, and (2) the test item has no resonances below 5 Hz, therefore, not enveloping from a qualification standpoint has been historically acceptable with proper technical explanation.

Thus, the proper correction for impacts is to remove the corrupted part of the data block while maintaining the proper signal characteristics. If the isolated spike can not be properly removed, the test must be conducted again. The historical problem is that the response accelerometers have had the data reducted after the test item has been removed from the shake table.

Signal Saturation

Signal saturation is a conservative event in test response enveloping for seismic qualification. The problem in fragility testing is that a tested item may show failure at a saturated level, wherein, in the unsaturated condition the tested device operated because the reported acceleration level is in reality significantly higher as the acceleration time history would be unsaturated.

This saturation can occur both on the table control accelerometer and the specimen mounted accelerometer in a cabinet qualification. The majority of the saturations occur on the specimen accelerometers. A response acceleration at a device location in a cabinet is tape recorded, wherein the voltage level of the accelerometer may be greater than the permitted input to the tape recorder (i.e. a 4 volt signal processed into a 2.8 volt limited tape recorder). A 1 g/volt amplifier setting is initially selected at the start of a test program to maximize signal to noise ratio. As the acceleration levels increase, a 10 g/volt setting may be required because of tape recorder input saturation.

In the control accelerometer example, increasing the fragility levels cause the amplifier to saturate. This can be avoided only if the operator monitors the time signal.

Figure 5 upper plot shows an unsaturated time signal and the lower plot shows the identical time signal saturated. Note, the saturated signal has the acceleration peaks flattened at the same level.

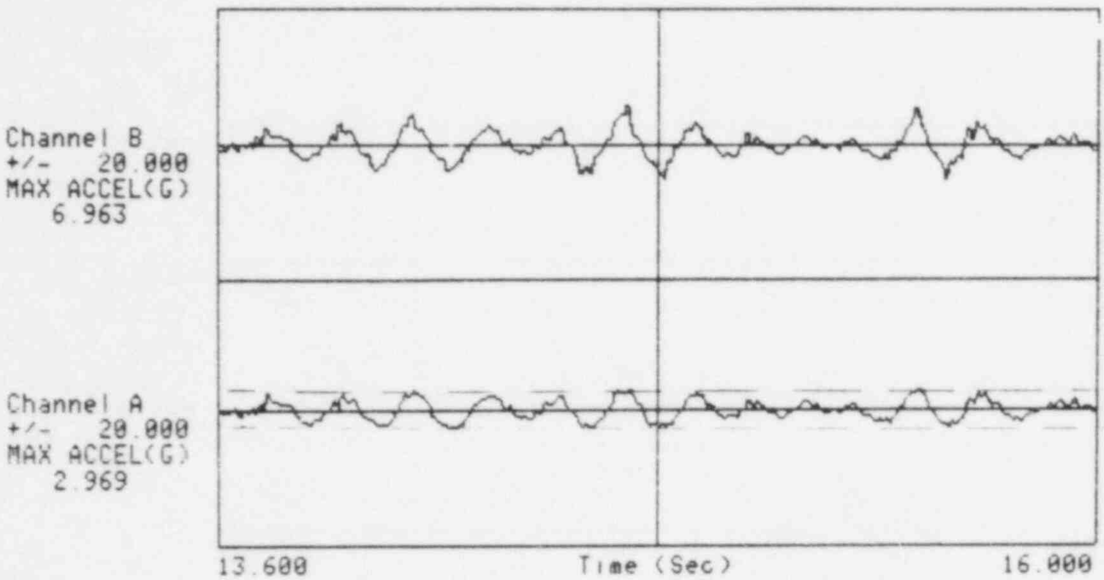


Figure 5
Unsaturated Time Signal and Saturated

Figure 6 is the saturated TRS with a maximum shock response acceleration of 35.8 g's. Figure 7 is the unsaturated TRS with a maximum acceleration of 49.4 g's or approximately 40% higher than the saturated signal.

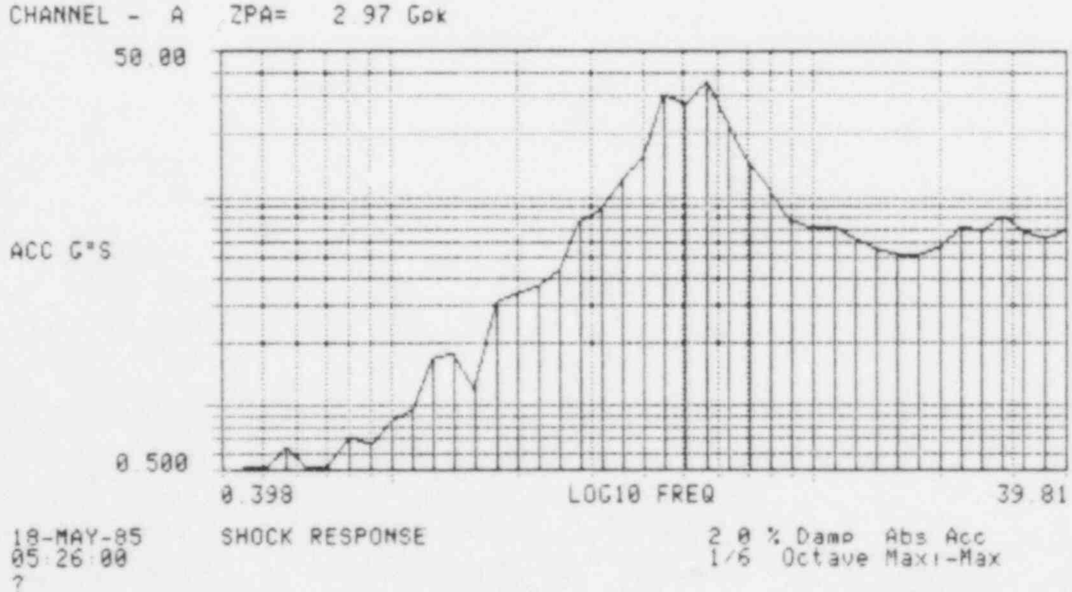


Figure 6
Saturated Signal

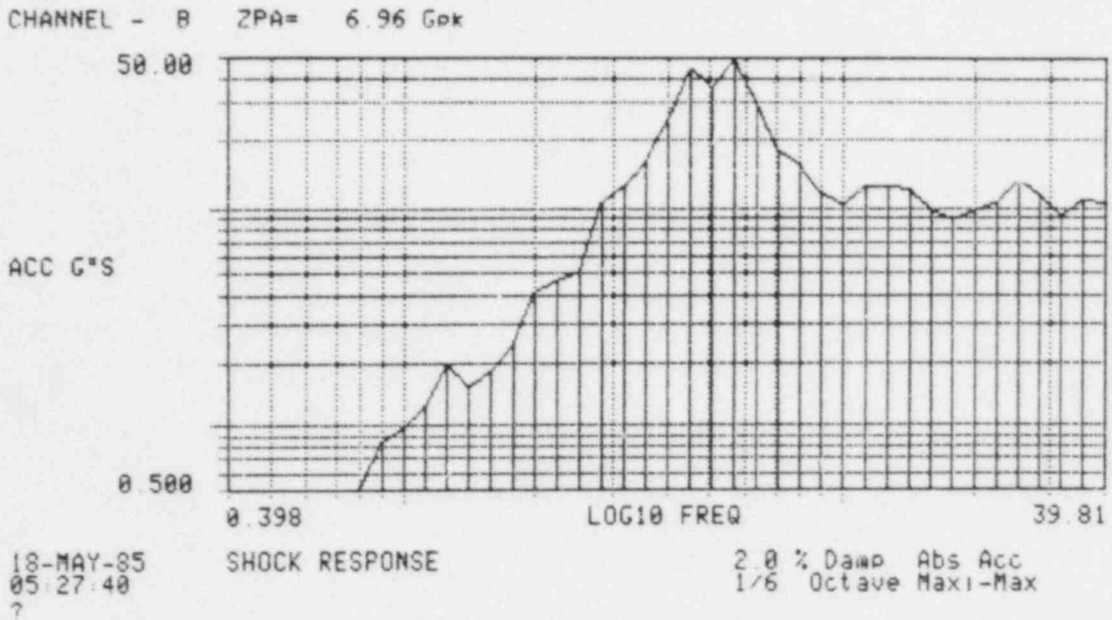


Figure 7
Actual Signal

ZPA

The definition of the Zero Period Acceleration (ZPA) is, "the maximum acceleration level within the frequency range of interest".

In qualification, the ZPA has historically been measured at the high frequency flat portion of the TRS generated to 100-200 Hz. Generally, the ZPA is greatly exceeded in qualification testing. The new draft IEEE-344 states that the most accurate way to determine the ZPA is to read the maximum acceleration level off the time signal because reading higher frequency values may not represent the true ZPA level.

If the maximum acceleration is an important variable as used in some generic and fragility programs, then the technique for determining the ZPA needs to be clearly defined. Note that the problems encountered with amplifier saturation and impact previously discussed will also distort the ZPA values. If the ZPA is to be used in fragility testing, then it is suggested that this variable be determined from the time signal. An application of ZPA is provided in the example below.

Q-Factors Can Bridge the ZPA and the FRS

Normally, engineers use Q-factors in qualification when relating one form of damping to another form of damping when reanalysis of the original time signal is no longer possible.

The application in fragility testing is more with respect to a check and balance on data quality by relating the true value of the ZPA to the proper quality Fragility Response Spectra (FRS). Table 1 shows that the 5% Q-factors for fragility tests are 73 to 100% of the theoretical values and 54 to 80% for the 2% theoretical values. Thus, establishing the proper test ratios can assist in determining the proper data quality. Test technicians have been able to identify problems when the table control peak accelerations of the TRS have not been consistent with the Table 1 ratios. Generally, the problem areas are from impacts and amplifier saturation.

Actual and Theoretical
Q-Factors
From Some Fragility Tests

Damping	Maximum Response Acceleration	ZPA Actual Time Signal	Ratio	Published Q-Factors Theoretical
5%	16.2 g's	6.1 g's	2.7	3
	10.1 g's	4.6 g's	2.2	3
	10.8 g's	4.9 g's	2.2	3
	18.6 g's	7.6 g's	2.4	3
	18.1 g's	5.9 g's	3.0	3
2%	28.5 g's	8.7 g's	3.3	5
	22.0 g's	7.0 g's	3.1	5
	20.6 g's	5.2 g's	4.0	5
	23.5 g's	8.6 g's	2.7	5
	25.0 g's	6.4 g's	3.9	5

Figure 3 shows 9.45 g's at 31.62 Hz (which is a very high frequency to select versus 5-20 Hz) and at a 3-4 ratio for Q results in a projected ZPA of 3.15 - 2.36 which is significantly less than the 5 g's reported. Whereas, Figure 4 shows a peak of 5.89 g's divided by 3-4 results in a project ZPA of 1.96 - 147 g's which encompasses the actual 1.69 g's.

Fragility Test Duration

The total fragility test duration and the duration of strong motion needs to be defined. We have defined fragility duration as 30 seconds of strong motion with a 3 second pre-ramp and post-test duration weaker "ramp" acceleration period to minimize "shock" input to the test item. The significance is that a 20 second strong motion random noise excitation will provide approximately 80 to 85% of the amplitude of a 30 second strong motion signal. Qualification overtesting is not that much of a concern

since the emphasis is on enveloping, wherein, fragility testing needs a consistent technique to establish a comparison of data.

Multi-Axis Test

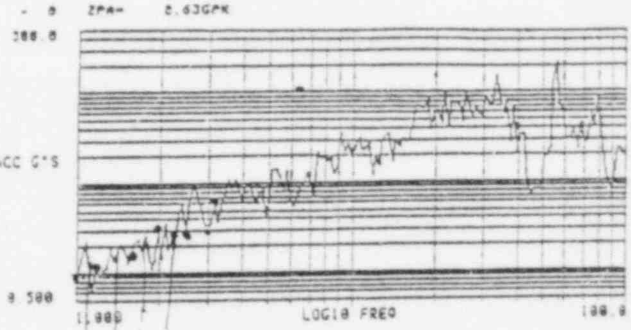
Technical papers have been published over the previous years with respect to the theoretical coupling of axes. Additionally, independent studies on low level response spectra tests have either been conducted or data was collected on specific qualification programs. The general conclusions between independent biaxial and independent triaxial is that an independent biaxial test increases per-axis acceleration by 10 to 15% appears to simulate the vibration of a triaxial test.

There have been no comparisons regarding these ratios for fragility tests. Further, the configurations of cabinets or the individual tests of an electrical device have not been addressed. In qualification testing the concern is to envelop the RRS and as such the importance of these variables is not as great. These variables could become very important in fragility testing because nonlinearities increase as the forces increase, and, therefore, the required correction factors to account for absence of excitation input direction could change substantially.

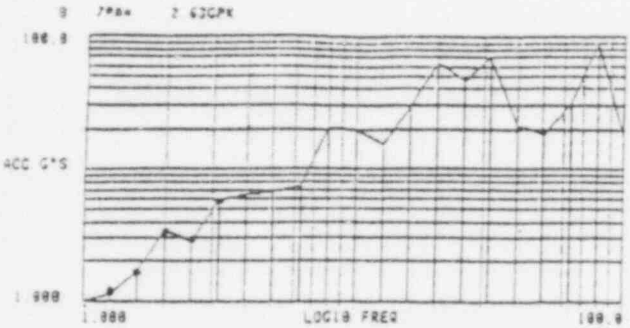
Shock Response Calculations

In qualification today's standards require 1/3 octave or narrower shock response calculations. In the draft standard of IEEE-344, the suggested calculation is to be performed at 1/6 octave. In normal qualification, to ensure enveloping the RRS 1/3 octave input are adjusted until an adequate envelop is achieved. In the fragility level test, because of the amplifications of the test signal with the inherent characteristics of random noise, the determination of fragility levels and the averaging techniques to be employed on the final data will become very important. Table 2 shows how a response curve changes characteristics as the calculational process becomes narrower (1/3, 1/6, 1/12 and 1/24 octave calculations). The left plot is at 1/3 octave and the right plot is at 1/24 octave.

Table 2



Freq	Ampl	Freq	Ampl	Freq	Ampl
1.00	0.70	4.73	8.60	22.39	41.56
1.03	1.10	4.87	4.22	23.04	76.34
1.06	1.33	5.01	6.70	23.71	74.42
1.09	2.30	5.16	14.37	24.41	79.50
1.12	0.84	5.31	13.26	25.12	45.46
1.15	0.63	5.46	11.80	25.85	103.29
1.19	1.27	5.62	8.37	26.61	69.34
1.22	0.80	5.79	13.63	27.38	52.07
1.26	1.11	5.96	6.47	28.18	66.46
1.30	1.16	6.13	5.58	29.01	58.05
1.33	1.09	6.31	7.22	29.85	50.41
1.37	1.33	6.49	8.39	30.73	90.29
1.41	1.70	6.68	10.48	31.62	70.45
1.45	2.11	6.88	13.07	32.55	69.66
1.50	1.75	7.08	9.50	33.50	153.04
1.54	1.21	7.29	7.21	34.47	95.13
1.58	1.63	7.50	21.40	35.48	56.51
1.63	2.20	7.72	17.84	36.52	82.34
1.68	2.39	7.94	20.36	37.58	27.63
1.73	1.81	8.18	17.76	38.68	64.81
1.78	2.66	8.41	19.26	39.81	21.17
1.83	1.94	8.66	12.27	40.97	34.27
1.88	1.11	8.91	16.23	42.17	34.04
1.94	1.36	9.17	34.93	43.40	11.04
2.00	3.44	9.44	21.37	44.67	6.54
2.05	1.44	9.72	27.12	45.97	8.34
2.11	3.65	10.00	19.32	47.32	8.44
2.18	1.34	10.29	25.20	48.70	7.43
2.24	2.42	10.59	32.69	50.12	10.30
2.30	2.96	10.90	22.65	51.58	19.03
2.37	5.05	11.22	25.03	53.09	23.57
2.44	5.89	11.55	29.54	54.64	133.95
2.51	2.81	11.89	11.79	56.23	224.40
2.59	3.79	12.23	18.99	57.88	71.66
2.66	10.00	12.59	15.02	59.57	57.63
2.74	8.13	12.96	29.32	61.31	30.60
2.82	5.50	13.34	35.60	63.10	30.85
2.90	4.05	13.72	35.30	64.94	39.90
2.99	2.75	14.13	16.64	66.83	23.20
3.07	3.63	14.54	30.52	68.79	45.67
3.16	5.86	14.96	24.80	70.79	27.06
3.25	3.72	15.40	30.79	72.86	28.30
3.35	6.40	15.85	20.97	74.99	57.27
3.45	7.27	16.31	31.30	77.18	43.44
3.55	10.58	16.79	45.50	79.43	89.10
3.65	8.70	17.28	73.51	81.75	46.39
3.76	10.94	17.78	64.39	84.14	13.22
3.87	9.30	18.30	65.73	86.60	10.23
3.98	6.26	18.84	87.48	89.13	6.71
4.10	7.10	19.39	39.56	91.73	12.13
4.22	10.23	19.95	62.10	94.41	23.69
4.34	7.79	20.54	61.95	97.16	22.12
4.47	5.76	21.13	43.00	100.00	10.17
4.60	7.13	21.75	90.69		



Freq	Ampl	Freq	Ampl	Freq	Ampl
1.00	0.70	5.01	6.70	25.12	45.46
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1.58	1.63	7.94	20.36	39.81	21.17
2.00	3.44	10.00	19.32	50.12	10.30
2.51	2.31	12.59	15.02	63.10	30.85
3.16	5.86	15.85	20.97	79.43	89.1[illegible]
3.98	6.26	19.95	62.10	100.00	10.17

Determination of Natural Frequencies

The application of fragility testing by single frequency excitation was a very common technique in the 1960's. Thus, it is very important to determine the natural frequency for utilization of those frequencies as the locations for conducting discrete dwell tests.

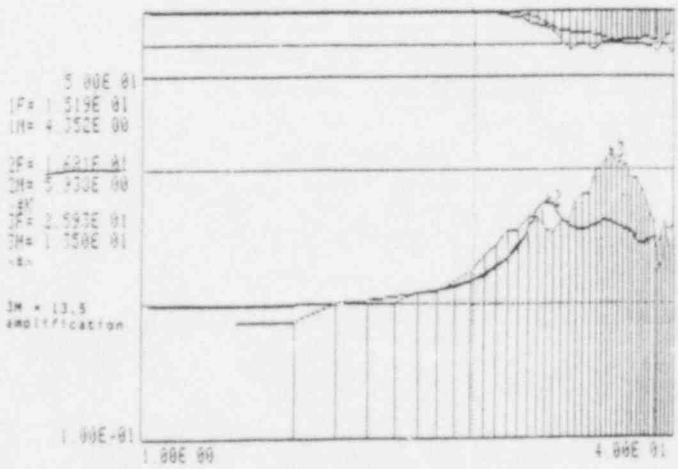
It is very difficult to determine the natural frequencies of a test item because of all the influences that change the specific results. Some typical resonance search data examples are:

- Single axis, low level tests on a shake table
  - Increased torquing on connection bolts can shift frequencies 20%
  - Increased level of acceleration excitation can shift frequencies 20%
- TRS specimen acceleration divided by control acceleration per axis
  - Shifting in frequencies and amplitude per acceleration levels (see Figure 8)
  - Presentation of totally new dominant mode by multi-axis excitation.
- Installation of equipment in a power plant with 3 plus feet of concrete floors has shown significant increases over the same results from a shake table resonance search test.

Figure 8
Exploratory Search by Full Level Testing

A typical single direction low level (.2 g's) sine sweep in the Y direction with the first natural frequency at 16.81 Hz (2F).

When the natural frequency of the cabinet is determined by the transmissibility of the TRS, the first natural frequency shifts to 15.19 Hz (approximately 90% of low level) and a second mode shows up at 25.93 Hz (approximately the X direction low level mode).



The utilization of transmissibility data in determining test item natural frequencies should be avoided in fragility testing if accuracy within ± 20% is desired because of the typical variations resulting from different installation conditions and different levels of excitation in determining natural frequencies. This would indicate that a fragility response spectra is much more attractive from a quality of data standpoint than single frequency fragility testing.

Report Data Formating

The closest industry standard today is NSAC-58 for documentation. The number of organizations following this format is very limited. NSAC-58 does not provide specific directions on recording data. A standard on documentation format needs to be established to ensure that future data can be traceable (i.e. did the data orginate from the test or was the data used in the fragility program obtained from hardware induced results).

Conclusion

In conclusion, the above variables all need futher research to determine their unique applications in fragility testing and the appropriate benefits they can bring to ensuring reliable quality data.

IMPACT ON FRAGILITY LEVEL TEST BY VARIOUS TYPES OF MULTIAXIS EXCITATION

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ABSTRACT

The purpose of this paper is to provide input guidelines in evaluating various types of multiaxis excitation on fragility level testing of electronic devices.

There are many variables that must be considered in establishing fragility test programs. This paper is limited to the discussion of three types of multiaxis excitations. This evaluation consists of dependent biaxial tests, independent biaxial tests and triaxial tests. The test inputs were generated by independent random noise sources with a Gaussian distribution.

The test sample was a two bay electrical cabinet. This cabinet was loaded with dummy weights to simulate installed instrumentation. Accelerometers were mounted on the cabinet in the principal direction of exitation, which was also the principal plane of the cabinet. Accelerometers were mounted on the outside upper corner and at mid-height inside the cabinet.

The problem of fragility testing becomes more complex as the response spectra increases. As the floor level base acceleration axial input increases, the resonance frequencies change throughout the cabinet and the corresponding values of damping were changed (reduction or amplification of energy) due to structural non-linearities. Thus, the performance characteristics of the panel/device were subjected to input amplification that were continually changing, as the acceleration magnitude increased from some nominal level to the fragility level. Wherein, at some acceleration levels of a discrete frequency, the panel/device was highly excited, and at the next higher input acceleration level, the systems natural frequency was shifted and the above discrete frequency may not be excited to its former level.

Compounding this problem is the number of axes of excitation. Cross-coupling in the cabinet/panel is the characteristic of concern. The vibration response from each of the three principle planes is transmitted through the structure. It should be noted, however, that electronic

devices located in cabinets are not typically installed in horizontally symmetrical cabinets, which, therefore, exhibit some level of directional coupling. The questions to be answered are: "Is the device/panel/cabinet sensitive to structural coupling?", and "Does the test technique adequately excite the structure?"

The data for the comparisons will include the peak accelerations (ZPA) from the response accelerometers and the total time duration accelerometer (TRS). Selected data is presented in overlaying plots and tabulated in normalized form. The normalized form is triaxial test data set to unity (one).

INTRODUCTION

The purpose of this paper is to provide input guidelines in evaluating various types of multiaxis excitation on fragility level tests.

There are many variables that must be considered in establishing fragility test programs. This paper is limited to the discussion of three types of multiaxis excitations.

This evaluation consists of dependent biaxial tests (hereafter referred to as vector), independent biaxial tests (hereafter referred to as biaxial), and triaxial tests.

The historical qualification approach on the application of multi-frequency/multi-direction tests has been to demonstrate that the test response spectrum (TRS) envelops the site specific required response spectrum (RRS) by a margin of 10%. The margin is to account for unknowns (such as calibration tolerances, etc.) in test data collection and processing techniques. The major reason to perform testing is to demonstrate device operability during the seismic events. It is generally accepted that electronic devices are acceleration magnitude sensitive, wherein, increasing acceleration magnitudes generally result in increased lack of performance characteristics. In simple terms, electronic contacts demonstrate increasing durations of discontinuities with increasing acceleration levels.

The problem becomes more complex as the response spectra increases. As the floor level base acceleration axial input increases, the resonance frequencies change throughout the cabinet and the corresponding values of damping are changed (reduction or amplification of energy) due to structural non-linearities. Thus, the performance characteristics of the panel/device are subjected to input amplification that are continually changing as the acceleration magnitude increases from some nominal level to the fragility level. Wherein, at some acceleration levels at a discrete frequency the panel/device is highly excited, and at the next higher input acceleration

level, the systems natural frequency has shifted and the above discrete frequency may not be excited to its previous level.

Compounding this problem is the number of axes of excitation. Cross-coupling in the cabinet/panel is the characteristic of concern. The vibration response from each of the three principle planes is transmitted through the structure. It should be noted, however, that electronic devices located in cabinets are not typically installed in horizontally symmetrical cabinets, which, therefore, exhibit some level of directional coupling. The questions to be answered are: "Is the device/panel/cabinet sensitive to structural coupling?", and "Does the test technique adequately excite the structure?"

IEEE-344 provides some guidelines on multiaxis testing as follows. "Seismic ground motion occurs simultaneously in all directions in a random fashion. However, for test purposes, single axis, biaxial and triaxial testing is allowed. If single-axis or biaxial tests are employed to simulate the three-dimensional environment, they should be applied in a conservative manner to account for the absence of input motion in the other orthogonal direction(s). One factor to be considered is the three-dimensional characteristics of input motion. Other factors are the dynamic characteristics of the equipment, flexible or rigid, and the degree of spatial cross-coupling response. Single-axis and biaxial tests should be applied to produce adequate levels of excitation to equipment where cross-coupling is significant and yet minimizes the level of over testing where cross-coupling is not significant. In order to expose potential failure modes, single-axis and biaxial tests must be performed in a number of directions as described below and, therefore, in terms of total duration and fatigue induced, these tests are intended to be conservative".

IEEE-344 further states that "biaxial tests should conservatively reflect the seismic event at the equipment mounting locations, and thereby account for the absence of motion in one orthogonal direction for independent input motion in the other two orthogonal axes, or for the absence of motion in two orthogonal directions if dependent inputs are used. The factors to be considered include the directional nature of the input motion and the cross-coupling of the equipment. Biaxial testing should be performed with simultaneous inputs in a horizontal and vertical axis. The selection of the horizontal axis may include the principal axes or some other direction selected to expose potential failure modes by testing the equipment in its most vulnerable direction".

The problem with this direction is the use of "weasel words" such as conservative and significant. Thus, regardless of whether we are talking qualification or fragility, the problem still remains as to how to reflect simulated triaxial testing.

Technical papers have been published over the previous years with respect to the theoretical (analytical) coupling of axes. Additionally, independent test studies on low level response spectra have either been conducted or data was collected on specific qualification programs. The general conclusions on independent biaxial versus independent triaxial excitation is that an independent biaxial test increases the per axis acceleration by 10 to 15% in simulating the vibration of a triaxial test. No studies have addressed vector testing.

There have been no comparisons regarding these ratios for fragility tests. Further, the configurations of cabinets or the individual tests of electrical devices have not been addressed. In qualification testing, the concern is to envelop the RRS, and as such, the importance of these variables were not as great. These variables could become very important in fragility testing because nonlinearities increase as the forces increase, therefore, the required correction factors must account for the absence of one or more excitation input directions which could substantially increase structural response.

This study is a scoping document to provide insight into the establishment of a more detailed and expanded evaluation.

Test Approach

A two bay electrical cabinet was mounted on a triaxial seismic simulator in the principal direction of excitation. The test input consisted of three (3) independent random noise sources with a Gaussian distribution tape recorded for repeatability. The simulated earthquake signal characteristics were measured on the seismic simulator center line plane and had a maximum cross correlation of under 20% and an average coherence of under 20% for any combination of the three perpendicular axes.

Initially, the cabinet was bolted. Seven 5/8" bolts torqued to 90 foot pounds were used. The setup parameters were adjusted to test the cabinet to 10 g's at 2% broadband normalized in all three directions. Thereafter, by neutralizing one axis, a biaxial test could be conducted and compared to the triaxial results, and then by applying the same random noise signal to one horizontal and the vertical axes simultaneously, a vector test could be simulated. After establishing the proper pre-test conditions (triaxial reference test case), the cabinet was examined and one of the bolts had sheared. Toe-clamps were used inside the cabinet in addition to the bolts to provide for a better connection to the simulator. Thereafter, a resonance search was conducted on the cabinet followed by a biaxial and a vector test in the weak axis of the cabinet. Additionally, a triaxial test was conducted to compare to the initial pre-test conditions (triaxial test). Between each test, the bolts and toe clamps were checked. The later triaxial test was used as the reference base test because of the same mounting conditions (toe clamps and bolts) as the other two test cases.

The test duration was a 3 second acceleration ramp to full level, 30 seconds of strong motion, and a 3 second de-acceleration ramp. All response accelerations are presented at 1/6 octaves and 2% damping.

It is estimated that the simulated vector test was conducted at approximately 40° versus the typical 45° slope. This was a result of normalizing the triaxial set-up first, with the resulting horizontal and vertical inputs at the same equipment settings as used in the triaxial test.

Test Cabinet and Seismic Simulator Description

The test cabinet is a two bay electronic cabinet approximatley 60" in length, 30" Deep and 90" tall with front and rear entrances. The front right hand side had 4 racks at 113 pounds of simulated mass and the left hand side had 4 racks at 142 pounds. The rear right hand side had 4 racks at 445 pounds and the left hand side had 4 racks at 160 pounds. The rear view of the test cabinet is shown in Figure 1. This cabinet has a weight of approximatley 1000 pounds with 860 pounds simulating sixteen electrical racks for a total weight of approximately 1800 pounds. This is a heavily loaded cabinet and is not perceived to be representative of the majority of installed electrical cabinets. The cabinet was setup for training and test studies. The cabinet is very flexible in the side to side direction.

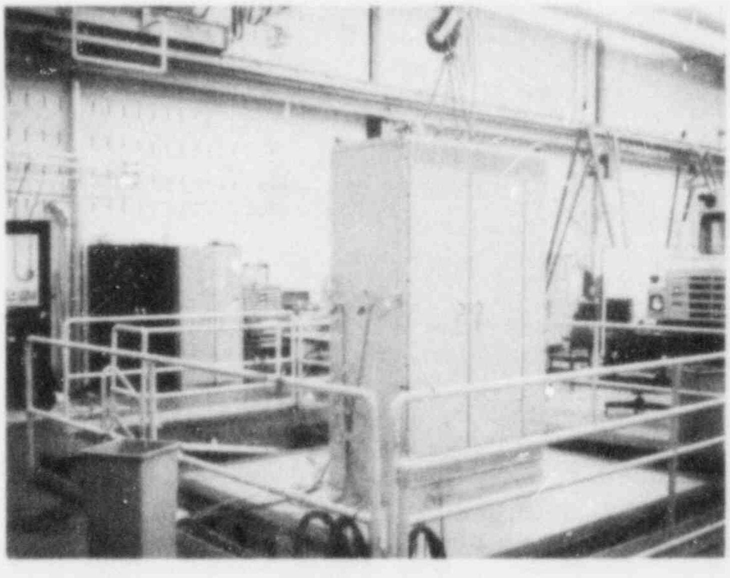


Figure 1
Rear View of Test Cabinet

This cabinet had the following resonances determined by a low level 0.2 g's sine sweep.

Case Study Side to Side		Off-Axis Front to Back		Vertical	
Frequency	Amplitude	Frequency	Amplitude	Frequency	Amplitude
4.9	8.8	5.4	14.6	24.3	4.9
14.0	<2.0	28.2	2.2	25.9	5.5
28.0	<2.0*			27.4	3.9
39.0	<2.0*			32.4	2.5

Figure 2 shows the resonance search plot for the side to side direction measured on the top of the cabinet. These (*) modes were more dominant at the mid-height of the cabinet. Obviously, the dominate modes are 4.9 Hz side to side and 5.4 Hz front to back. Basicially, the side to side and front to back have the same natural resonance although during full level testing the side to side demonstrated much more displacement.

Triaxial accelerometers were mounted on the top corner of the cabinet. An additional triaxial accelerometer was mounted inside the cabinet, slightly above mid-height on the post between the two bays.

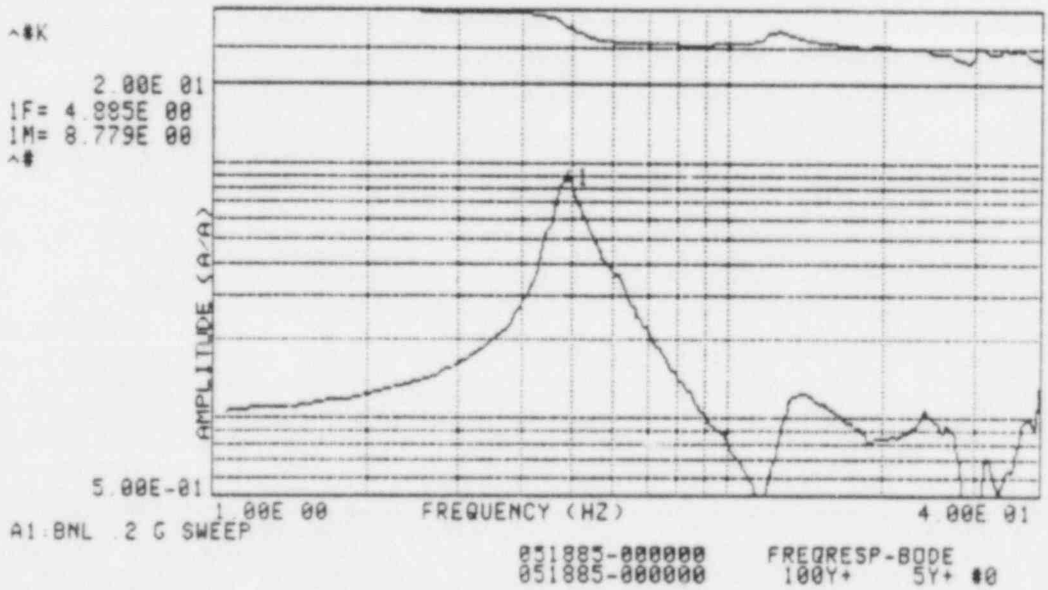


Figure 2
Resonance Search
Side to Side
Top of Cabinet

The cabinet was installed parallel to the principal axes of the simulator. The cabinet was installed and centered on the two horizontal planes.

The seismic simulator is 120 inches by 120 inches. The force rating is 30,000 pounds vertical and 20,000 pounds in each horizontal direction. The displacement is 8 inches peak to peak in each of the directions from 10 inch cylinders. The flow rating is 33 ips vertical, 25 ips horizontal North-South (cabinet front to base) and 23 ips horizontal East-West (cabinet side to side).

Test Data Repeatability

Triaxial tests were conducted with the same equipment settings used throughout the program. Figure 3 shows the Base Triaxial Test used in this study. This test was conducted after the biaxial and vector test. The response at the top (0—0), mid-height (X—X) and table surface (•—•) are presented. Additionally, the initial pre-test series triaxial test base excitation is also presented by a circle within a square (⊡). Please note that most 1/6 octave calculations show repeatability within 3% for the table surface accelerometers. The ZPA for the base study triaxial test is 4.32 g's and the pre-test series was 4.37 g's.

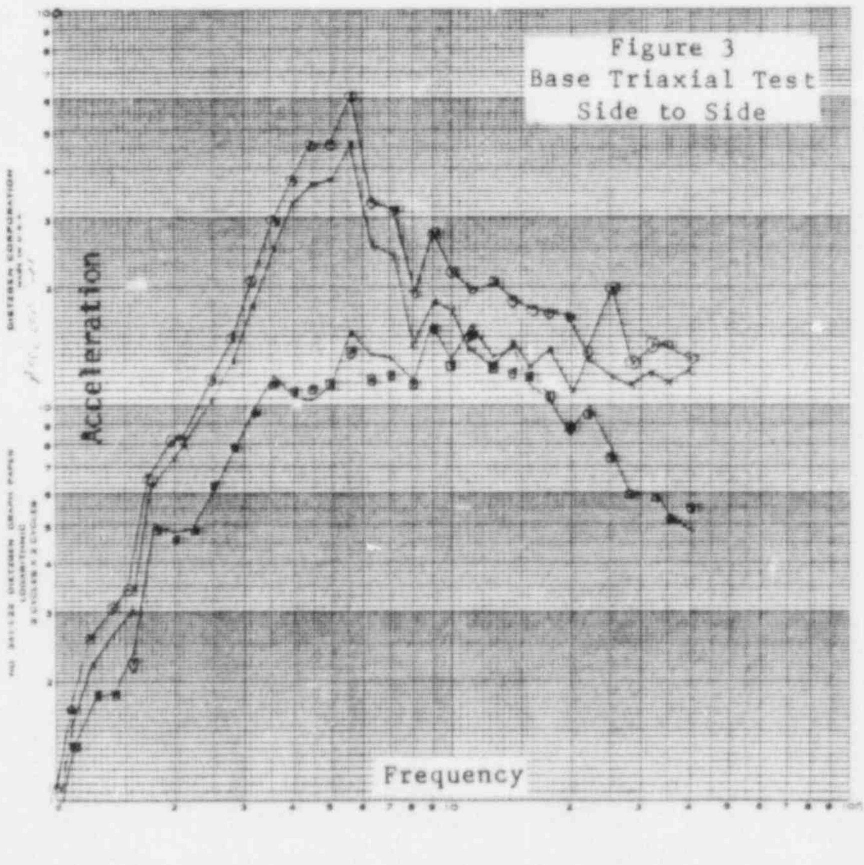


Figure 3
Base Triaxial Test
Side to Side

Figure 4 shows the base table surface trial test front to back direction by circles connected with lines and the pre-test series base table surface test with X's and dashed lines. Again, the deviation is only a few percent. Additionally, the mid-height is compared between the pre-test and base triaxial test. The circle within a circle (0) connected with dashed lines is the mid-height base triaxial test and the pre-test as shown by X's within a circle connected by dots. The base triaxial test has a ZPA of 6.91 g's and the pre-test has a ZPA of 6.96 g's.

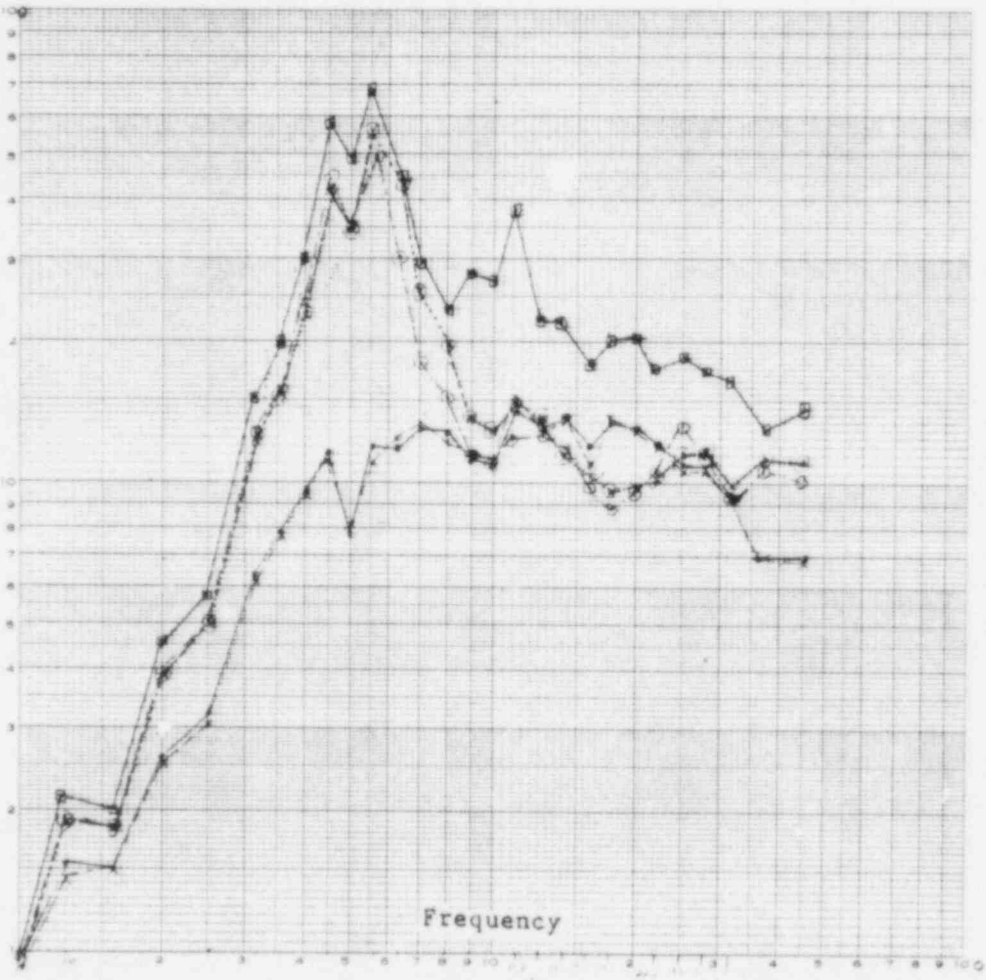


Figure 4
Front to Back
Base Triaxial Test

The mid-height and top of the pre-test side to side accelerometers had their amplifiers overdriven, therefore, the comparisons could not be conducted.

Thus, with the pre-test triaxial table accelerometers for both horizontal directions being within a few percent of the base reference triaxial test (last test conducted), it can be concluded that the comparison to the biaxial test and vector test conducted between the two triaxial tests (without any test equipment adjustment) is valid.

Biaxial and Vector Off Axis Acceleration

Figure 5 presents the off axis acceleration, front to back, versus the on-axis side to side acceleration. The top of the cabinet side to side indicates simular biaxial and vector acceleration levels. Front to back off axis acceleration levels indicate that the biaxial acceleration is greater above 8 Hz than vector and vector acceleration is greater below 8 Hz.

A crude square root sum of the square, SRSS, calculates in ($\sqrt{15^2 + 18^2}$) shows a general 10-13% coupling for frequencies above 10 Hz.

Figure 5
Biaxial (•—•) and Vector (□—□)
Off Axis Acceleration (Bottom Curve) Versus
On Axis Acceleration (Top Curve)

Normalized Response Spectrum Side to Side Excitation

The triaxial response spectra in the cabinet side to side direction has its acceleration levels set equal to one. The other response spectra for biaxial and vector testing are then ratioed to the triaxial test. Figure 6 shows the ratios for the base accelerations, Figure 7 shows these accelerations for the mid-height accelerations and Figure 8 shows these accelerations for the top of the cabinets.

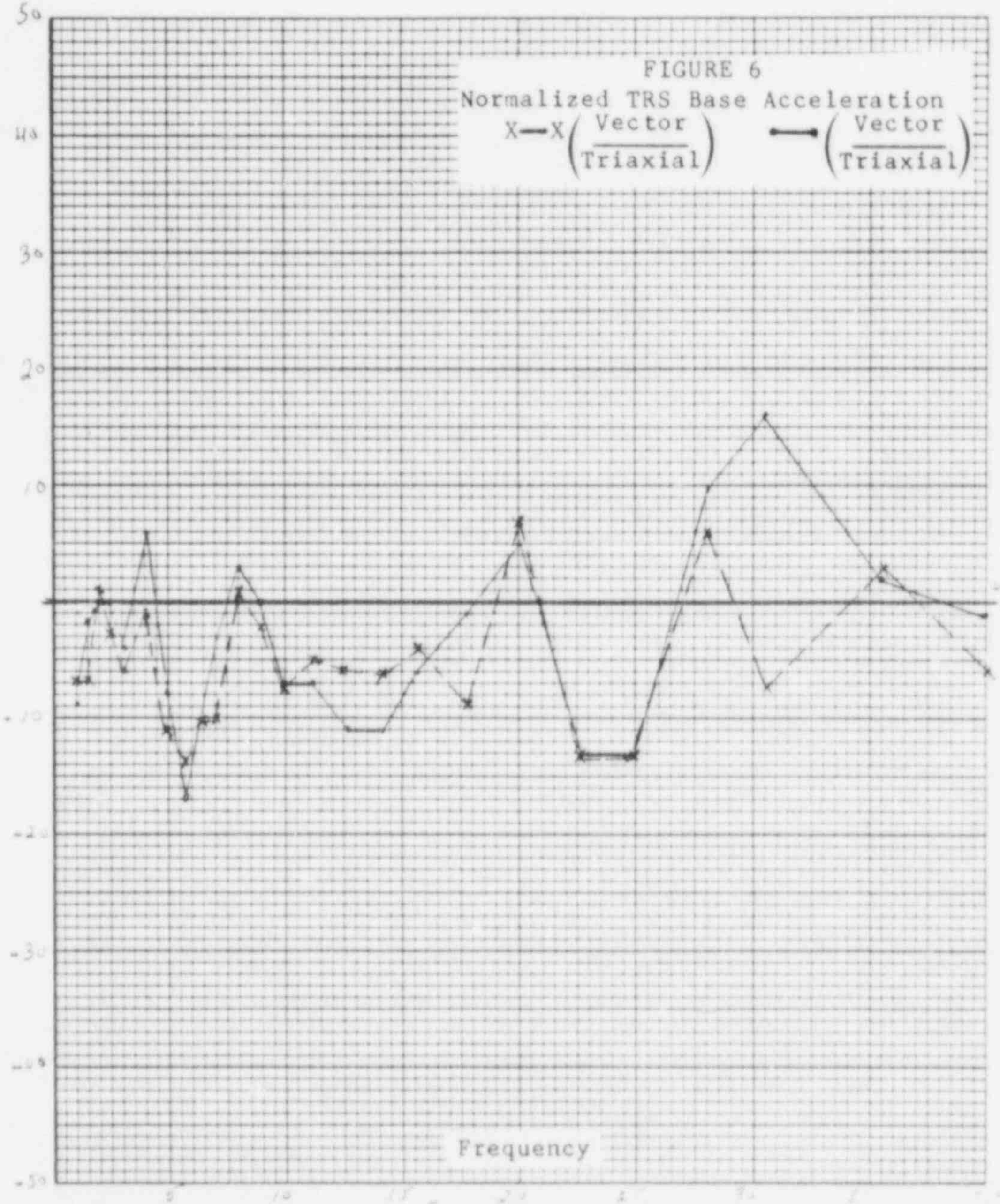
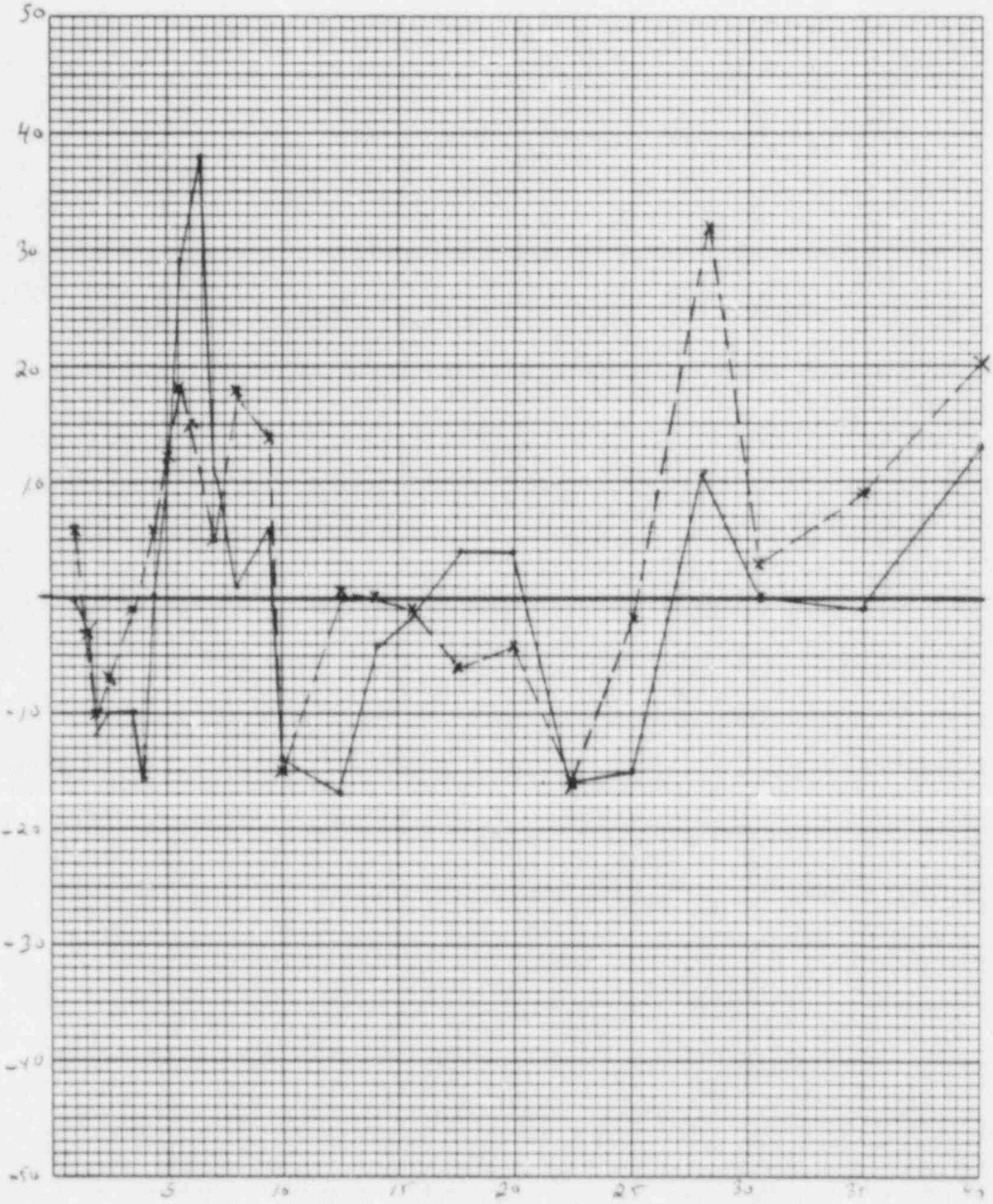


FIGURE 6
Normalized TRS Base Acceleration
X—X (Vector / Triaxial) —— (Vector / Triaxial)



Frequency

Figure 7
Normalized TRS Mid-Height Acceleration

X—X $\left(\frac{\text{Vector}}{\text{Triaxial}}\right)$ — $\left(\frac{\text{Biaxial}}{\text{Triaxial}}\right)$

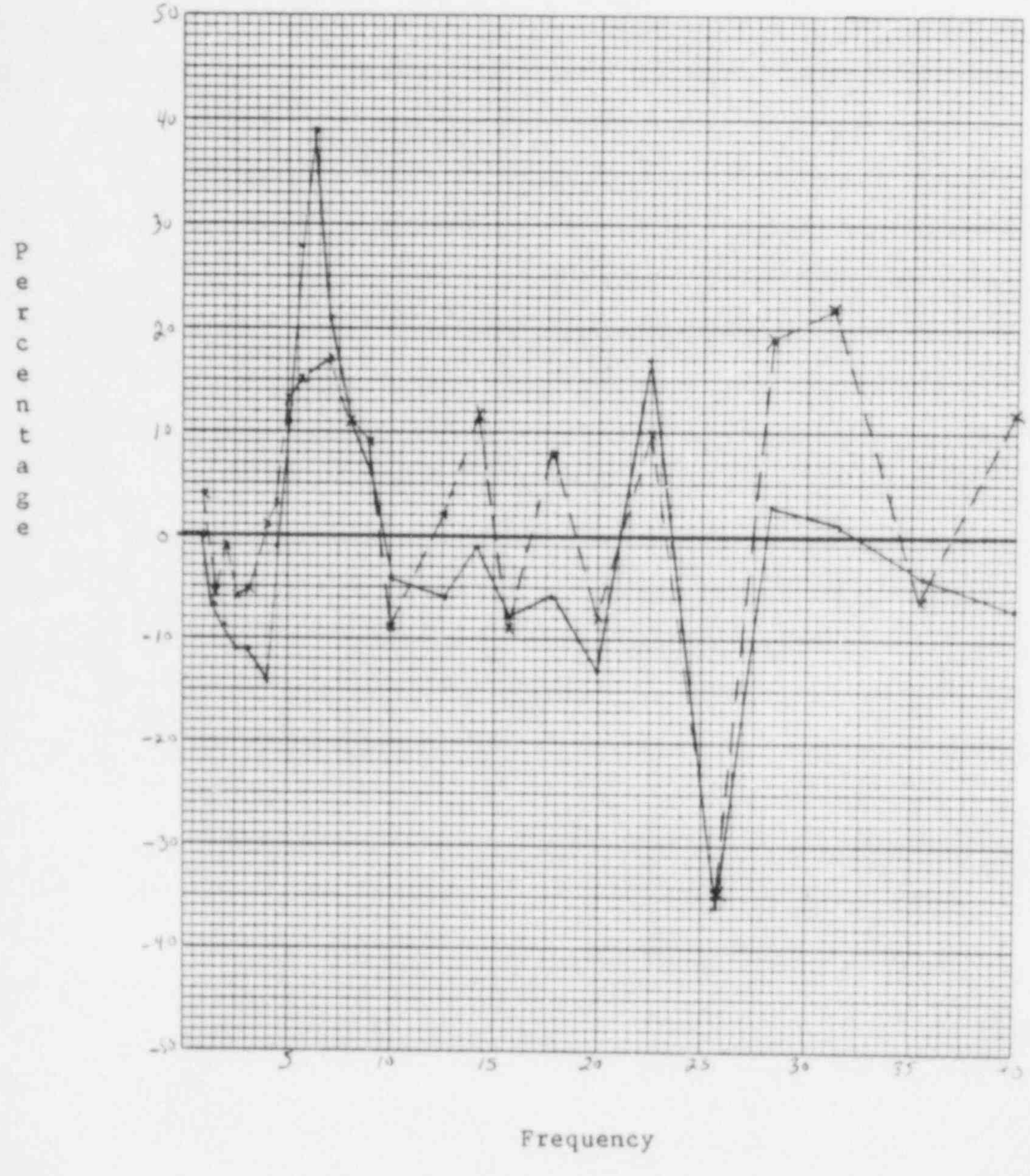


Figure 8
Normalized TRS Top Cabinet Acceleration
X—X $\left(\frac{\text{Vector}}{\text{Triaxial}}\right)$ —— $\left(\frac{\text{Biaxial}}{\text{Triaxial}}\right)$

At resonances, it appears that biaxial and vector testing is more responsive than triaxial testing, otherwise the average is approximately 5 to 7% under triaxial acceleration. The averages are based on the data presented in Table 1. The response at high frequency shows biaxial to be

simular to the triaxial testing. The possible explanation for the vector test being higher than the other tests at 25-35 Hz is the phase coupling with the vertical resonances, thereby amplifying the response more than the other two cases.

Figures 6, 7 and 8 show substantial differences in peak acceleration at the major resonance between triaxial versus biaxial and triaxial versus vector testing.

Table 1
Figure 6, 7 and 8
Estimated Curve Fit Average (Area Under Curve)
Over Select Frequency Ranges

	Base		Mid-Height		Top	
	Biaxial	Vector	Biaxial	Vector	Biaxial	Vector
1 - 5 Hz	-2%	-2%	- 8%	- 2%	- 5%	- 2%
5 -10 Hz (Resonance)	-5%	-6%	+10%	+11%	+11%	+11%
10-17 Hz	-5%	-5%	- 8%	- 7%	- 5%	0%
17-25 Hz	-5%	-5%	- 1%	- 7%	[illegible]	- 7%
25-35 Hz (Resonance)	+6%	-2%	+ 1%	+11%	- 3%	+11%

Peak Accelerations and Normalized Side to Side Accelerations

Table 2 presents peak accelerations for the side to side response normalized to 1 for triaxial testing.

Using the initial argument of severity before undertaking the test program leads to some interesting results. The initial argument was, "If the normalized peak acceleration value for the independent or dependent biaxial test is less than one, equal to one, or greater than one, then, the corresponding test can be considered less severe, as severe, or more severe (respectively) than the triaxial test that was assigned a value of unity with all other variables remaining constant".

This indicates that biaxial is approximately 5% less severe than triaxial, and vector is 5 - 7% less severe than triaxial testing based on the base accelerations and the top of the cabinet accelerations. The accelerations at mid-height indicate that triaxial testing is approximately 8% outside of the resonance points and more severe than vector or biaxial testing, again outside of the resonance points. This is probably due to the unusual nature of the cabinets closely coupled modes having simular frequencies in both horizontal directions.

Table 2
Normalized Peak Acceleration (g's)

	Horizontal East-West (Side-to-Side)		
	Base	Mid-Height	Top
Triaxial	4.32 (1.0)	7.42 (1.0)	10.18 (1.0)
Biaxial	4.00 (.93)	8.21 (1.11)	9.34 (.92)
Vector	3.91 (.91)	8.00 (1.08)	10.21 (1.0)
	Vertical		
	Base	Mid-Height	Top
Triaxial	*	*	*
Biaxial	4.45	4.84	6.87
Vector	4.47	5.58	5.62
	Horizontal North-South (Front-to-Back)		
	Base	Mid-Height	Top
Triaxial	5.23	6.91	9.62
Biaxial	.35	1.97	3.61
Vector	.31	1.80	2.61

* Data collection malfunction, unable to process data

Visual observations during the test by the four authors concluded that the vector test looked and sounded more severe than the biaxial test. The triaxial test appeared to be the most severe.

The vector test high acceleration in the Horizontal North-South may be explained by the repetitive nature of the forcing function of the cabinet with no lateral bracing, simular to in-phase momentum taking effect.

Conclusion

The response for different axes of excitation is highly dependent on the test configuration, ie. cabinet structure.

No clear conclusions can be drawn as no consistant variations appear. There is a random flip-flop of the biaxial and vector test result versus triaxial results.

Previously it was concluded that 10-15% additional acceleration for a biaxial test would simulate triaxial. Figure 9 shows triaxial on-axis (side-

to-side) and off-axis (front-to-back) versus biaxial on-axis (side-to-side) acceleration at the top of the cabinet. On-axis results show triaxial responses greater than biaxial through 4.5 Hz and after 10 Hz while biaxial is greater between 4.5 and 8 Hz (the natural frequency of the cabinet). This indicates that a simple multiplier may not be possible or may be overly conservative at major structural natural frequencies of cabinets.

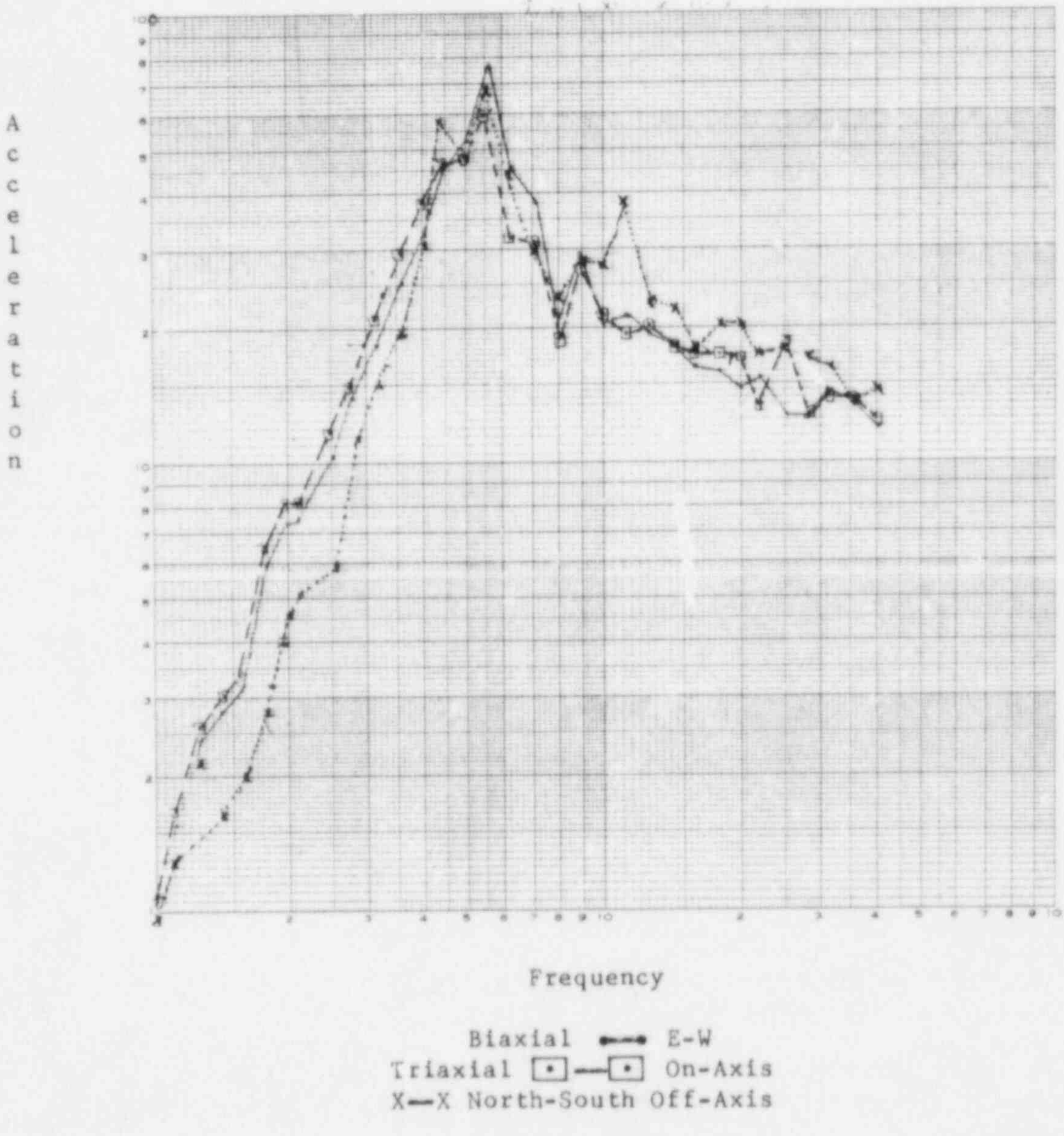


Figure 9
Triaxial On and Off-Axis and
Biaxial On-Axis Top of Cabinet

In future comparative research programs, the vector setup should be simulated first with the triaxial test and biaxial test parameters derived from the vector test setup. Both horizontal and vertical inputs should be compared and set the same for the vector test. The simulated vector behavior is difficult to evaluate in that the angle is not a pure 45° (it was estimated at 40°).

Electrical items should not be simulated in cabinets because there are an infinite number of load combinations and cabinet designs. Prior to this test series, there appears to be consistency in lightly loaded cabinets tested below 10 g's amplitude.

The variations increased significantly as local flexibilities of cabinets came into play. It is possible that coupled single axis resonances in the horizontal and vertical directions with very flexible cabinets will cause vector testing to be more severe than triaxial testing.

The theory of coupling at 10% and the limited result of this program in nonflexible frequency regions would indicate that a 10% increase in response spectra could be the "CONSERVATIVE MANNER" that is currently undefined in IEEE-344. This should not be overly conservative since at any resonances it appears that biaxial and vector testing results in higher acceleration levels than in triaxial testing.

EVALUATION OF EQUIPMENT ANCHORAGE CAPACITIES

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ABSTRACT

One important parameter in determining the overall dynamic fragility of equipment is the capacity of the base anchorage. This paper deals with the subject of how to evaluate anchorage capacity in a more reasonable and straightforward manner.

An interactive software package has been developed to evaluate anchorage pattern using a portable microcomputer (IBM PC or compatible.) The purpose of this software package configuration is to provide existing plants with the means of immediately determining the capacities of in-place equipment anchorages. In addition, the software package allows new design postulation in the field for nonconforming anchorage patterns. All evaluations are stored on disk and may be printed out at day's end.

The solution algorithm is of interest in that difficulties in anchorage evaluation usually arise from estimating the state of equilibrium and in estimating the effective stiffness of the anchorage tensile elements and the bearing area. A solution algorithm utilizing the lower bound theorem of plasticity and linear programming without the need to estimate anchorage or bearing effective stiffness is presented in the paper. The solution technique is found to be systematic and efficient, and therefore is ideal for computer implementation.

INTRODUCTION

A solution methodology for the ultimate capacity of equipment base anchorage subjected to equivalent static loads is presented in this paper. The method is based on the lower bound theorem (or static formulation) of plasticity and is solved utilizing linear programming (LP) techniques.

The analysis and design of base anchorages falls in two main groups, the elastic analysis and the limit analysis. For the current base anchorage problem, the limit analysis method is used. The reasons are:

(1) limit analysis accounts for the reserved strength of the system,
(2) stiffness information for base anchorage, which is required in elastic analysis, is usually not available,
and (3) efficient solution algorithms based on linear programming are available.

To solve general or complex limit analysis problems, mathematical programming techniques provide engineers with a systematic formulation and efficient solution. References [1,2] give the state-of-the-art of this technique.

BASE ANCHORAGE MODEL

The structural model for the base anchorage is shown in Figure 1. The compression zone of the base is discretized into finite areas. Each compression area is defined by its area, its crushing stress, and its location (x and y coordinate.) The fineness of the grid depends the specific requirement of each problem. The compression areas does not resist any shear in the current formulation. However, it can be easily extended to incorporate shear resistence capacity.

Each steel anchor bolt is modeled by tension, f_{ti}, and shears in two directions, v_{xi} and v_{yi}. The properties needed for anchor bolts are the shear and tension ultimate capacities, or the shear-tension interaction equation.

Loadings for the system include the dead load, W, and the equivalent static loads for the seismic effect in the three directions. The equivalent static loads are assumed to applied proportionally as represented by the load factor λ.

FORMULATION OF THE PROBLEM (The Static Approach)

According to the lower bound theorem of plasticity: "For any distribution of internal stresses, $\underline{r}$, that satisfy the yield constraints, $\underline{N}\,\underline{r} - \underline{K} \leq \underline{0}$, and the equilibrium equations, $\lambda \underline{P} = \underline{H}\,\underline{r}$, the load factor, λ, is less than or equal to the critical load factor, λ_c." The problem can be formulated as follows:

Maximize λ

Subjected to $$\lambda \underline{P} = \underline{H}\,\underline{r} \qquad (1)$$

and $$\underline{N}\,\underline{r} - \underline{K} \leq \underline{0}$$

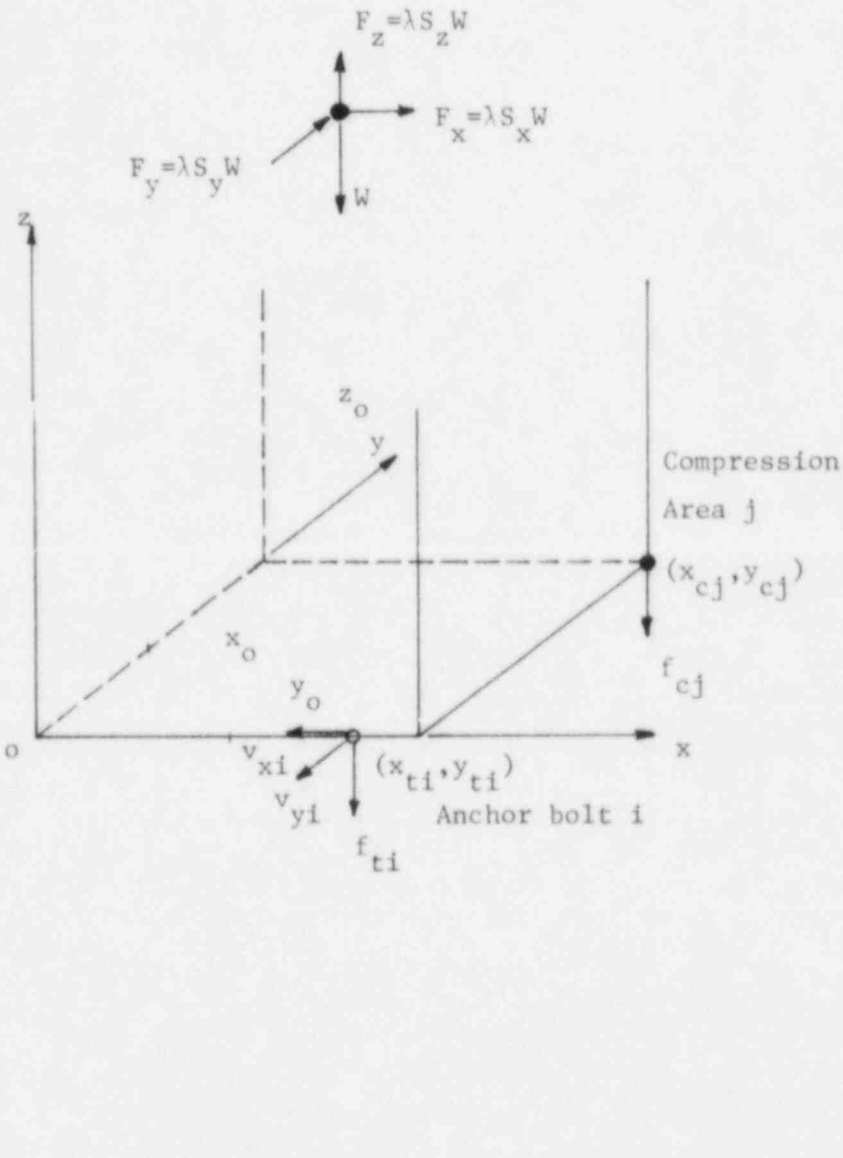

Figure 1: Idealized Model for Base Anchorage

where $\underline{r}$ = the internal load vector, f_{cj}, f_{ti}, v_{xi}, and v_{yi},
$\underline{P}$ = the unit external load vector, including the three forces, the two moments, and the torsion, acting on the anchorage base,
$\underline{H}$ = the transformation matrix,

and $\underline{N}$ and $\underline{K}$ defines the failure surfaces for the compression areas and the anchor bolts.

The six equilibrium equations for the model shown in Figure 1 can readily be written. The yield constraint for f_{cj} takes the form:

$$-F_{cj} \leq f_{cj} \leq 0 \qquad j = 1 \text{ to \# of compression areas} \qquad (2)$$

Similarly, if tension-shear interaction is neglected, the yield constraints for the anchor bolts are:

$$0 \leq f_{ti} \leq F_{ti}$$

$$-V_i \leq v_{xi} \leq V_i \qquad i = 1 \text{ to \# of anchor bolts} \qquad (3)$$

$$-V_i \leq v_{yi} \leq V_i$$

However, in general, the failure surfaces for shear-tension interaction are curved. To keep the problem linear, the failure surfaces are represented by piecewise linear plane surfaces. In practice, these plane surfaces are chosen to inscribe the curved surfaces. The failure surfaces are now:

$$\frac{f_{ti}}{F_{tik}} + \frac{v_{xi}}{V_{xik}} + \frac{v_{yi}}{V_{yik}} \leq 1 \qquad \begin{array}{l} i = 1 \text{ to \# of anchor bolts} \\ k = 1 \text{ to \# of failure planes} \end{array} \qquad (4)$$

$$f_{ti} \geq 0 \qquad (5)$$

Due to the symmetry of the failure surfaces to v_x and v_y, the three dimensional interaction curve can be obtained from typical two-dimensional interaction diagrams. The cross-section of the failure surface for any constant f_{ti} is a circle. The typical failure surface for an anchor bolt and the planar approximation is shown in Figure 2.

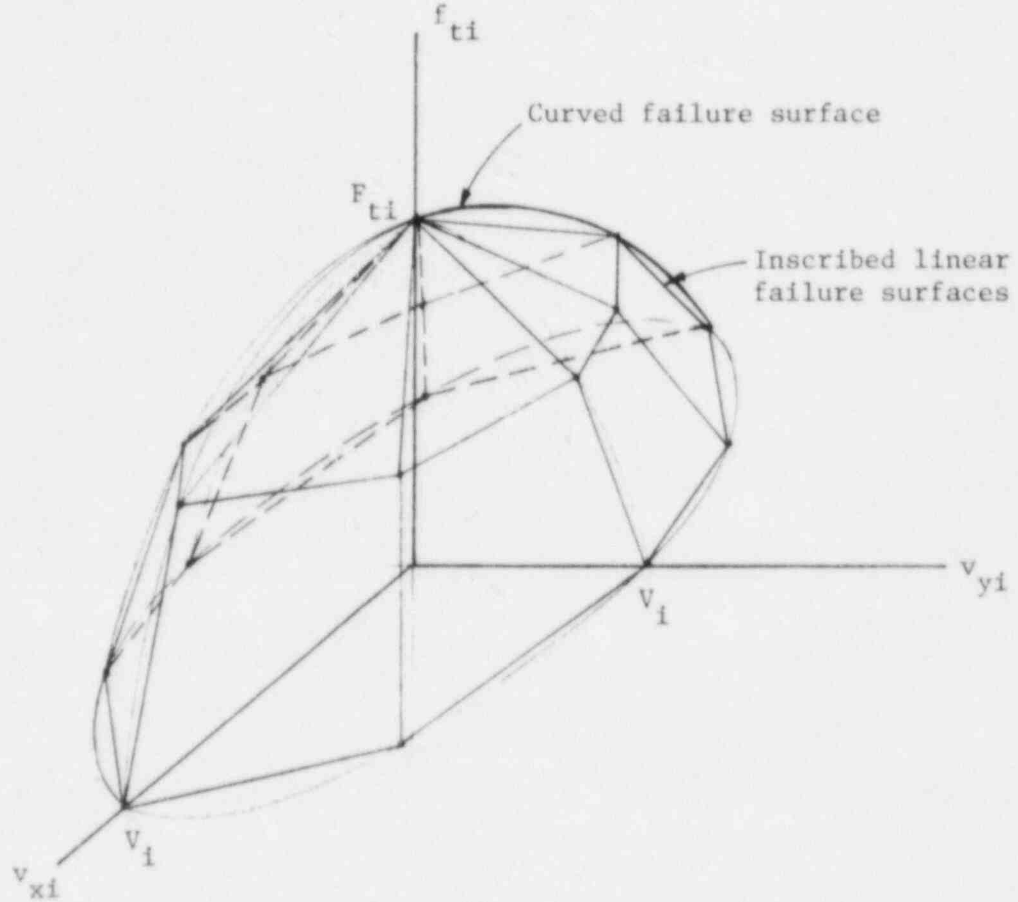

Figure 2: Failure Surface for the Anchor Bolts and the Planar Approximations

NUMERICAL SOLUTIONS

Equation (1) is a linear programming problem. It can be transformed to standard LP format and solved using commercially available mathematical programming packages. One can also take advantage of the specific format of the matrix and create a much more efficient algorithm for the particular problem at hand. Since reduction to standard LP form greatly increases the dimension of the coefficient matrix, a problem specific algorithm based on the simplex method is developed for the program. Using the developed solution procedure, the deformation and displacement at collapse are obtained as a by-product

DUALITY AND THE KINEMATIC APPROACH

Instead of using the lower bound theorem, the upper bound theorem can also be used to formulate the base anchorage problem. Mathematically the two formulations correspond to the dual relationship in a LP formulation [3]. The two formulations will yield the same solution for the critical load factor. Therefore, the solution for Equation (1) is the unique solution for the critical collapse mechanism.

COMBINATION OF EARTHQUAKES

Unlike the elastic analysis, the stresses due to earthquakes in different directions using limit analysis cannot be combined readily at the element level. Then how do we check for the safety of the base anchorage using limit analysis?

The earthquake is assumed to act in an arbitrary direction in the three-dimensional space. The critical g-level is determined using the limit analysis. By investigating all possible directions, a failure surface in the space is established. The failure surface is to be compared with the earthquake loading surface. The minimum ratio of the distasnces of the surfaces from origin defines the minimum factor of safety. The shape of the earthquake loading surface depends on the criteria for earthquake combinations.

A simple two-dimensional case is shown in Figure 3(a). The rectangle represent two earthquakes acting simultaneously, the ellipse represents the loading surface when the two earthquake effects are SRSS summed.

The three-dimensional loading surfaces are illustrated in Figure 3(b). Three situations are shown:

(1) Three-dimensional simultaneous,
(2) One horizontal and one vertical simultaneous,
and (3) Three-dimensional SRSS.

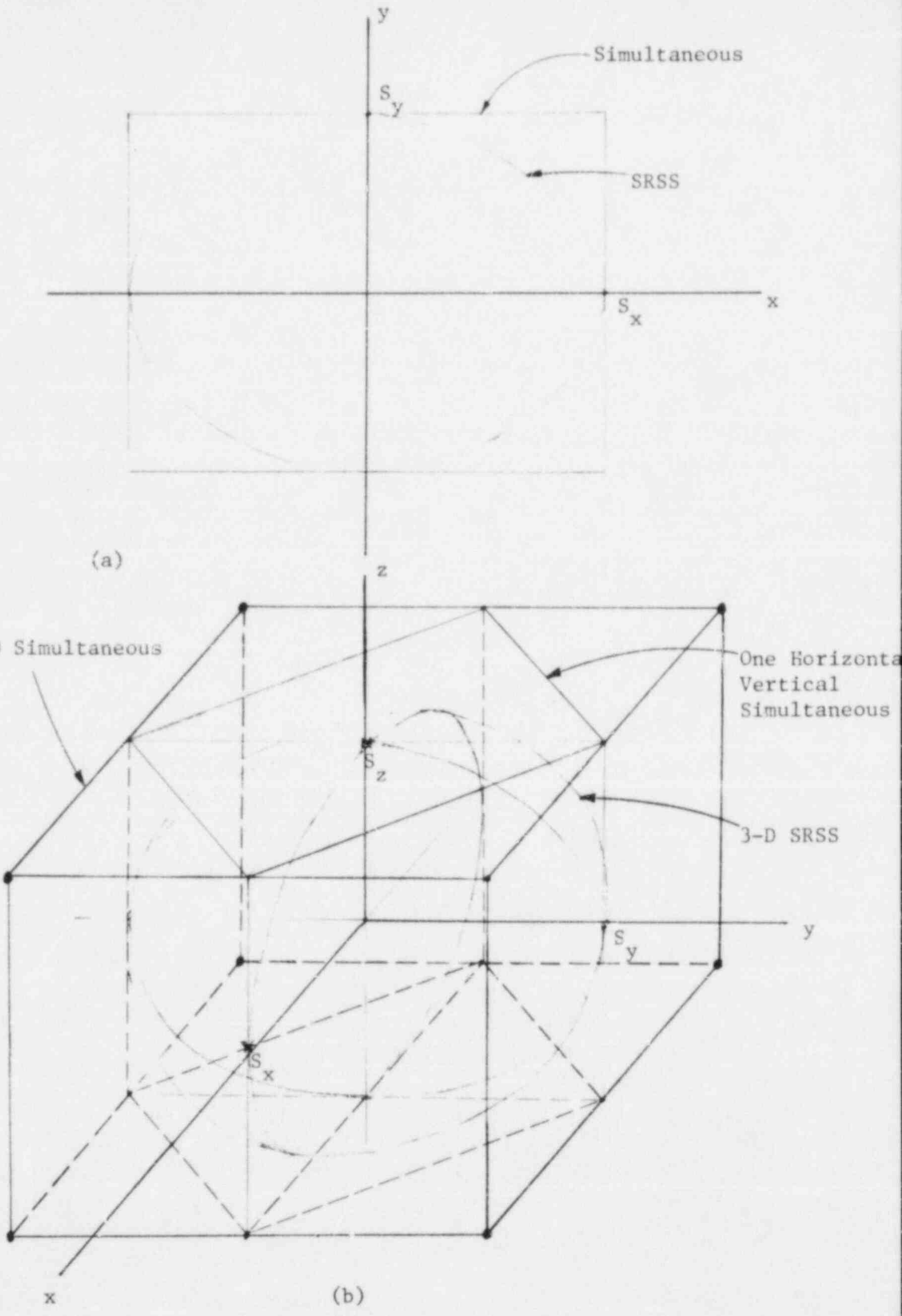

Figure 3: Loading Surfaces for Earthquakes, (a) Two-Dimensional Case, and (b) Three-Dimensional Case.

For cases (1) and (2) above, only eight corner points need to be checked for minimum factor of safety. This is because the failure surfaces are always convex, so that the minimum factor of safety can occur only in the direction of the corners. For case (3), the critical point can occur in any direction, all the directions must be checked.

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SEISMIC FRAGILITY RESULTS
DURING EPRI'S AGING/SEISMIC RESEARCH

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ABSTRACT

EPRI has sponsored research on the effects of aging on seismic performance of safety-related equipment for the last six years. During this research a total of 4653 electrical equipment items have been seismically tested to seismic levels in excess of 10g ZPA, using random multifrequency input with biaxial and triaxial methods. Both aged and unaged equipment types were tested in order to determine whether there are any seismic performance differences between them. The aged devices were both naturally and artificially aged. The devices, assembled and mounted simulating typical installation in nuclear power plants, were subjected to six seismic test response spectra, the greatest of which enveloped spectra used by the laboratory for most previous equipment tests for plant specific applications. Thus both aging and seismic stresses were purposely more severe than typically required for equipment qualification.

In spite of the severe seismic levels achieved in the simulations, a fragility level was found on only two percent of the components. The component types experiencing fragility were pressure switches, relays (general purpose and time delay), contactors, lamps, electronic alarms, switches (limit, rotary, and snap acting), a fuse block, and mounting brackets on several equipment types.

Fragility levels were not reached for transistors, diodes, integrated circuits, SCR, resistors, capacitors, P.C. boards, connectors, terminal blocks, fuses, transformers, solenoid valves, RTD, pressure transmitters, power supplies, meters, control stations, motors, circuit breakers (molded case), or inductors.

The fragility level was exhibited as structural failure for the mounting brackets, one of the pressure switches, and a fuse block. For the rest of the devices, the fragility level was detected as a change of state or temporary interruption in circuit contact (contact chatter). In these cases, the device operation was proper following seismic testing. Fragility levels were detected at ZPA ranges of 1.6g to 48g horizontally and 1.6g to 11g vertical. In the case of the pressure switches, the fragility level was related to the pressure applied to the switch. For three types, rotary switches, pressure switches, and limit switches, the fragility was related to aging.

INTRODUCTION

During research performed on the effects of aging and seismic performance, a significant amount of fragility data has been gathered on electrical safety-related equipment. The research has been sponsored by the Electric Power Research Institute (EPRI) and has been performed by Wyle Laboratories. The purpose of the research is to analytically and experimentally evaluate the correlation between aging and the ability of safety-related electrical components and devices to perform in a seismic environment. Testing was performed on over four thousand electrical equipment items. Approximately half of these items were aged. The aging simulated 50 years of time-temperature effects aging, a radiation level of 1E6 rads, and 50 years of operational cycling. All of the devices were then seismically tested. The seismic levels reached in excess of those normally required for equipment qualification.

RESEARCH PROGRAM

The program consisted of selection of equipment, aging, and seismic testing. Each of these is further discussed.

Selection of Equipment

All of the safety-related electrical equipment normally located in areas of nuclear plants not subject to steam line breaks was reviewed for possible inclusion in the research. From this equipment, test specimens were selected. The selection rationale excluded equipment which fell into one of three categories: equipment which is normally qualified for steam line breaks; equipment for which a multitude of designs and applications limit the practicality of generic type testing; and excessively large, complex, or costly equipment. Representative samples of the remaining equipment were selected for testing. The list of test equipment is shown in Table 1.

Table 1. Device Types Seismically Tested

Transformers	Inductors
Solenoid Valves	Pressure Switches
RTD	Electronics (ICs, SCRs, transistors, diodes, resistors)
Pressure Transmitters	Capacitors (Al, Mylar, Polyester, Tantalum, Ceramic, Paper, Polycarbonate)
Power Supplies	Terminal Blocks (Nylon, DAP, Melamine, Glass Phenolic, Phenolic)
Meters	Fuse Blocks (Phenolic, Melamine, Laminate, Polyester, Polycarbonate)
Control Station Assemblies	Fuses (Dual Elements, Single Element, Fast Acting, Slo-Blow, Fibreglass, Fibre, Melamine, Ceramic, Glass)
Switches (Rotary, Limit, Snap Acting)	
Relays (Time Delay, G.P., Contactors)	
Electronic Alarms	
Motors	
Circuit Breakers (Molded Case)	

Also, the selection process included analysis of the age sensitivity of the test specimens. Certain models of each device type were chosen because they contained age sensitive materials in critical applications. Thus the selection process assured that the most age sensitive materials were tested.

Aging

The testing program was designed such that both aged and unaged devices of the same device type would be seismically tested at the same time. This assured that both aged and unaged devices experienced the same seismic levels. The aged devices were made up of devices which were both naturally and artificially aged. The naturally aged devices were provided by utilities and had been in use for approximately twelve years. New samples of each device type were artificially aged to the equivalent of fifty years. This was accomplished by performing an accelerated aging program.

The accelerated aging consisted of simulation of the aging effects of time-temperature, radiation exposure, and operational cycling. Time-temperature effects were simulated by thermal aging at high temperatures. Arrhenius techniques were used to provide the equivalent of 50 years of thermal aging. Additional samples were aged to the equivalent of 12 years for a comparison with the naturally aged devices. The radiation exposure was accomplished by exposing the devices to the ionizing radiation of Cobalt-60 in a hot cell. The total integrated dose was 1E6 rads. Operational cycling was accomplished by operating the devices, such as energizing and de-energizing relays by applying electrical power and removing power. For relays which could normally cycle frequently, the number of operational cycles was 60,000. The total operational cycles for switches, circuit breakers, pressure switches, solenoid valves and motors, which normally cycle less frequently, was 400.

The devices tested during this research, their age status, and quantities are listed in Table 2.

Table 2. Test Specimen Age Status and Quantities

Device	Total	Unaged	Naturally Aged	Artificially Aged	
				12 Yr	50 Yr
Diodes	100	25	0	0	75
Transistors	80	20	0	0	60
IC	206	63	0	0	143
SCR	45	15	0	15	15
Resistors	2168	1048	0	63	1057
P.C. Boards	41	14	0	0	27
Connectors	16	8	0	0	8
Sockets (IC, Transistor, Relay)	258	76	0	0	182

Table 2. Test Specimen Age Status and Quantities (Continued)

Device		Total	Unaged	Naturally Aged	Artificially Aged	
					12 Yr	50 Yr
Capacitors -	Aluminum	280	140	0	20	120
	Ceramic	100	25	0	0	75
	Mylar	50	25	0	0	25
	Polyester	100	50	0	0	50
	Paper	150	45	0	30	75
	Polycarbonate	100	50	0	0	50
	Tantalum	80	20	0	0	60
Terminal Blocks -	Nylon	20	10	0	0	10
	DAP	20	10	0	0	10
	Melamine	48	24	0	12	12
	Nylon 6.6	56	28	0	14	14
	G.F. Phenolic	70	30	0	10	30
	G.P. Phenolic	50	12	10	6	22
Fuse Blocks -	Phenolic	60	20	0	10	30
	Melamine	20	10	0	0	10
	X Laminate	2	1	0	0	1
	G.F. Polyester	4	2	0	0	2
	Polycarbonate	20	5	0	5	10
Fuses -	D.E. Fibreglass	20	10	0	0	10
	D.E. Fibre	20	10	0	0	10
	Melamine	20	10	0	0	10
	Ceramic SB	40	20	0	0	20
	Glass	20	10	0	0	10
	D.E. SS	20	10	0	0	10
	Glass SB	20	10	0	0	10
	Glass Melamine	20	10	0	0	10
Wire - PVC		300'	150'	0	0	150'
Transformers -	Filament	8	2	2	2	2
	Instrument	6	3	0	2	1
Solenoid Valves		7	1	5	0	1
RTD		6	1	2	0	3
Pressure Transmitter		6	1	4	0	1
Power Supplies		3	1	1	0	1
Meters		9	1	6	0	2
Control Stations		6	2	0	2	2
Lamps		15	4	3	4	4
Lamp Sockets		15	4	3	4	4
Rotary Switches		10	2	4	2	2
Time Delay Relays		16	2	10	2	2
Contactors		7	2	1	2	2
Electronic Alarms		4	1	2	0	1
Motors		4	1	2	0	1

Table 2. Test Specimen Age Status and Quantities (Continued)

Device	Total	Unaged	Naturally Aged	Artificially Aged	
				12 Yr	50 Yr
Pressure Switch Assembly	18	8	0	7	3
Switches	30	13	0	12	5
Circuit Breakers - MC	23	6	5	6	6
Inductors	26	12	2	0	12
Limit Switches	6	1	3	0	2
Relays G.P.	79	27	5	22	25
Snap Acting Switches	25	11	0	7	7

Seismic Testing

Seismic testing was performed in two phases. Phase one was performed biaxially on some of the components, and its results are presented in Reference 1. Phase two was performed triaxially on the majority of devices. Its results await publication. All devices of the same type were tested together so that the seismic levels of the aged and unaged devices would be the same. Each device was mounted simulating its typical mounting and orientation in nuclear plants. For instance those items such as transistors and integrated circuits (ICs) were mounted on P.C. boards, installed in card racks, and mounted in cabinets. Pressure switches were mounted on steel panels which were attached to unistrut which was attached to rigid wall fixtures. This level of detail in the mounting assured applicability to actual field installed configurations.

The seismic spectra for these devices was determined from a review of architect-engineer's seismic required response spectra from over twenty nuclear plant specifications. A spectrum was generated by enveloping all of these spectra. The result is shown as the Generic Response Spectrum (GRS) on Figure 1.

All devices were subjected to six earthquake simulations of increasing magnitude. The majority of these earthquakes envelop response spectra used by the laboratory in equipment tests for plant specific applications. Thus the seismic stresses were purposely more severe than typically required for equipment qualification. Figure 1 also shows a typical horizontal control accelerometer mounted on the table on one of the seismic test runs. Additional accelerometers were utilized to record the motion of each device tested.

RESULTS

The devices were operational and monitored during and after the seismic testing in order to determine the performance of the devices. The results were analyzed for performance during the seismic tests and after the seismic tests. In spite of the severe seismic levels achieved in the simulations, a fragility level was found on less than two percent of the devices. The results during seismic testing are presented first.

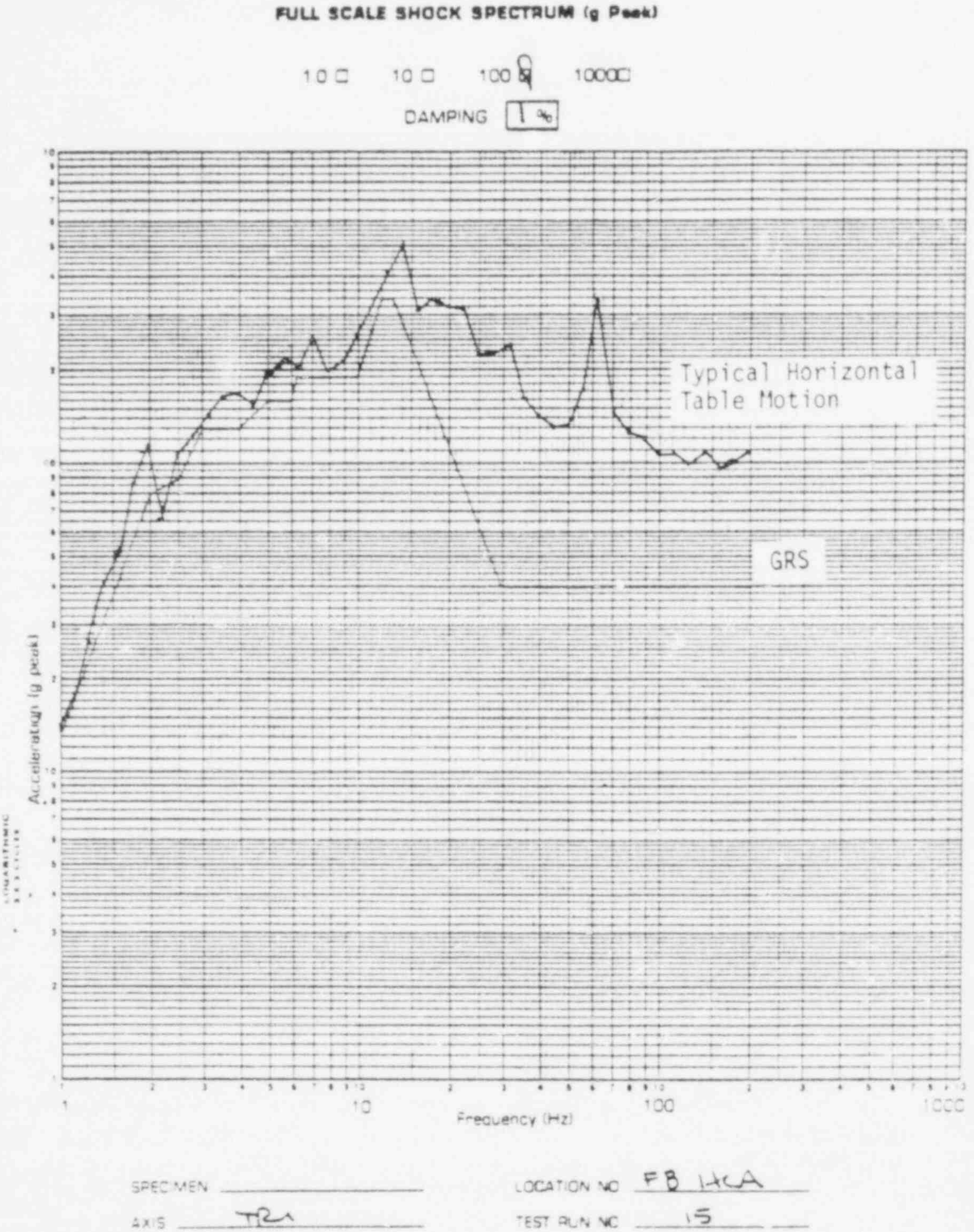

Figure 1. Comparison of Typical Horizontal Table Motion To Generic Response Spectrum (GRS)

During seismic testing the vast majority of devices did not experience fragility. Table 3 shows the results of the devices which did experience fragility during the testing (less than two percent). It also shows the total of each of the devices tested and the type of fragility noted. Contact chatter represented 86 percent of the fragility failures, which for some applications may not be a critical failure mode. The fragility level for each of these devices is shown in Table 4, which represents the lowest seismic level in zero period acceleration (ZPA), horizontally, and vertically at which each type of device experienced fragility.

For those devices not experiencing fragility during seismic testing, the highest seismic level achieved without fragility is shown in Table 5.

Table 3. Test Results During Seismic Testing

Device	Aged Failures/Total	Unaged Failures/Total	Type of Fragility
Rotary Switches	7/7	0/2	Contact Chatter
Electronic Alarms	2/3	0/1	Contact Chatter
Contactors	3/5	1/2	Contact Chatter
Lamps	5/8	4/4	Broken Element
Limit Switches	4/5	0/1	Contact Chatter
Pressure Switches	11/17	7/13	Contact Chatter
Relays	18/46	10/25	Contact Chatter
Snap Acting Switch	3/14	1/11	Contact Chatter
Time Delay Relays	7/14	2/2	Contact Chatter
Meter	1/8	0/1	Loose Screw
Motor Bracket	1/1	0/1	Structural Failure
Fuse Blocks	1/68	0/88	Structural Failure

Table 4. Lowest Fragility Level Noted

Device	ZPA (g)	
Rotary Switches	H-8	V-3
Electronic Alarms	H-3	V-1.7
Contactors	H-20	V-1.7
Lamps	H-40	V-8
Limit Switches	H-3	V-3
Pressure Switches	H-1.6	V-1.6
Relays	H-4	V-2
Snap Acting Switches	H-8	V-3
Time Delay Relays	H-3	V-1.7
Motor Bracket	H-3.8	V-2.9
Fuse Block	H-48	V-11

Table 5. Highest Seismic Level Without Fragility

Device	ZPA (g)
Transformers	H-50 V-10
SOV	H-10 V-12
RTD	H-12 V-10
Pressure Transmitter	H-12 V-10
Power Supplies	H-29 V-12
Meters	H-29 V-12
Control Station Assemblies	H-50 V-12
Motors	H-12 V-12
Circuit Breakers	H-50 V-12
Inductors	H-50 V-12
Electronics	H-22 V-30
Terminal Blocks	H-50 V-12
Fuses	H-50 V-12

For three devices, rotary switches, pressure switches, and limit switches, the fragility was related to aging. For the pressure switches, fragility was also related to having air pressure applied to the switches. More aged pressure switches and fewer unaged pressure switches experienced contact chatter when air was applied to the switches.

For post-seismic operability, only twelve devices, representing one fourth of one percent of those tested, were not operational after seismic testing (see Table 6).

Table 6. Results: Post-Seismic Operability

Device	Aged Failures/Total	Unaged Failures/Total
Fuse Blocks	1/68	0/88
Lamps	5/8	4/4
Pressure Switches	1/17	0/13
Motor Bracket	1/1	0/1

It was interesting to note that for all of the fragilities relating to aging, the failure mode was contact chatter with the exception of the motor bracket. This result may not be significant in actual applications because contact chatter may not affect safety-related functions in many applications. Also, since the most age sensitive materials were tested in this research, devices containing less age sensitive materials may not exhibit fragility. Lastly, the fragility levels are significantly greater than the seismic levels experienced in actual earthquakes.

SUMMARY

This research has tested significant quantities and varieties of safety-related electrical equipment to significant seismic levels. The levels tested are higher than are

predicted by the plant designers of nuclear plants. Less than two percent experienced fragility. Of those experiencing fragility, eighty-six percent of the fragility failure modes was contact chatter, which is not a significant failure mode in many device applications. Fragility failures which resulted in post-seismic operability failures were detected in less than one fourth of one percent of those tested.

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SESSION III

CATEGORIZING EQUIPMENT AND EXISTING TEST RESULTS

GENERIC SEISMIC QUALIFICATION OF EQUIPMENT USING EXISTING TEST DATA

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ABSTRACT

This paper presents the results of the first phase of an ongoing program sponsored by the Electric Power Research Institute with overall objective of demonstrating the seismic adequacy of as much nuclear power plant equipment as possible by means of collating and evaluating existing seismic qualification test data. These data are used to construct "ruggedness" spectra below which equipment in operating plants designed to earlier earthquake criteria would be generically qualified.

INTRODUCTION

Concern over the seismic adequacy of equipment in older operating nuclear plants not designed to today's rigorous standards has motivated several recent studies which utilize a new approach to demonstrate the seismic "ruggedness" of mechanical/electrical equipment. The first characteristic of this new approach is the use of "experience" data. The second characteristic is the demonstration of adequacy on a "generic" basis. In 1982, the Seismic Qualification Utility Group (SQUG) sponsored a study [1] that investigated the seismic adequacy of eight classes of equipment using historic earthquake data. Based upon the compiled experience data which demonstrated that hundreds of equipment items found in several non-nuclear power plants were undamaged and functional after experiencing earthquakes, the SQUG proposed that, on a generic basis, the eight classes of similar nuclear plant equipment could function following seismic motion levels less than or equal to the documented earthquake motion levels, so long as certain conditions were met. An independent panel of experts, the Senior Seismic Review Advisory Panel (SSRAP), reviewed the proposed generic approach and, after an extensive review, concluded [2] that, with certain caveats (restrictions), the equipment within the eight classes found in nuclear power plants need not be further tested or specifically (traditionally) reviewed for seismic adequacy.

Another type of experience data available is the large amount of information collected during seismic qualification testing of nuclear power plant equipment. The inclusion of test data would augment the historical earthquake data by further demonstrating the seismic adequacy of equipment

at high motion levels and by specifically addressing the issue of functionality during a seismic event. In 1984, the Electric Power Research Institute (EPRI) initiated a project to collect and evaluate existing seismic test data. The overall objective of this project is to demonstrate the seismic adequacy of as much nuclear power plant equipment as possible by means of collating and evaluating existing test data. The specific goals are to establish 1) the classes of equipment for which sufficient qualification test data exist, 2) the generic ruggedness level for each equipment class, and 3) the functionality of equipment required to operate during seismic motion ("operability") and after seismic motion ("survivability"). The anticipated program results are 1) both operability and survivability ruggedness levels for each identified equipment class, 2) inclusion rules and cautions for each equipment class, 3) field checklists for screening of equipment for class applicability, and 4) a computerized EPRI data base readily available to utilities. The project is divided into two phases. Phase I [3] was a pilot program. Phase II (ongoing) involves extension of the methodology to additional equipment classes.

The specific objectives of the pilot program were 1) develop a list of candidate equipment classes using utility input; 2) establish locations of test data sources and their quantity, quality, and availability for the candidate equipment classes; 3) develop and demonstrate technical approaches for collecting and evaluating available test data; and 4) implement the collection and evaluation procedures for eight selected equipment classes. This paper gives a brief overview of the pilot EPRI program.

CANDIDATE GENERIC EQUIPMENT CLASSES

In order to define the equipment in operating plants which would be addressed by generic studies, the SQUG identified the nuclear plant equipment types necessary for achieving and maintaining a safe hot shutdown status, assuming loss of off-site power under an assumed no-LOCA condition. Table 1, generated from the SQUG-identified hot shutdown equipment list, gives the candidate equipment classes for the EPRI test data program.

SCOPE AND APPROACH

The scope of the pilot program was to develop the methodology for establishing generic ruggedness levels and to demonstrate the methodology for the following equipment classes:

- Batteries and Battery Racks
- Inverters
- Battery Chargers
- Electrical Penetration Assemblies
- Motor-Operated Valves
- Motor Control Centers
- Switchgear
- Relays

TABLE 1: CANDIDATE EQUIPMENT CLASSES FOR EPRI STUDIES

Mechanical

MOTOR-OPERATED VALVES*† (motor operators, valves with operators)
AIR-OPERATED VALVES* (pneumatic operators, valves with operators)
SOLENOID VALVES
HVAC (fans, blowers, chillers, dampers)
HORIZONTAL PUMPS AND MOTORS
PUMPS (turbine and diesel-driven)
MAIN STEAM ISOLATION VALVES
PILOT-OPERATED S/RVs
SPRING-OPERATED S/RVs
PORVs
[NSSS MECHANICAL EQUIPMENT] (CRDMs)
[VERTICAL PUMPS AND MOTORS*]
[AIR COMPRESSORS]

Electrical

SWITCHGEAR*† (medium-voltage, metal-clad switchgear <5,000 V, low-voltage metal-enclosed switchgear <600 V, control/protective relays, auxiliary devices)
MOTOR CONTROL CENTERS*† (low-voltage MCC <600 V, high-voltage motor starters <5,000 V, motor starters, contractors, circuit breakers, fusible switches, control/protective relays, panels, transformers, auxiliary devices)
BATTERIES AND RACKS† (lead acid storage batteries, rack with batteries, battery cells)
BATTERY CHARGERS† (single-phase, three-phase, <600 V, floor and wall mount, controls/protective relays)
INVERTERS† (single-phase, three-phase, <600 V transformer, controls/protective relays)
DISTRIBUTION PANELS (AC/DC panel boards, switchboards, circuit breakers, switches, <600 V)
ELECTRICAL PENETRATION ASSEMBLIES†
TRANSFORMERS (other than unit substation, dry type, <600 V)
AUTOMATIC TRANSFER SWITCHES
[TRANSFORMERS*] (unit substation type, 5,000 V/600 V)
[MOTOR GENERATOR SETS]
[DIESEL GENERATORS AND AUXILIARY EQUIPMENT] (engine, generator, turbo charger, intercooler, lube pump, water pump, air-start valve, <10,000 kW)

Instrumentation

TRANSMITTERS (pressure, level, flow)
SWITCHES (Pressure, level, flow)
CONTROL PANELS (and associated components)
INSTRUMENT RACKS (and associated components)
INSTRUMENT READOUTS (displays, indicators)
[RTDs AND T/Cs]
[NEUTRON DETECTORS]

Relays

CONTACTORS
CONTROL/PROTECTIVE RELAYS†

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* = Addressed in SQUG pilot earthquake data program.
† = Addressed in EPRI pilot test data program.
[] = Not recommended for EPRI Phase II program.

In general, the pilot study approach involved the identification, collection, and aggregation of existing qualification and fragility test data into a computerized data base. First, the sources of test data were identified, then test data were extracted from the available test reports and collected into a structured data base. Once the data had been collected, they were aggregated into sets for which a Generic Equipment Ruggedness Spectrum (GERS) was eventually constructed.

The GERS is defined as the response to input motion at the base or support point for which equipment of a given class have been demonstrated, on the basis of test experience, to have sufficient ruggedness to perform as required.

The procedure for constructing GERS described in this paper is intended to produce a qualification spectrum that has a confidence level comparable to qualification spectra generated by the test or analysis methods in current industry standards. Therefore, it can be used to qualify a particular equipment item that 1) satisfies specific "inclusion rules" (to be discussed further below) and 2) has a Required Response Spectrum (RRS) that is enveloped by the GERS.

The GERS can also be used as a basis for judging the seismic adequacy of equipment in older plants <u>not</u> designed to current qualification standards or to estimate the seismic margin of equipment in plants that may be reevaluated with respect to earthquake levels <u>greater</u> than the design SSE. However, the manner in which equipment input motion should be specified for these uses of the GERS approach will be investigated in future EPRI studies.

DATA COLLECTION

The methodology involved data collection from utilities, test labs, and other sources. The pilot program showed that there is extensive test data available with relatively high input motion levels, that proprietary issues can be handled without difficulty, and that it is feasible to collect the data.

The collection procedure requires that certain information be extracted from test reports and evaluated in a computerized data base. Given a test report that has met the initial screening requirements concerning suitability and completeness, certain data are extracted and entered into a computer file structure, organized into "fields" for subsequent manipulation and accessing. The data base fields provide a basic description of the equipment item and summarize the information available. The data base includes information concerning the equipment descriptors; the size, weight, and manufacturer; the type of tests and test documentation; the anchorages used during testing; the number of subcomponents tested (if any); the number of TRS available; and the results of function tests (if performed), including failures (if any).

DATA EVALUATION

Data are evaluated in the following manner. The data base is accessed to aggregate data corresponding to specific parameters of interest. The spectral data are standardized to 5% spectral damping, and the TRS are weighted according to whether they are biaxial or single-axis excitation and random or narrow-banded input motions. The diversity of the equipment represented by the test data is established, and subclasses are defined, as required, which have low diversity. The final step of the evaluation is to construct a GERS for the specified subclass of equipment. This evaluation procedure is outlined in Figure 1.

In general, a low-diversity subclass of equipment would include several manufacturers and models which are essentially similar in dynamic behavior, mechanical design, internal components, operating principle, etc. Each item would have its own set of test data, and some failures may have occurred. First, the representative TRS data (SSE level) for the tests without failures are combined and an upper envelope constructed. In general, the GERS would conform to these guidelines:

- The GERS will be equal or less than the envelope of the representative spectra of tests without failures.

- As a practical matter, GERS are constructed with a maximum of four or five straight line segments beneath the envelope of satisfactory data (this automatically introduces a degree of conservatism).

- In general, the GERS is constructed with as high an amplitude as possible in accordance with engineering judgement concerning the number of manufacturers represented, number of different models, number of items tested, etc. Special attention is paid to specification of ruggedness spectral amplitude in the range of natural frequency noted for the items tested.

- Next, the representative spectra for the tests with failures are combined and a lower envelope constructed. The GERS is checked to ensure that it is beneath the lower envelope of test spectra that produced failures. In some cases, however, the failure test spectra can have regions (usually regions of frequency extremes) that have lower spectral amplitude than the GERS but which are not likely to have affected the failure mode. Thus, on a case-by-case basis, a GERS may be greater in certain frequency regions than the lower envelope of failure data.

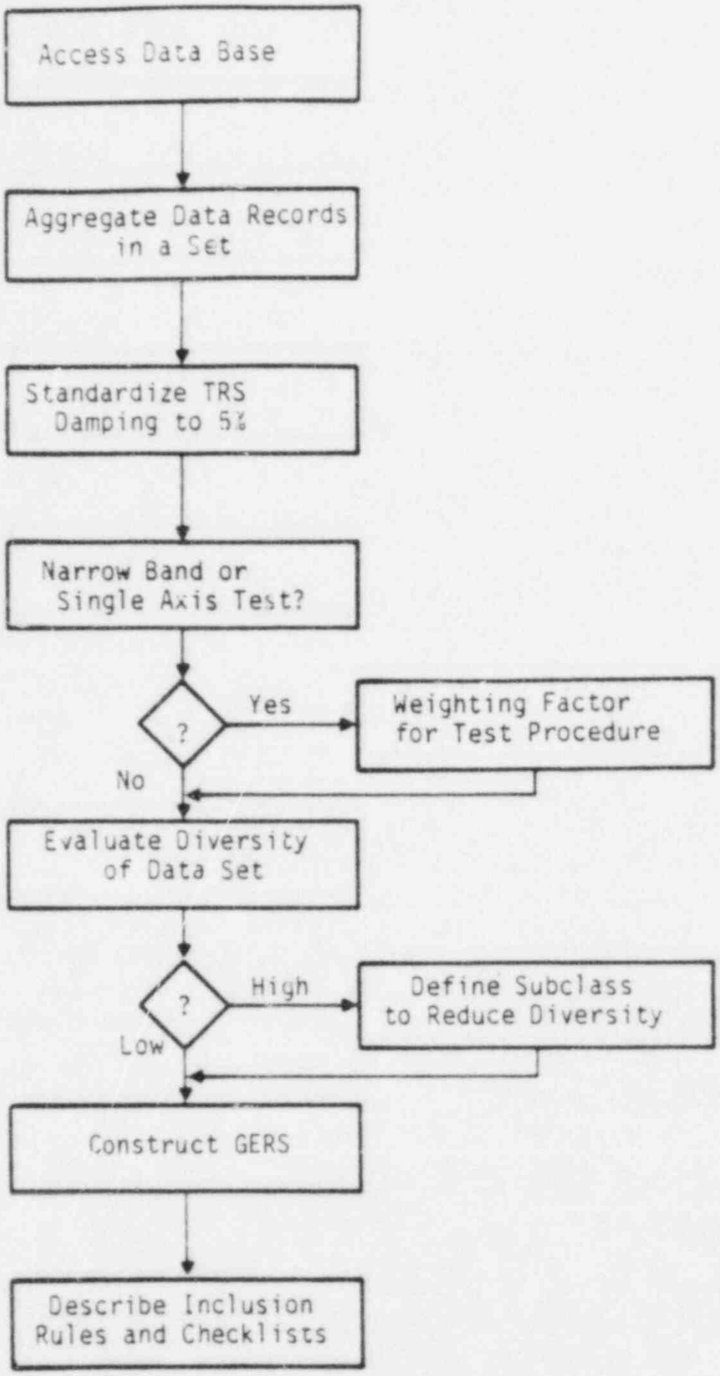


Figure 1: Evaluation Procedure

RESULTS

For five of the eight equipment classes (battery racks, battery chargers, inverters, motor valve operators, and electrical penetration assemblies) examined in the pilot study, preliminary generic equipment ruggedness spectra (GERSs) were developed from existing test data. These preliminary GERSs may change depending upon evaluation of additional data in Phase II of the EPRI program. In all cases in the pilot program, the GERSs correspond to a level for which all the equipment in the class demonstrated operability. To date, there is insufficient data to develop potentially greater GERSs corresponding to survivability or structural integrity. For floor- or wall-mounted equipment (battery racks, battery chargers, inverters, and electrical penetration assemblies), the GERSs developed have amplitudes which are in the range of 2 to 5 g (when normalized to five-percent spectral damping). Spectral amplitudes for line-mounted items (motor valve operators) are in the range of 10 to 20 g. These ruggedness levels exceed the amplitude of moderate earthquake floor spectra by a factor of 2 to 5. Therefore, it is expected that the final GERSs would be sufficient to qualify almost all equipment within these classes in all but plants with very high required response spectra. More work is also needed to establish the applicability of the preliminary GERS to older vintage equipment.

EXAMPLE: RACKS WITH STATIONARY BATTERIES

The following example for racks with stationary batteries illustrates a typical data set and the construction of a GERS. The data set includes 19 sets of OBE/SSE qualification tests conducted on lead storage batteries supported on racks with rail restraints. Rack configurations represented are two-step, multi-cell and single-tier, three-cell racks. Thirty-five different models distributed among three major manufacturers are represented in the data set. In total, over 150 separate cells were subjected to a rack-mounted seismic environment. Included in the data are generic test programs conducted by each manufacturer to qualify their cells/racks to sufficiently high input levels which would preclude any additional qualification effort required for specific nuclear applications. Virtually all stationary batteries used by the power industry are represented by these data. Both bolted and welded rack anchorages were utilized in the test programs.

Tests were performed using random, independent, biaxial inputs. Tests were performed with both new and aged specimens. Both artificially and naturally thermally aged specimens were tested. However, all manufacturers have had difficulty with artificially aged cells failing prematurely (cracking and spurious operation) due to material degradation caused by accelerated aging procedures which use excessively high temperatures. Thus, in some cases, naturally aged cells were removed from service and utilized in the test programs.

Acceptable battery performance is usually defined in test reports to be

the ability to deliver 80% rated current and voltage during or after the tests without spurious operation. In a typical test, voltage and current for an artificial load were monitored.

Performance exceptions noted in the test reports were limited to cracking of artificially aged plastic jars, propagation of existing (i.e., prior to test) jar cracks, and a flame arrester cracked in cell shipment. The exceptions concerned with pre-test defects are not considered relevant; however, the issue of artificially aged specimens developing cracks, demonstrating spurious behavior, and not meeting post-test performance cannot be evaluated without further information. For purposes of the pilot study, they were considered failures. A failure in one test showed the importance of proper placement of spacers and shims between individual cells and between cells and racks to prevent independent motion of the cells. A gap between two cells and an adjacent spacer caused crushing of a plastic spacer and allowed a cell to impact the restraints, resulting in spurious behavior.

Figures 2 and 3 show the horizontal TRS (standardized) data for which the test batteries performed satisfactorily. The proposed GERSs shown for both rack configurations are less than the envelope of the satisfactory test data.

ADDITIONAL RESULTS

Preliminary GERSs for battery chargers and inverters are shown in Figures 4 and 5, along with the data for satisfactory tests. Associated with each final GERS will be inclusion rules which define the characteristics of the equipment included in the subclass and covered by the GERS. In general, the inclusion rules will specify the characteristics (weight, size, etc.) of the equipment comprising the data base and, perhaps, limitations on the manner in which the equipment is installed.

For three of the equipment classes (motor control centers, switchgear, and relays) considered in the pilot program, definition of GERSs is not possible at this time. The diversity of equipment characteristics within these three classes is such that additional data is required for definition of ruggedness levels for both operability and survivability. Sources with readily available additional data have been identified in Phase I.

CURRENT WORK

Additional work is being performed in Phase II, planned for 1985-1986. The effort includes the evaluation of some additional data for the pilot program equipment classes, collection and evaluation of data for approximately 20 additional classes of equipment, construction of additional GERSs, and corresponding inclusion rules and cautions.

A GERS provides a measure of equipment capability based on available test data. It does not address 1) the issue of in-plant anchorage capacity

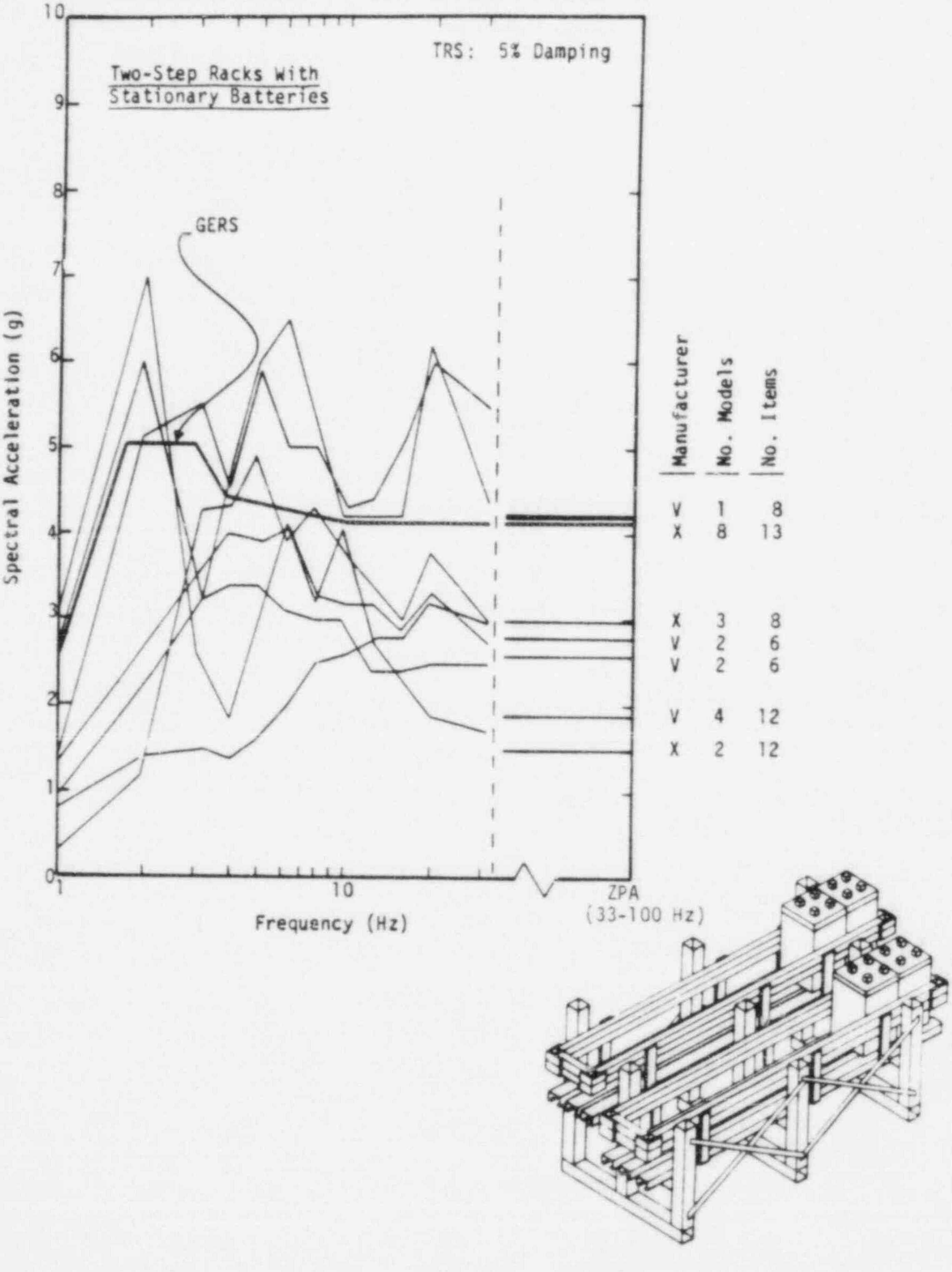
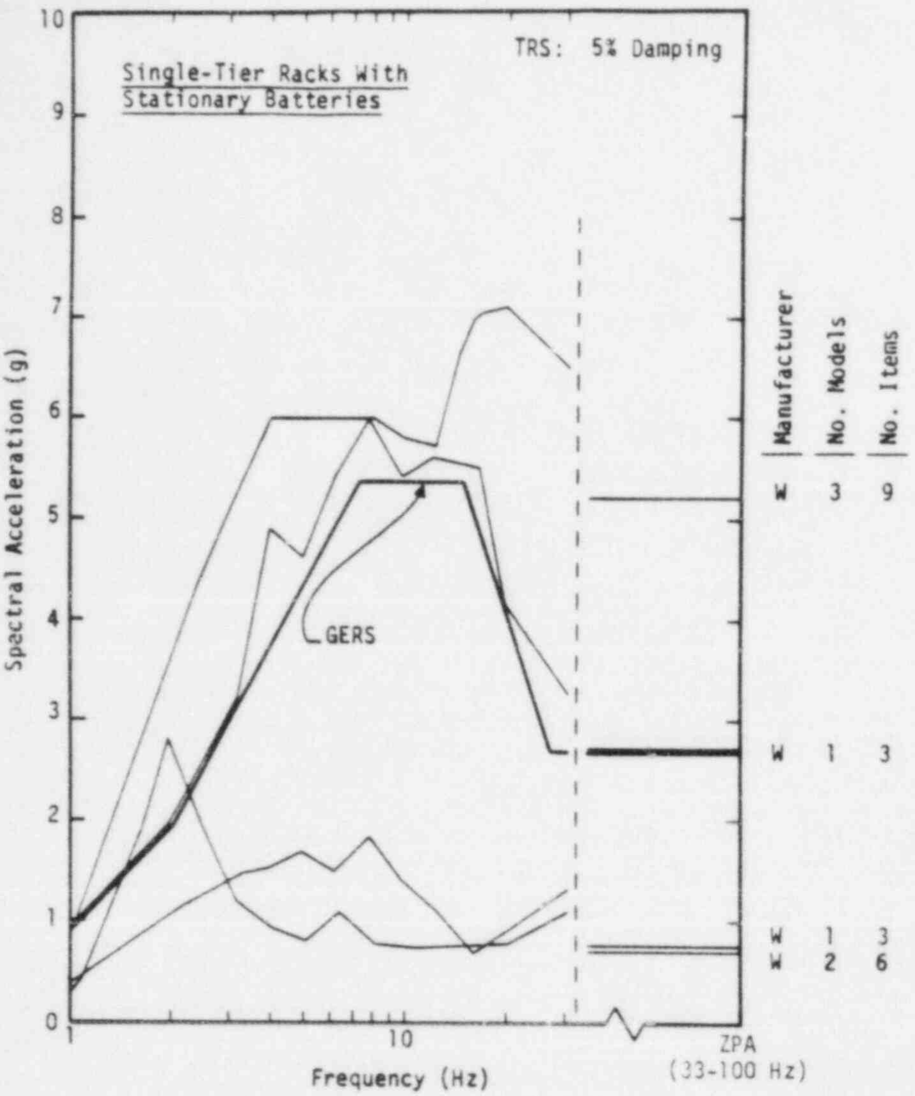


Figure 2: Comparison of GERS With Ruggedness TRS DATA: Operability for Two-Step Racks With Stationary Batteries



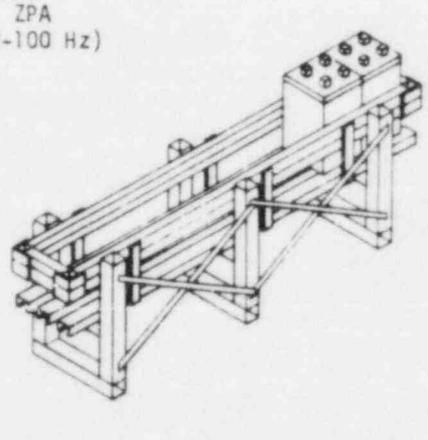
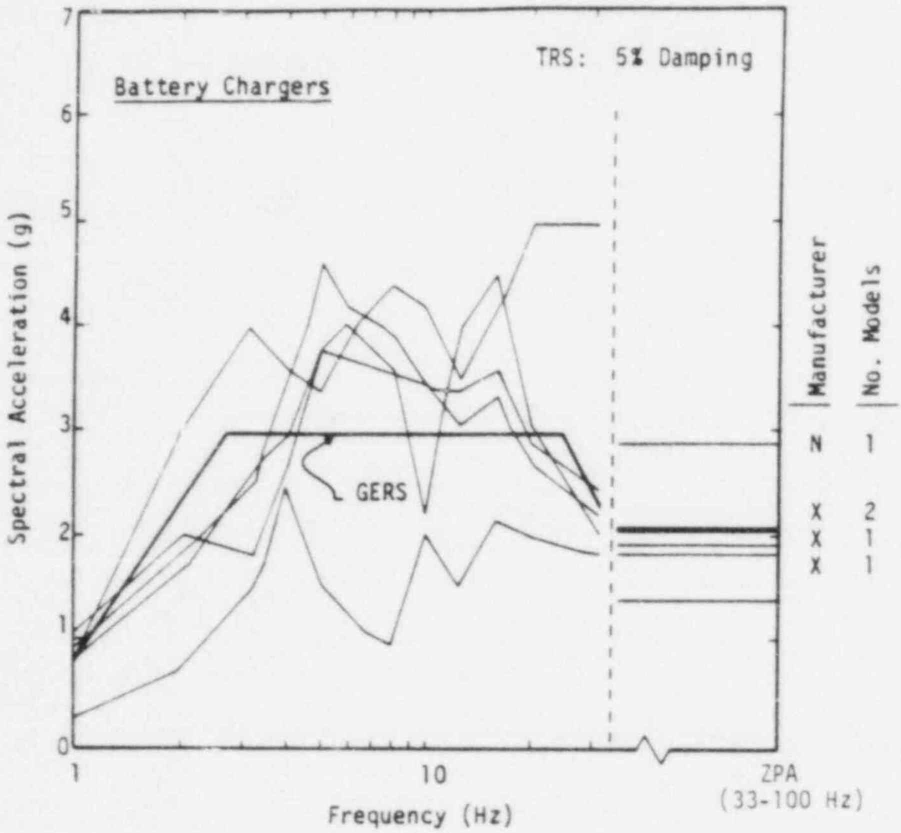


Figure 3: Comparison of GERS With Ruggedness TRS DATA: Operability for Single-Tier Racks With Stationary Batteries



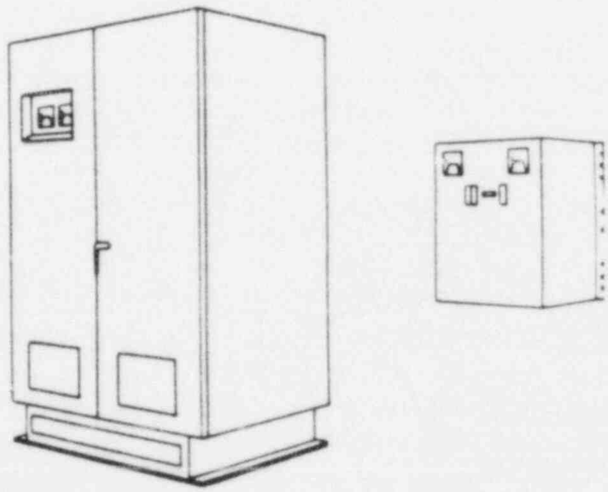
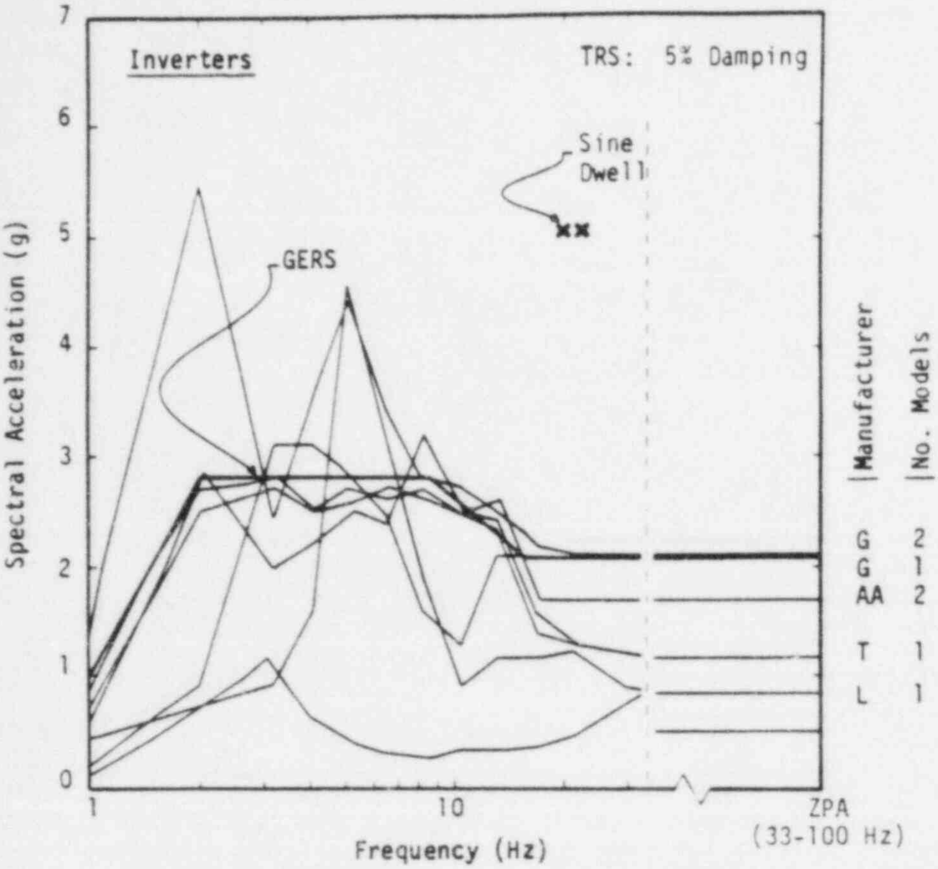


Figure 4: Comparison of GERS With Ruggedness TRS DATA: Operability for Battery Chargers



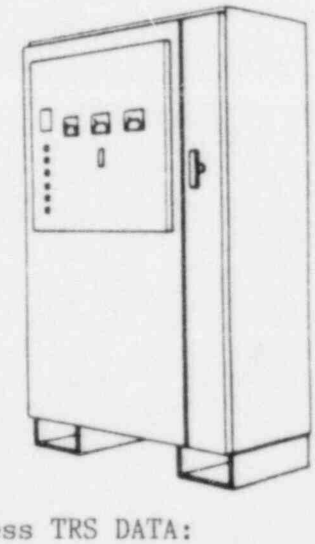


Figure 5: Comparison of GERS With Ruggedness TRS DATA: Operability for Inverters

or 2) any plant-specific situation which could affect equipment performance during an earthquake (e.g., impact of nearby structures). Inspection procedures to be developed in Phase II will include cautions concerning equipment condition and proximity of adjacent equipment and structures. Guidelines for anchorage adequacy are being developed in other EPRI projects.

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REVIEW OF VALVE-OPERATOR FRAGILITY RESULTS

By

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ABSTRACT

In BWR nuclear plants, a large number of motor-operated valves are located inside the Reactor Building or on piping attached to it, and are therefore affected by the suppression pool hydrodynamic loads, in addition to seismic loads. Since the valve operators are used industry-wide, and initial results of piping analyses from various BWR plants showed significantly high levels of accelerations due to these dynamic loads, a program to qualify the actuators to their fragility limits was developed and carried out. Also, these dynamic loads are caused by a large number of hydrodynamic events which translate into thousands of stress cycles that can contain frequency content typically up to 100 Hz. Therefore, the program was designed such that if an anomaly were to occur at any stage of the testing, the tests completed up to that stage would be meaningful. The completed tests would allow setting specific qualification limits for various dynamic loading contributors and combinations, with consideration of magnitudes, stress cycles and frequency content. These limits can be later reconciled with the final accelerations (corresponding to these loads) obtained from the as-built piping analyses.

The material presented herein discusses the dynamic qualification requirements, development of a fragility test method and its rationale, test plan and test results with observed anomalies. The tests identify qualification limits for these actuators, which are applicable provided certain corrective actions are taken.

INTRODUCTION

The tests discussed herein were conducted in the 1981 - 1982 time frame, primarily to facilitate qualification of valve operators used in Boiling Water Reactor (BWR) nuclear power plants. Since the final dynamic loads at the valve operators from the piping analysis were not available at that time, it was necessary to establish fragility limits for these operators. The fragility results were later used as one of the acceptance criteria for piping design. The normal seismic qualification test program was modified to address the BWR containment dynamic load characteristics, i.e., large number of loading events and frequency content up to about 100 Hz. Two motor-operators were selected in this test program to qualify a family of Limitorque motor-operators.

The development of the test program was based on the dynamic input parameters enveloping several BWR plants. The tests were conducted in two test facilities. The first series of tests was performed on two valve-operator assemblies, but in the second series of tests, only the motor-operators were tested. The tests considered loads from the seismic and hydrodynamic events, and the applicable load combinations.

A single-frequency test method, consisting predominantly sine-beat test was used to qualify these actuators. In addition, to cater to any hard-mounted operators, random, multifrequency testing was also performed. Initial testing was performed to a specific set of accelerations for each loading condition. The test levels were then increased in incremental values, and at each level, tests were performed for several sine-beats at test frequencies in the range 1 - 100 Hz. Thus, fragility levels were established for both actuators. The results of these tests are summarized herein.

SEISMIC/DYNAMIC AND FUNCTIONAL REQUIREMENTS

The fragility test program consisted of the following requirements for the qualification of the motor-operators:

- ° Preparatory Baseline Tests-stroke times with different voltages.
- ° Resonance search, aging the operator to normal plant vibrations.
- ° Dynamic testing to the following loads and load combinations:
  - (a) SRV - Number of tests simulate all the SRV events during plant's life.
  - (b) SRV & OBE - Equivalent to 5 OBE events, with simultaneous occurrence of SRV discharge events.
  - (c) SRV & SSE & LOCA - Equivalent to 1 SSE event, with simultaneous occurrence of SRV and LOCA events.
  - (d) LOCA - Number of tests simulate the LOCA event, primarily the chugging phase of LOCA.
- ° Check the functional operability during and after each series of tests, i.e.:
  - (a) Verify electric continuity of the limit switches.
  - (b) Record storke times.
  - (c) Check tightness of operator mounting screws after the tests.

QUALIFICATION METHOD AND TEST PLAN

The dynamic fragility qualification method included performing both random, multifrequency testing and single frequency testing consisting of a series of sine-beat tests. The single frequency sine-beat tests account for the hydrodynamic loading durations and fatigue cycles, and the frequency content of the dynamic loading. These tests are performed at frequencies in the range 1 - 100Hz at intervals of no greater than 1/3 octave. The initial series of beat tests would establish specific acceleration limit for the worst load combination (SSE, SRV and LOCA). In addition, a large number of beats are applied at various smaller magnitudes which account for the SRV, Upset and LOCA loading conditions.

The next series of sine-beat tests increases the previously established worst load combination level in 2g increments, until the table limits, or the fragility limits are reached. The test plan requires that throughout the tests, at appropriate intervals, the specimens be cycled and results compared with the baseline data.

TEST RESULTS

TEST SERIES PHASE 1 - ASSEMBLY TESTING

The objective of this test was to establish fragility limits for two typical motor-operator valve assemblies, which included Limitorque motor-operator models SMB-000-5 and SMB-0-25, gate and globe valves. Observed anomalies included excessive chatter, loose internal limit switch screws and gross structural failure in the form of a broken limit switch rotor. Specific corrective procedures for limit switch finger assembly adjustment, and screw tightning torque valves were developed with the manufacturer and a second series of tests were undertaken.

TEST SERIES PHASE 2 - OPERATOR TESTING

In this series of tests, the corrective actions from the first test series were implemented and motor operator models SMB-000-5 and SMB-0-25 were subjected to fragility testing. First, biaxial, random-multifrequency tests were conducted with the TRS corresponding to the table limits. The minimum ZPA levels obtained were 6.0g for operator SMB-000-5 and 12.0g for operator SMB-0-25. This was followed by sine-beat testing. The initial combined loading condition level selected was 6.0g, with tests due to other plant conditions conducted at lower magnitudes. After this series of testing was completed, test levels were increased in increments of 2.0g's, and testing was performed at 8.0g, 10.0g, 12.0g and 14.0g. At each level of test, a minimum of 15 beats were applied at each test frequency in the range 10 - 100 Hz with a maximum of 1/3 octave interval. Due to table limitations, accelerations of 9 to 12g's only could be reached in the range of 5 - 16 Hz. Contact chatter did not exceed 5 milisecond, which was acceptable. Thus, a 14g limit was established for both motor-operators.

CONCLUSIONS

Two Limitorque motor-operators, models SMB-000-5 and SMB-0-25 were dynamically tested. A fragility limit of 14.0g was established for both operators, provided the following corrective actions are taken:

a) The manufacturer recommended procedure for checking and adjusting the geared limit switch finger assembly, including the specific normal gap measurement between the rotor and the finger, are implemented to preclude chatter.

b) The manufacturer recommended pre-load torque values are used and tightness procedures implemented for the limit switch and torque switch internal screws.

The active components of these operators are primarily the motor and the limit and torque switches, which are generally similar in other Limitorque operator models. Therefore, this testing may allow dynamic qualification of various Limitorque models to 14.0g level.

OVERVIEW OF RELAY AND AUXILIARY COMPONENT SEISMIC FRAGILITY

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ABSTRACT

Documentation from forty-eight seismic tests of switchgear assemblies contains a large amount of component fragility/ruggedness data. Much of the data is in rigorous detail but extraction and summarization into a usable format has not been accomplished. In many cases, the test documentation provides sufficient data to serve as a direct source of component qualification results as well as fragility data. In all cases the data expands our knowledge of component seismic capability and frequently it is a useful augmentation to other data for increased confidence in performance predictions. The complexities introduced by variations in testing technique and performance requirements underscore the need for a detailed understanding of the functions and limitations of critical components during vibration.

TYPES OF COMPONENT DATA

There have been a number of techniques used to derive component generic seismic qualification data. Each specific test program has variations in details but two broad categories of component programs dominate.

IEEE Standard Seismic Testing of Relays ANSI C37.98-1978

In recent years the principal source of component generic data has been testing per ANSI C37.98, a standard developed by the IEEE Power Systems Relaying Committee. The usual interpretation of this document calls for multifrequency biaxial testing in horizontal and vertical orthogonal axes to envelope a Standardized Response Spectrum shape (SRS) analyzed at 5% damping. Most of this type of testing attempts to define the highest SRS which the component can endure without malfunction. Many qualifiers simply tabulate the zero period acceleration of the SRS to which the component was qualified. Figure 1 shows the shape of the SRS as defined in ANSI C37.98.

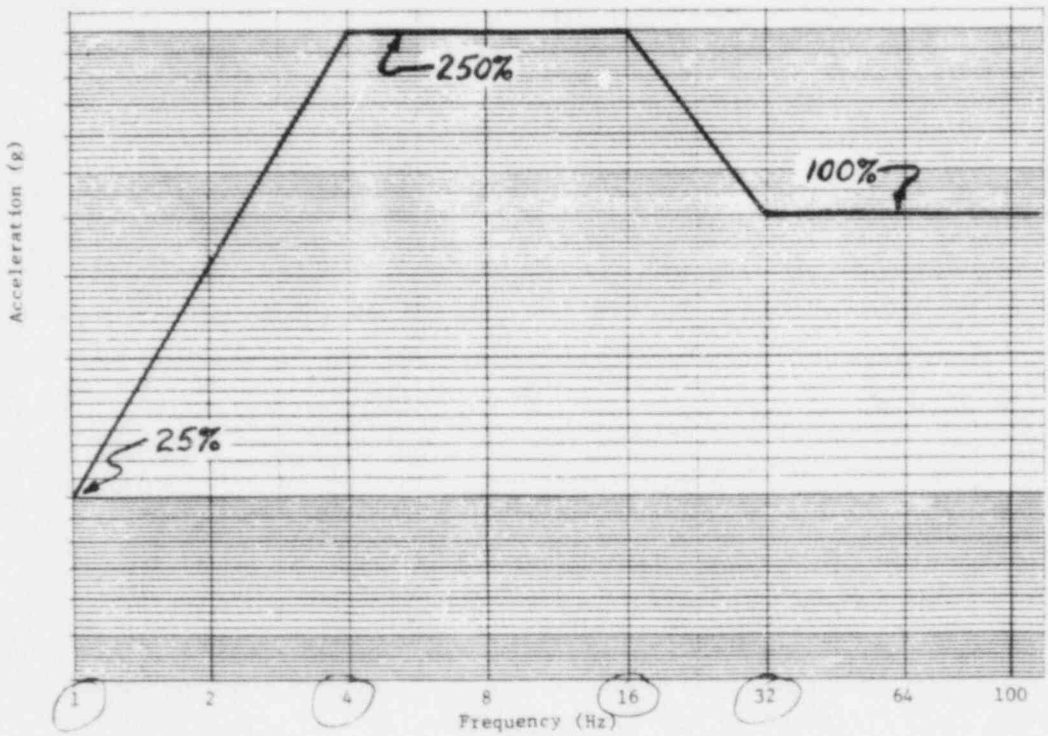

FIGURE 1

SRS for Multifrequency Component Tests - 5% Damping

With this SRS approach, an application may require a higher specific frequency acceleration value than the SRS envelopes. The data does not qualify the component for that application unless the TRS is available and shows the testing to meet the higher value.

Other Generic Vibration Tests of Components

Earlier there were other techniques used to evaluate component fragility. Typically these programs used single frequency excitation in which the acceleration level was progressively increased until malfunction occurred. Sine beat inputs were usually used to reduce the overexcitation and high energy of this type of test. Where frequencies are sufficiently close to assure that resonances are identified, these tests provide very useful plots of fragility. Although multi-mode effects are not covered, this data will identify the vibration amplitudes and frequencies that actually cause malfunction.

Results of this technique from several different relay investigations are shown in Figures 2, 3, 4, and 5. A detailed understanding of the specific technique is important to evaluate these data. Figs. 2 & 3 accelerations were separately taken in each orthogonal axis. The most critical contact establishes fragility level for this auxiliary relay.

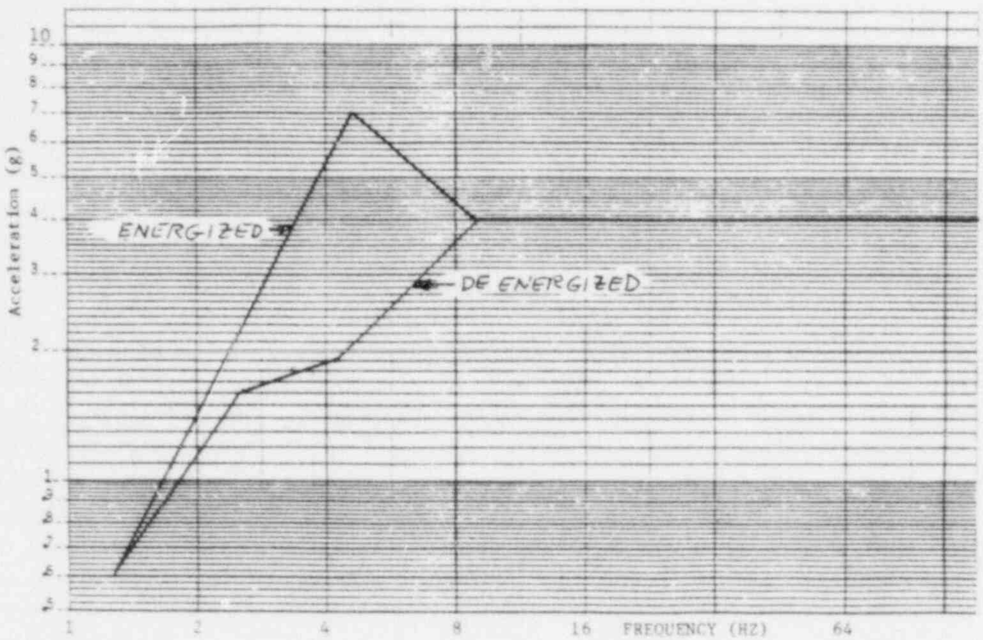

FIGURE 2

Relay "A" Ruggedness - Horiz. Front to Back

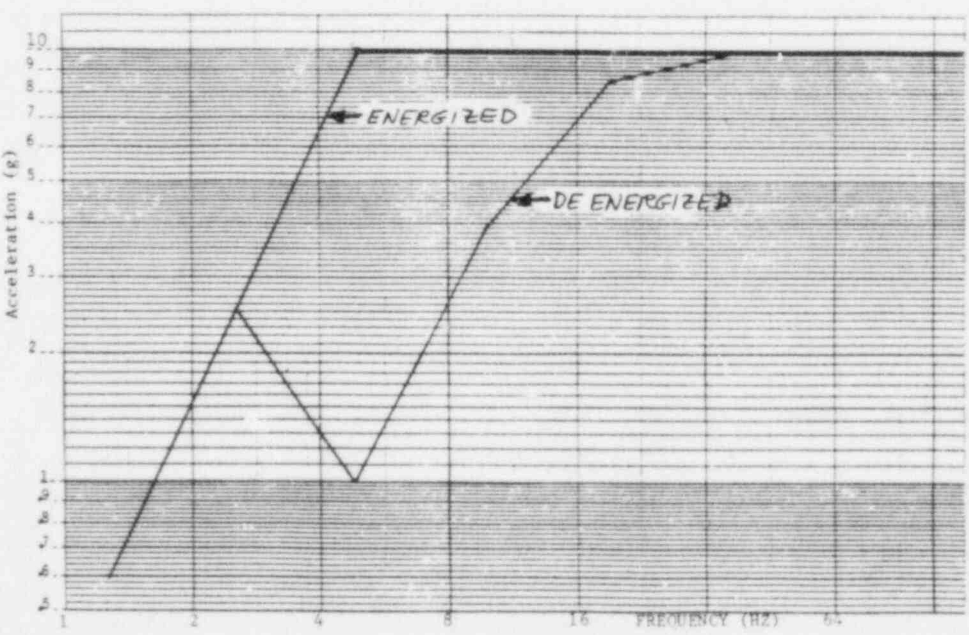

FIGURE 3

Relay "A" Ruggedness - Horiz. Side to Side

Figure 4 shows results of testing a different auxiliary relay with the actuator at an angle to all orthogonal axes of the samples.

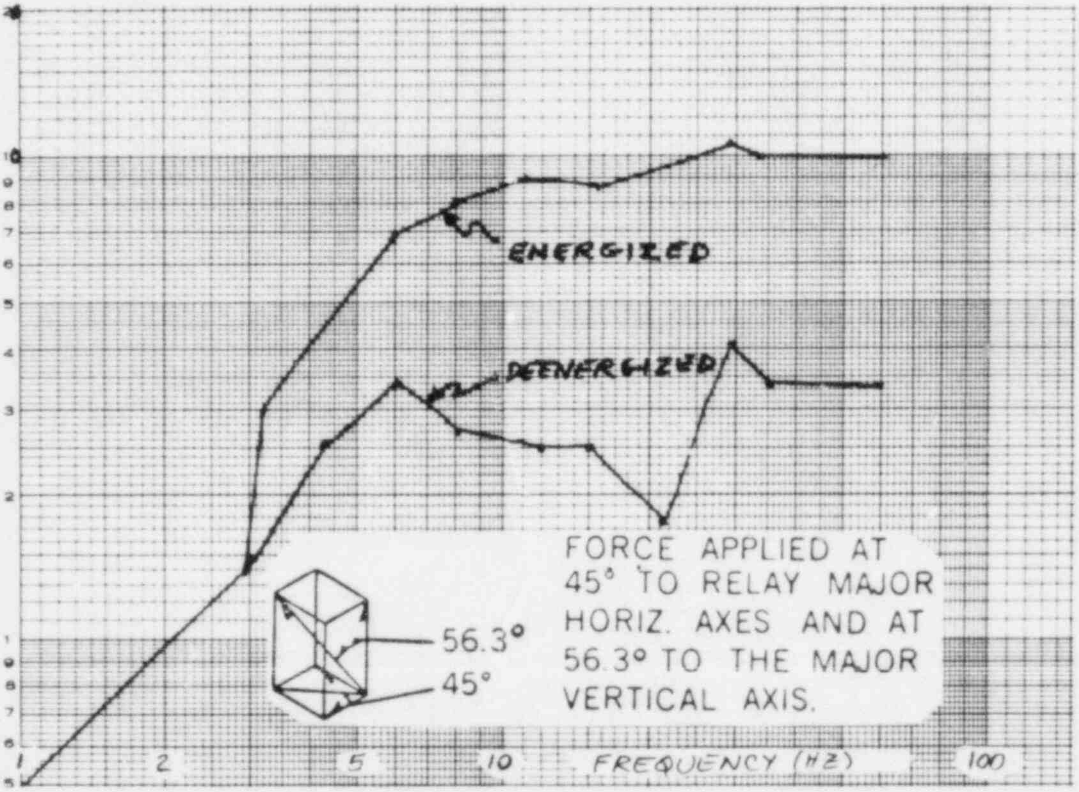

FIGURE 4

Relay "B" Ruggedness

This seismic data presentation raises a question. Where actuation is not along orthogonal axes, can the applied response be used directly or should it be resolved into individual orthogonal components? The former would ordinarily be acceptable only if the application direction was the most sensitive axis to vibration effects. Lacking verification of this, the accelerations must be resolved for comparisons with requirements and/or other test data.

In Figure 5 we see another approach to presenting single frequency test results which provides some information on axis sensitivity where differences are significant. This data is on a third type of auxiliary relay but only provides deenergized state results.

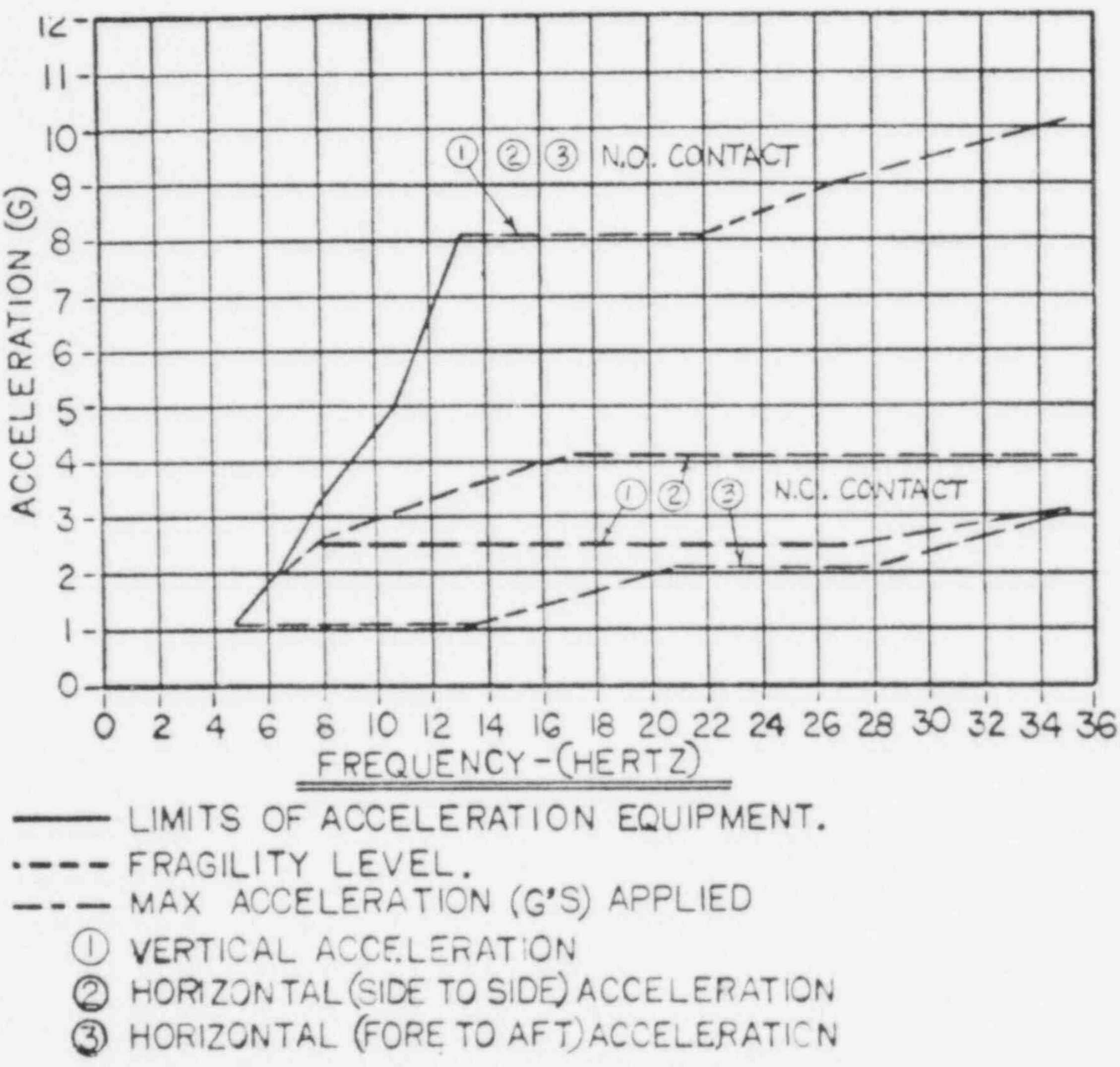

FIGURE 5

Relay "C" Ruggedness - Deenergized

Component Data Derived from Assembly Testing

Another potential source of component seismic information exists which is not readily available to component qualifiers. Where a larger assembly has been seismically tested and relays and other components of interest have been monitored, there is an opportunity to extract pertinent data on component fragility and/or qualification from the assembly test documentation. In this case, the vibration to which the component is exposed is the assembly test response spectrum as transmitted through the structure to the component mounting location. The component response spectrum is not controlled because testing is oriented to the assembly. The requirement imposed on the component is, however, appropos for use in that assembly. Figure 6 shows the test table response (TRS) and a component mounting location response spectrum from a switchgear assembly test program.

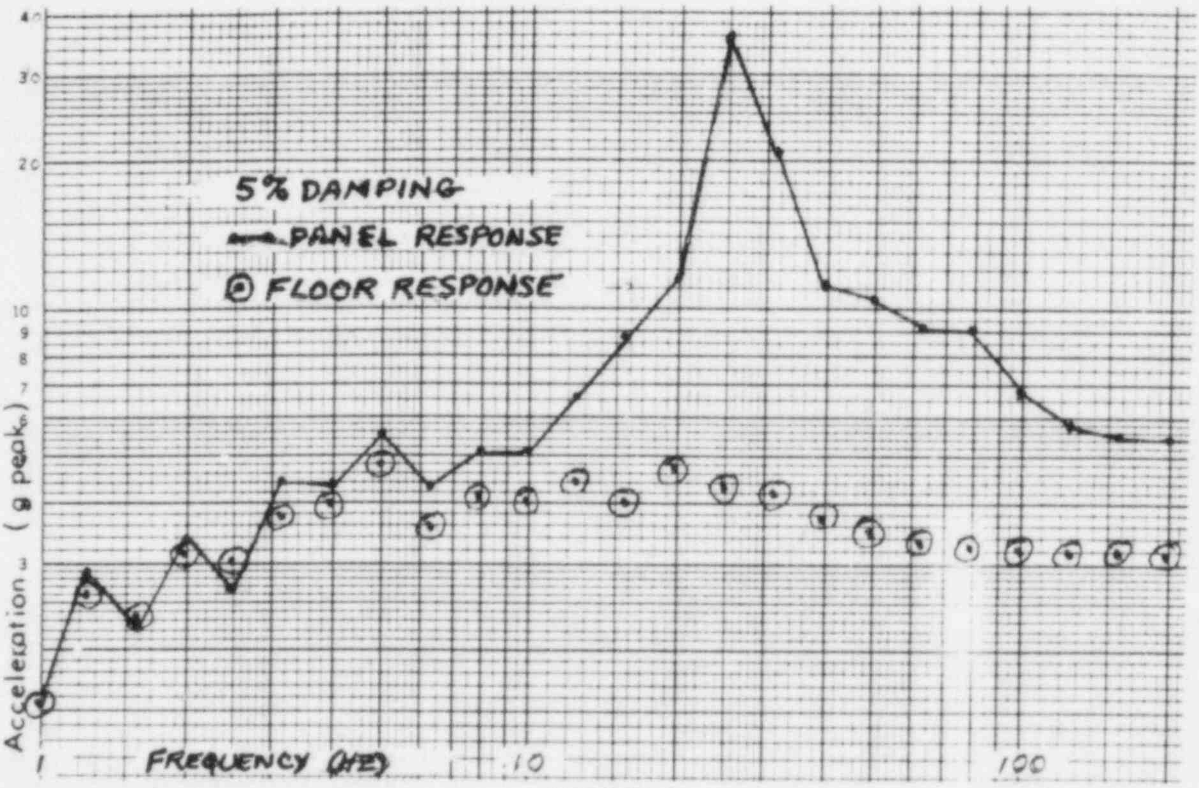

FIGURE 6

Component location Response Compared to Floor Response
Horizontal Front-to-Back Axis-Relay Mounting Normal

Where a number of programs containing the same component are available, there is a strong possibility of defining fragility in terms of realistic mounting location response spectra.

COMPONENT EVALUATION CRITERIA

The criteria for pass-fail determination may or may not be of critical importance for component fragility evaluation by test, depending on the function. Examples of components for which the criterion is unimportant are terminal blocks, wiring, fuse holders, fuses, latches, and structures. The reason is the simplicity of the function and the ease of determining loss of function. These components have non-reversible failure modes without outside intervention.

There are certain other static electrical components such as small transformers, transducers, and other solid state electronic components which also exhibit failure modes which are non-reversible. For this type of component, electrical instrumentation <u>during</u> vibration testing is unnecessary. Testing is conducted as a series of test runs with an opportunity for inspections and functional checks between runs. The acceleration level causing malfunction of this type component is identifiable when appropriate checks are made, so there is an option of electrically instrumenting or detailed inspections between runs.

In contrast, electro-mechanical components with an operability requirement involving contact closing and opening are subject to reversible malfunction and <u>must</u> be instrumented to monitor contacts during the seismic vibration. Examples of these types of devices are protective relays of all types, auxiliary and timing relays, contactors, and switches sensing mechanical position. It is only reasonable to expect that a component relying on gravity, friction, or location to perform its function may operate differently during periods of vibration. These components must be monitored to detect contact chatter, change-of-state, and, on some, transition timing.

Today, the required relay settings, monitoring criteria and component input recommendations for relays are clearly delineated in the relay seismic standard, ANSI C37.98. Previous testing of relays and data from assembly tests will vary from these recommendations, therefore comparisons between test results may not be apples vs. apples , depending on the type and configuration of the relay. For example, the time dial setting is very important on induction disk relays such as are used for overcurrent protection but only at the low end of the adjustment. The same type of relay may perform differently with variations in loading (simulating normal load vs. no load). The essential characteristic of useful test data on operating electro-mechanical components is therefore meticulous documentation. Without details on how a relay was set, connected, loaded and monitored, correlations between performance on a test and in a plant are questionable.

COMPARISON OF FRAGILITY DATA

To illustrate the variations in available data presentation we look at a hypothetical auxiliary relay called Relay "X". One of the simplest of the electro-mechanical contact-making devices, it is a self-reset relay with no intentional time delay. This relay is typically used as a contact multiplier. Designed to be surface-mounted on a vertical surface, it has a horizontal coil and a vertical hinged armature as depicted in Fig. 7. The relay has two types of contact, normally closed (in the deenergized condition) and normally open (in the deenergized condition). When the coil is energized with 125 VDC potential, the armature is attracted to the coil and the contacts change state. When the coil is deenergized the armature is released and the contacts change back to the original state.

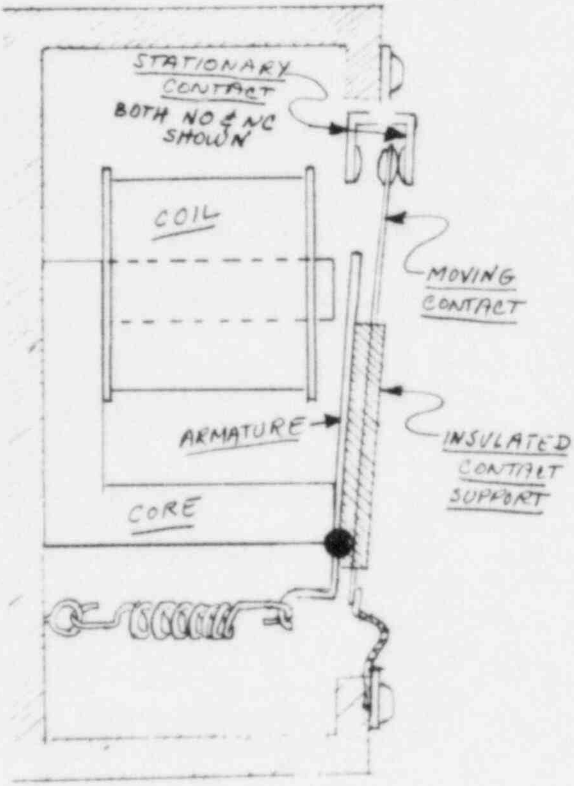

FIGURE 7

Side View of Relay "X"

ANSI C37.98 Qualification Data

A qualifier of Relay "X" proceeds to test the relay per ANSI C37.98 on a rigid fixture with a multifrequency biaxial test program involving two test orientations. The results of the testing are shown in Table 1.

	NC Contact	NO Contact
Deenergized	0.5 g.	3.0 g.
Energized	4.0 g.	1.5 g.

TABLE 1

Relay "X" contacts will not change state (chatter) for more than two milliseconds when subjected to vibration described by an SRS with ZPA values as shown above.

The SRS plots for this ruggedness data are shown in Figure 8. The acceleration values are responses in orthogonal axes but the axis of lowest fragility is not identified. Neither do we know the increment below fragility or the actual test response margin.

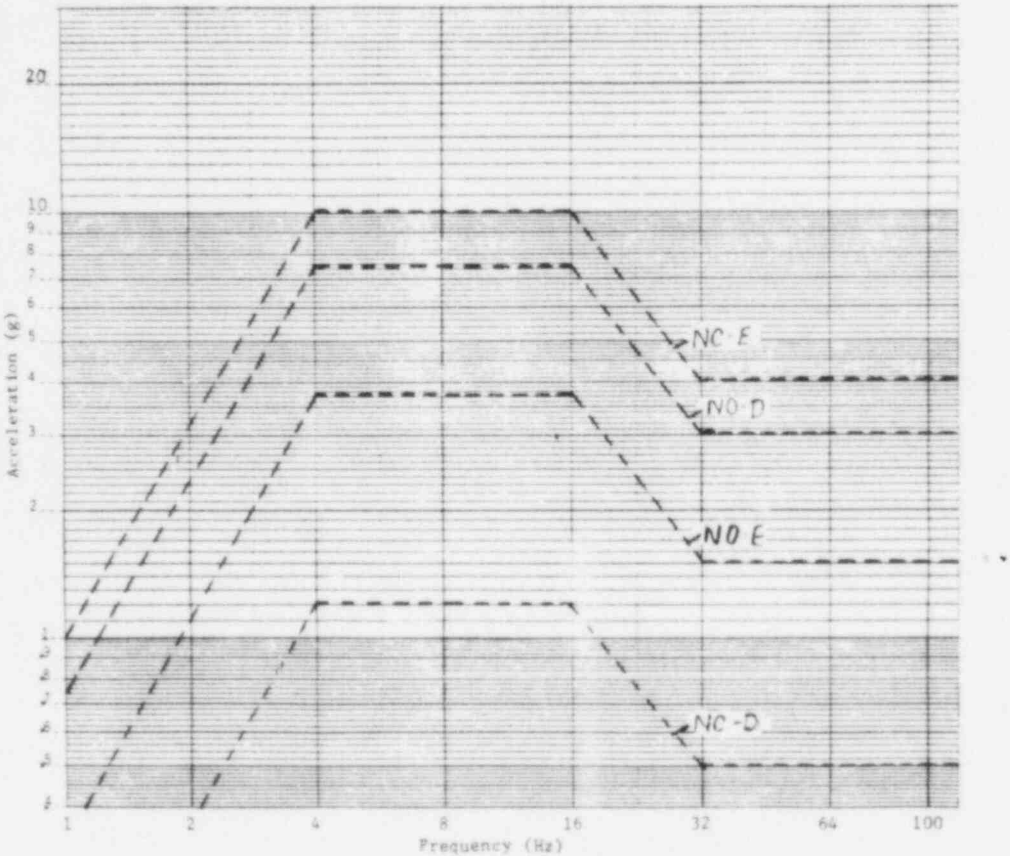

FIGURE 8

Plot of Four SRS Curves for Relay "X"

Single Frequency Ruggedness Data

In checking the archives it is found that single frequency experimental work was done on Relay "X" and resulted in fragility, or rather, ruggedness data which can be used for comparison with the C37.98 data. Due to the test program there was no distinction between contacts in establishing the fragility levels.

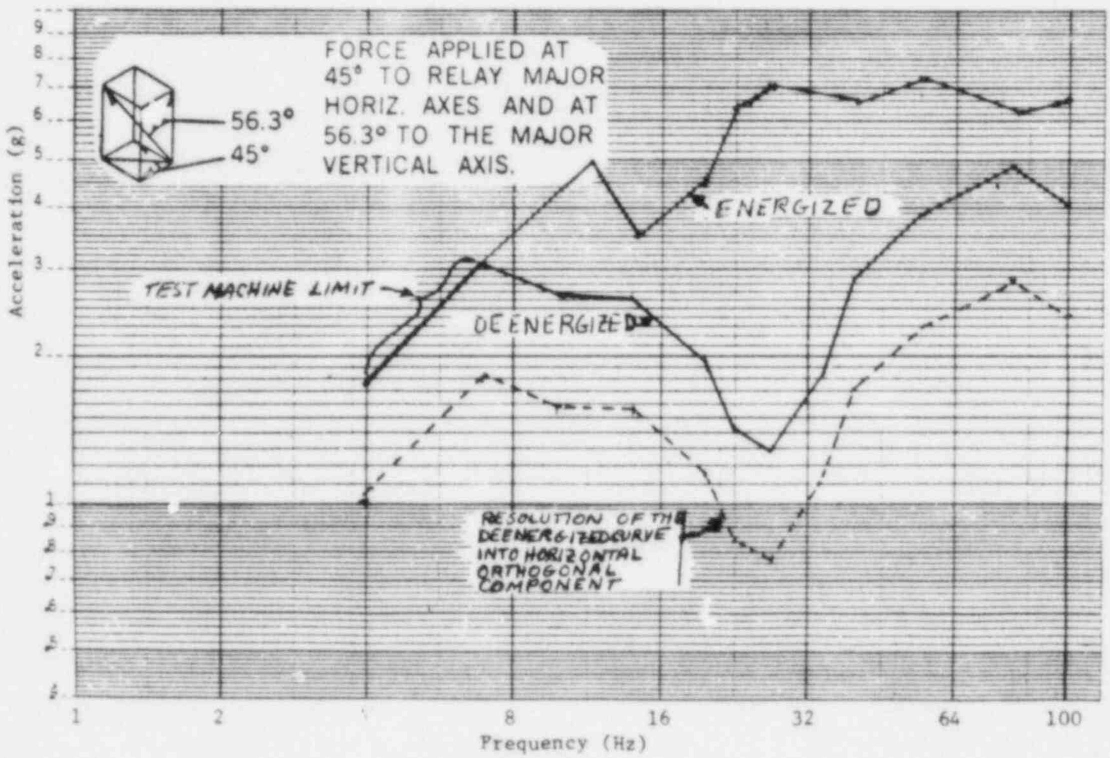

FIGURE 9

Ruggedness Plots for Relay "X"
from Single Frequency Testing

The accelerations shown in Figure 9 are in the actuator axis and must be resolved into orthogonal components. The horizontal front-to-back and side-to-side acceleration components are as shown dashed.

As with the previous data the increment between this ruggedness data and the fragility level is not identified, however since a specific response shape is not involved, the data does represent ruggedness levels across the spectrum. Again, there is no information on the limiting axis for fragility in this data presentation.

Relay "X" Performance Data From Assembly Testing

A test report and associated documentation from an assembly test is found to contain information on Relay "X". It was mounted on a large internal panel adjacent to an accelerometer oriented in the relay front-to-back axis. Both a NC and NO contact were monitored with oscillograph and chatter detector. The TRS for the accelerometer located next to the relay was analyzed at 5% damping as shown in Figure 10.

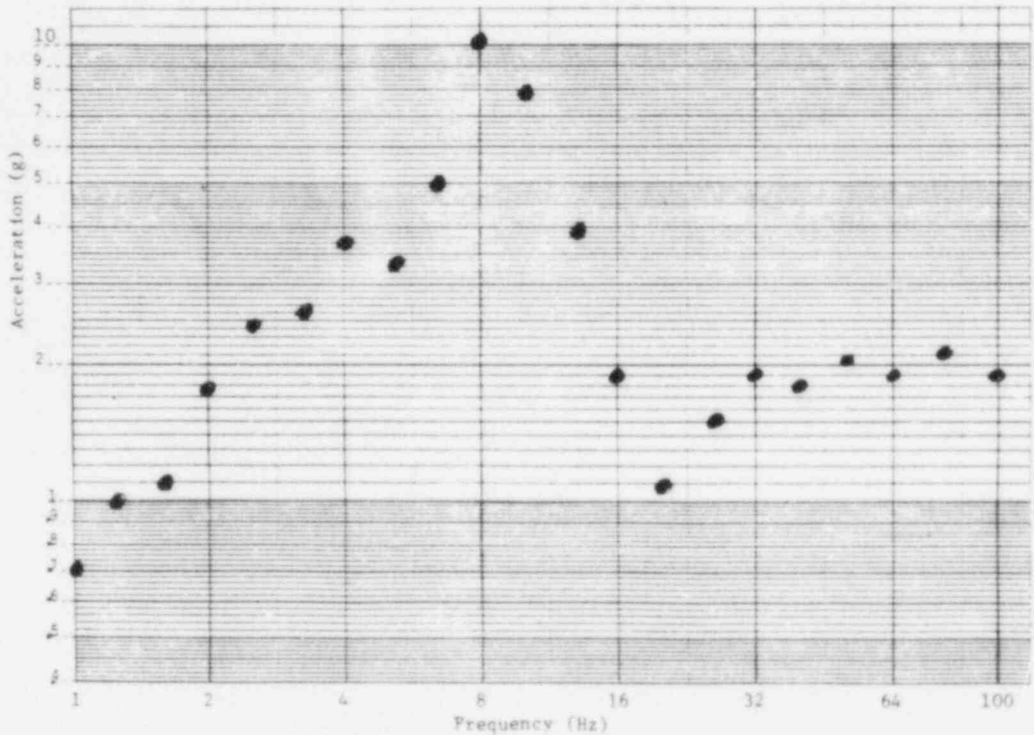

FIGURE 10

One Test Run, Relay "X", 5% Damping
From a Switchgear Assembly Test

The results of the chatter detector monitoring on this particular test run indicate that the normally open contact had a chatter anomaly which was one on which components were energized and deenergized. No mention was made of the normally closed contact indicating that chatter exceeding the criteria did not occur. So this TRS apparently establishes a spectrum for which the NC contact is qualified but the NO contact is not. Referring back to Fig. 8, this result is opposite to the expected performance. This experimental evidence conflicts with the NC contact having a much lower fragility level than the NO contact. A comparison of SRS ruggedness plots, the single frequency F-B axis ruggedness plots and the relay mounting location F-B TRS of Fig. 10 is shown in Figure 11.

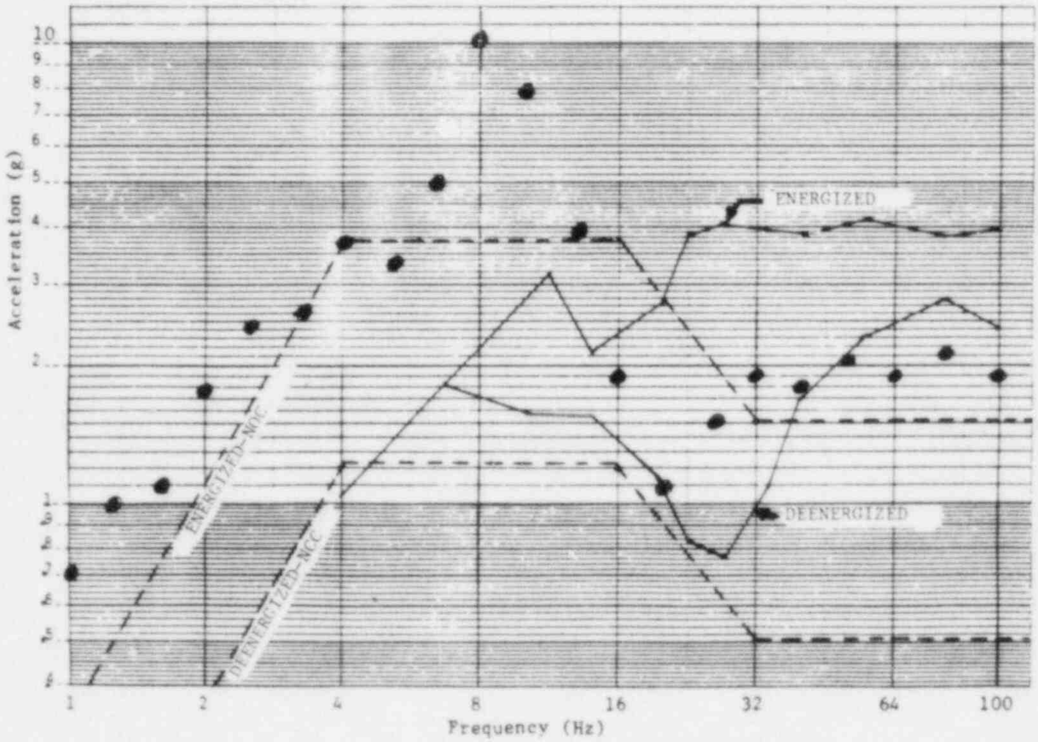

FIGURE 11

Comparison of Relay "X" Seismic Data

Bearing in mind that 5% damping analysis suggests a seismic environment less severe than a lower damping analysis of the same vibration and also recognizing that single frequency tests clearly provide a great deal more excitation of resonances, it becomes clear that a numerical correlation between single frequency and multifrequency fragility data cannot be made. The single frequency data is most useful for identifying the frequencies of concern and of course, where fragility is at a very high acceleration level at all frequencies, it provides confidence in relay ruggedness.

Comparison of the two sources of multifrequency data shows why the NO contact had chatter but also shows that the NC contact should have chattered. Possible explanations for the NC contact result are variations in the time history between the two tests and/or structural damping of frequencies that are critical to the relay on the assembly test. Assumptions must be made regarding the axis of lowest fragility for the single frequency data, but familiarity with relay configuration can help in this regard.

This hypothetical example illustrates the complexities involved in characterizing seismic ruggedness on a simple auxiliary relay to a clear-cut fragility criterion.

The 2 Millisecond Chatter Criterion

The convention which is almost universally accepted for defining significant contact chatter is a 2 ms. duration. It is necessary to define this for standardization purposes. Two milliseconds is a compromise between advocates of no chatter, perceived necessary for computers, and 4 or 5 milliseconds which is short enough that electro-mechanical devices will not operate. Recognition that input buffers are available for computers set the stage for the compromise.

The conclusions, or lack thereof, in the Relay "X" comparison have been based on the 2 ms. chatter criterion. As indicated earlier, the assembly test data also included oscillographic records of contact behavior. Figure 12 illustrates portions of the O-graph taken on the assembly test run of Fig. 10 & 11.

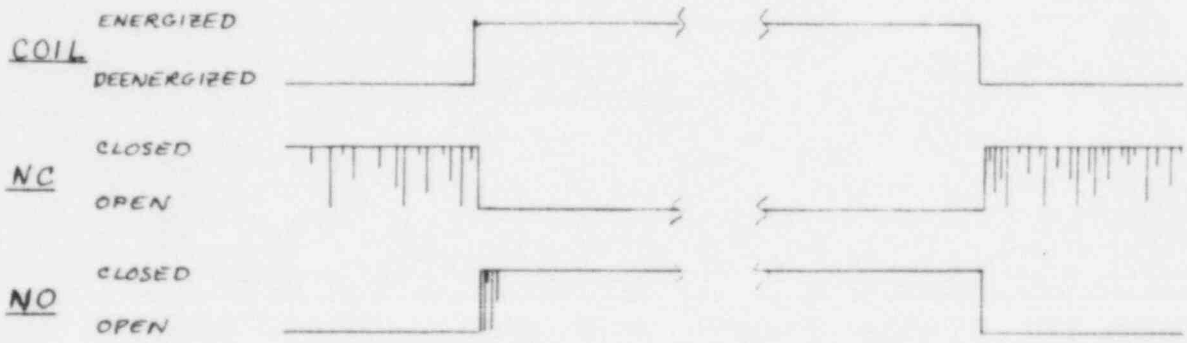

FIGURE 12

Record of Relay "X" Contact Behavior

Inspection of Fig. 12 shows that the NC contact in the deenergized state is unstable, but it apparently had no chatter exceeding the chatter detector setpoint. The NO contact was stable except for several bounces occurring within 20 to 50 ms. of closing. The recorder sensitivity is such that full scale galvanometer deflection occurs only if the discontinuity persists for 0.5 to 0.6 ms.

This information may put the status of these relay contacts in a different light. Depending on the circuit, the persistent chatter on the NC contact may not be acceptable, and perhaps the short duration contact bounce on the NO contact would be O.K.

Thus we see how the criteria can obscure details of performance which might be important. These considerations are particularly important when evaluating "marginal" devices, such as Relay "X" was for the assembly test shown.

OTHER RELAYS

The detailed data required to accurately portray the seismic performance of an auxiliary relay is quite extensive. As the complexity of the relay functions increase, such as with indicating targets, seal-in coils, restraint functions and other sensitive mechanisms in the relay enclosure, it is not difficult to understand confusion in defining ruggedness (fragility).

The data furnished on relay testing per ANSI C37.98 is ordinarily insufficient to evaluate marginal applications or to accurately portray ruggedness levels. The frequent result is rejection of adequate components, which is conservative but not cost effective if existing data will verify adequacy.

CONCLUSIONS

The holders of specific relay test results, both single frequency and ANSI C37.98, should be encouraged to share details of the test results such as: axis of fragility, actual TRS, fragility level, resonances, contact monitor results, transition timing data, etc. for key devices with ruggedness levels below a defined norm.

In addition to the two categories of relay seismic data, there exists another source of relay seismic performance data from those who included and monitored relays on enclosure tests. With added test data from relay qualifiers and extracted data from assembly tests, it is probable that ruggedness, fragility and the controlling variables can be understood and applied with more precision.

The popular technique of simplifying the issue for all to understand should be avoided in the case of protective and critical control components. These components are necessary and complex; consequently they should be understood in detail as entities themselves, not as subordinate items and not by use of a simple numerical rating.

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SESSION IV

METHODOLOGY AND APPLICATION OF FRAGILITY DATA TO EQUIPMENT ASSEMBLIES

RESERVE STRENGTH AS A MEASURE OF FRAGILITY

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ABSTRACT

It is well known that most components in a nuclear power plant have significant reserve strength and will provide an insignificant contribution to the probability of a major accident. However, when a utility undertakes a probabilistic risk assessment or systematic evaluation program, all components in the plant are normally considered of equal importance and a program of significant scope and expenditures is required to address them all. In this paper, a method to quantify this component reserve strength is presented. Its use allows the utility to focus its resources on those areas and components which are critical to overall plant safety.

In performing a probabilistic risk assessment, the key question which must be addressed is: "What is the probability that the critical applied stress will exceed the ultimate capacity of the component?" The answering of this question is referred to as fragility analysis. If reserve strength, which is the inherent capability of a structural component to accommodate applied stresses beyond its conservative strength limits, can be quantified by its mean value and its associated uncertainties, then this reserve strength can be used to indicate the structural fragility of any component. The reserve strength method presented in this paper provides a statistical approach for estimating the probability of failure of a component using the factors and uncertainties associated with the two key components of reserve strength, namely, applied stress and ultimate strength (or capacity). For a plant piping/support system, typical stress factors include damping, seismic loading, and method of analysis. Typical strength factors would include such items as stress criteria, material margin, and inelastic capability. While

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the detailed discussion and examples in the paper concentrate primarily on piping/support systems, the reserve strength method is general enough to be equally applicable to building structures, equipment or any other miscellaneous structure in a nuclear power plant. Finally, a key benefit of the reserve strength method is that there is sufficient information available in the open literature to perform the fragility screening evaluation.

INTRODUCTION

The use of Probabilistic Risk Assessment (PRA) by the Nuclear Regulatory Agency (NRC) to assess the safety of selected nuclear power plants is a relatively new concept. In PRA, a fault tree analysis is used to quantify the potential risk of a specific plant as the probability of a core melt down. As input into the PRA analysis, fragility parameters associated with the equipment, supports, piping and structures are used. These parameters are an estimate of the seismic capacity (strength and functional capability) in the various systems being evaluated.

That there is reserve margin (strength) in structural systems is well known. This concept is applied in structural codes through the use of safety factors or stress and reduction factors on ultimate strength. Reserve strength can be thought of as the amount of inherent margin within a structure to withstand increases in applied stress above the defined design loads before the ultimate capability (strength) is exceeded. The reserve strength in mechanical and electrical equipment is influenced by it's support system (structural), it's functional and operability characteristics (e.g. clearances), as well as the structural integrity of the equipment itself.

Many factors influence reserve strength. In determining these factors, consideration must be given to all that may affect the equipment support, function, operation, or any combination of these. Examples of these types of factors are:

1. Material Properties
2. Allowable Stress or Deflection
3. System or Equipment Damping
4. Analysis or Testing Method
5. Loading Combinations
6. Operating Characteristics
7. Environmental Conditions

Once these different reserve strength factors have been determined the system can be evaluated "against" failure as a probability problem.

> "What is the probability that the applied design loading will exceed the strength or defined operability limits?"

This procedure can be applied to building structures, equipment, piping systems and miscellaneous components that are part of a nuclear power plant. The probability of failure associated with the different design loading

conditions in the different components in the overall provides useful information that can be used by a utility, an A/E, or the vendor responsible for the evaluation of nuclear power plant safety systems. This method can be used in conjunction with a probabilistic risk assessment program or systematic evaluation program to focus attention on critical areas only; thus, the scope and expenditures for the regulatory program are not only minimized but used where they will provide the greatest benefit. Specific advantages associated with using reserve margin (strength) as a measure of fragility are:

1. It minimizes the scope of a PRA program,
2. It prioritizes the key equipment, structures, and piping systems to be evaluated, and
3. It justifies the postponement or elimination of non-critical items within a system that requires evaluation.

In this paper, the above evaluation technique is discussed in detail with examples. Emphasis is placed on seismic loading and analysis; however, the methods presented can be easily extended to other required design loading conditions. In the sections that follow, design margin factors are discussed along with the method of statistical combination of the design margin factors to obtain the probability of failure.

DESIGN MARGIN FACTORS

In order to define the fragility of structures, equipment, or piping systems, it is necessary to understand the use of design margin factors. Design margin factors represent the margin between an actual stress state and the allowable limit defining loss of function, operability, or structural integrity. The individual design margin factors are representative of the reserve strength associated with a given analysis or design parameter. This paper will concern itself with some of these factors; however, it is important to note that failure of part of a system, as defined by one specific design margin factor, does not mean that the system will no longer perform its intended function. Therefore the "total" reserve strength of a system will always be larger than the reserve strength associated with any one factor.

Design margin factors can be classified as stress factors, strength factors, and operability/functional factors. Examples of these factors include:

1. Margin in seismic ground response spectra,
2. Margin in the soil-structure interaction analysis methods,
3. Margin between the various seismic analysis methods (eg. time history, response spectra, static),
4. Margin in the floor response spectra and associated enveloping methods,

5. Margin in the critical damping values used for analysis,
6. Margin between design minimum and actual material strength,
7. Margin in the conservative design stress criteria and limits (e.g. strain rate effects)
8. Margin in the assumed worst environmental conditions
9. Margin in actual vs design loading combinations
10. Margin in generation of synthetic time histories for analysis,
11. Margin resulting from nonlinear "detuning" effects
12. Margin in inelastic response capability due to material ductility
13. Margin to structural collapse (e.g. plastic hinges)
14. Margin between loss of structural integrity and loss of function or operability

As evident from this list, there are many factors that can influence the reserve strength of a system. There are many on going programs with the purpose to quantify and document design margin and reserve strength. Two such programs are: (1) Seismic Safety Margin Research Program (SSMRP) , and (2) Probabilistic Safety study for selected plants. The results from many of these programs are available in the public literature in the form of NUREG's, society publications, or conference papers. General design margin factors are available from this literature for several of the above categories. Test or analytical programs can be pursued to quantify individual design margin factors for specific projects. In this paper, a selected number of design margin factors will be used to provide the reader with an understanding and appreciation of the method being presented. The factors used are based on information presented in the public literature. These design margin factors are discussed below in terms of stress and strength categories.

Stress Factors

A. Damping

Generally, Reg. Guide 1.61 has been used to define acceptable damping values for analysis. The conservatism in these values can be quantified by comparison with "realistic" damping values for buildings, structures, and equipment.

In Reference 1, recommended damping values have been given for different types and conditions of structures for different stress levels. For vital piping at or just below yield, damping values from 2 to 3 percent are recommended. For welded steel structures and bolted/riveted steel structures, both at or just below yield, damping values from 5 to 7 percent and 10 to 15 percent have been given respectively. For reinforced concrete at or just below "yield" a range of damping from 7 to 10 percent was given. It is stated on page 18 of Reference 1 that "the lower levels of the pair of values given for each item are considered to be nearly lower bounds, and are therefore highly conservative; the upper levels are considered to be average or slightly above average values, and probably are the values that should be used in design when moderately conservative estimates are made of the other parameters entering into the design criteria."

Reference 2 (page 129) recommends the use of the upper range of the Reference 1 damping values in the design or evaluation for stresses at or near yield. Reference 3, page 38, recommends that the damping values given in Reference 1 replace the Reg. Guide 1.61 Table 1 damping values.

A damping coefficient for the fundamental mode was estimated to be over 20% for the TOKAI - 2 reactor building in Japan. This was based on tests and was reported in Reference 4.

Reference 5 report damping values in excess of 10 percent for both piping systems and concrete structures.

Based on the above discussion, the following comparison can be made between Reg. Guide damping values and realistic damping based on Safe-Shutdown-Earthquake (SSE) levels

1. Piping: Reg. Guide Damping 3%; Realistic Damping 10%

2. Welded Steel Structure/Equipment: Reg. Guide Damping 4%; Realistic Damping 7%

3. Bolted or Riveted Structure/Equipment: Reg Guide Damping 7%; Realistic Damping 15%

4. Concrete Structure: Reg Guide Damping 7%; Realistic Damping 10%

The conservatism reflected as the design margin factor will be a function of the compounding effect of the individual elements (soil, building, support, equipment) that influence the seismic response of the system of interest as well as the ground response spectra, building frequencies, and equipment frequencies. A measure of the conservatism can be obtained from using the effect of damping on seismic response spectra curves. This yields a design margin factor of over 1.25. This is supported by Reference 6 where test results from Reference 7 pertaining to damping for Reactor Coolant Loop Components is discussed. It is stated in Reference 6 on page 185; "the 3% of critical damping allowed in the SSE occurs at an amplitude of 0.02 inches. Extrapolating to 0.5 inches deflection gives a damping factor of 10% which is more probable. If this were true, it can be seen from figures 3-14 of UCID 18111 (Reference 8) that there would be a factor of conservatism (FOC) of at least 1.25 in going to 10% damping."

B. Spectra Broadening

In Reference 6, a design margin factor of 1.17 (expressed as a factor of conservatism) is defined for broadened spectra. Reference 6 states on page 187:

"The study on broadening of floor spectra described in UCID 18104 (Ref.9) is an ingenious approach toward understanding the conservatism of the operation. This report ... contains new and significant results. The FOC of 1.17

found at the natural frequencies is the important factor since the highest stresses occur as a result of this motion. At other frequencies where the FOC is lower; stresses are also lower and the low FOC becomes irrelevant."

C. Response Spectrum Method

The conservatism in the response spectrum analysis method is discussed in Reference 6. A design margin factor of 1.44 is given expressed as an FOC. It is stated on page 188:

"The study on coupling effects described in UCID 18110 (Reference 10) also contains effects of time-history versus response spectra analysis. The conclusions are very interesting with a mean FOC of 1.44. However, the results are worth closer study when it is noted that the highest FOCs occur at points of highest stress. In terms of design controlling parameters, the higher FOCs are more significant."

Strength Factors

A. Stress Criteria

In this paper, design margin factors are presented for ASME Class 2/3 piping, structural supports, and equipment supports.

In Reference 11, pages 15 and 16, a range from 2.0 to 4.3 for nominal margin based on ultimate stress (Su) is given for ASME Class 2/3 piping at Code Level D. Nominal margin as used in Reference 11 is an indication of the reserve strength that is available when a calculated stress is at it's allowable stress. It is a measure of separation between the code allowable stress and some mode of failure. In this case, the mode of failure is structural integrity and the corresponding limit is defined by the ultimate stress. The nominal margin is the same as the design margin factor. The range in nominal margin results from different representative code minimum material properties and representative temperatures.

For structures, including equipment supports, the minimum nominal margin as defined by Reference 11 is 1.43 based on Su. This design margin factor is based on the design limit of 0.7 Su.

B. Material

The code allowable stress is based on minimum values of yield (Sy) and ultimate (Su) strength. Actual Sy and Su values will be higher. As an example from Reference 11:

"For materials which fall under the general description of 'hot finished carbon steel,' the available data indicates that (1) the mean value of Sy or Su is about 20 percent higher that the minimums ... and (2) the probability of obtaining a material with Sy or Su less than those used (minimum) ... is of the order of 0.01."

In Reference 6, page 178, it is stated that:

"Certain of the LLL reports in the current effort are devoted to the study of aspects of the Design Criteria Margin, e.g. (Reference 12) studied the difference between code specified material strengths and actual strengths and not surprisingly found an average of 17% margin for this particular component of the Design Criteria Margin."

From the above, a design margin factor associated with steel in piping, supports or equipment can be defined as 1.2.

In summary, the following design margin factors have been given:

1. Stress Factors

a. Damping	1.25
b. Response Spectra Broadening	1.17
c. Response Spectra Method	1.44

2. Strength Factors

a. Piping Stress Criteria	2.0
b. Support or Equipment Stress Criteria	1.43
c. Material	1.2

As noted previously, there are many additional areas where design margin factors could be defined. Examples are (1) Seismic input definition, (2) Seismic component response combination, and (3) Ductility and inelastic response. However, it will be shown in the following sections, that even if all these additional factors are neglected (assumed to be 1.0), there is still significant reserve strength and the probability of failure is small.

At this point it should also be noted that this same procedure of picking only the key factors that are well documented in the open literature could be applied to any component and/or safety system in a nuclear power plant. Moreover, the method is generally applicable and need not just be applied for seismic loading.

STATISTICAL COMBINATION OF DESIGN MARGIN FACTORS

In piping system subject to seismic stress, the critical concern is this:

> Is the strength of the structural components sufficient to withstand the stress induced by an earthquake?

This question can be posed as a probability problem:

> What is the probability that the applied stress will exceed the strength of the system: Pr [Stress > Strength]

For each specific piping design there exists such a probability which will differ from system to system. In order to be sure that the probability is small, many degrees of conservatism are applied. Structural components are "over-designed" to withstand much higher stress than what it will actually experience.

In a previous section, only three stress factors have been quantified and associated minimum design margin factors given. These are repeated below:

Stress Factor 1 = damping	1.25
Stress Factor 2 = response spectra broadening	1.17
Stress Factor 3 = response spectra method	1.44

These values are interpreted in the following way. Using the damping as an example, a nominal value of damping is 1.0, but a 25 percent level of conservatism has been created since the factor is 1.25. The other stress factors are interpreted in a similar manner.

There are at least two strength factors for piping systems that represent additional margin. The two previously defined for piping are:

Strength Factor 1 = piping allowable stress	2.0
Strength Factor 2 = material properties	1.2

And the two strength factors for supports are:

Strength Factor 1 = support allowable stress	1.43
Strength Factor 2 = material properties	1.2

For ease of explanation, the notation X_i ($i = 1, 2, 3$) is used to denote the stress factors and Y_j ($j = 1, 2$) the strength factors. Structural engineering methods indicate that the conservatism on the total stress factor can be expressed as a product of these factors.

That is,

$$\text{Stress factor} = X = X_1 \cdot X_2 \cdot X_3 \tag{1}$$

In a similar fashion,

$$\text{Strength factor} = Y = Y_1 \cdot Y_2 \tag{2}$$

The probability problem can be expressed as follows:

$$\Pr\ [\text{Actual stress} > \text{Actual strength}] = \Pr\ [\frac{S_X}{X} > S_Y Y]$$

where

S_X = Calculated stress with conservative loading, and

S_Y = Nominal strength based on code allowable.

If the nominal strength is set equal to the calculated stress with conservative loading, S_X equal to S_Y, then the following relations are obtained.

$$\Pr[\text{Stress} > \text{Strength}]$$

$$= \Pr[\tfrac{1}{X} > Y]$$

$$= \Pr[\ln(XY) < o]$$

$$= \Pr[\sum_{i=1}^{3} \ln X_i + \sum_{j=1}^{2} \ln Y_j < o] \qquad (3)$$

where ln X refers to the natural logarithm of X. Again, according to structural modeling, it is known that X_i and Y_j can be modeled as random variables. It is assumed that

$\ln X_i$ has a normal distribution with mean zero and standard deviation σ_i
$\ln Y_j$ has a normal distribution with mean zero and standard deviation s_j

Given below is the standard deviation associated with each of the stress and strength factors being considered in this example:

	Factor	Description	Conservatism	Std. Dev.
Stress factors for piping and supports	X_1	Damping	1.25	0.074
	X_2	Resp. Spec. Broad	1.17	0.052
	X_3	Resp. Spec. Method	1.44	0.122
Strength factors for piping	Y_1	Piping stress criteria	2.0	0*
	Y_2	Material	1.2	.061
Strength factors for supports	Y_1	Support stress criteria	1.43	0*
	Y_2	Material	1.2	.061

These standard deviations were obtained by assuming that the conservatism was set at the nominal value of 1.0 plus three standard deviations.

Now, consider stress alone. The meaning of the conservatism in each factor is that:

$$\frac{X_i}{\overline{X}_{i\,(\text{nominal})}} = \text{factor}$$

---

*A standard deviation of zero is used since this represents the factor required to remove the factor of safety in the code allowables.

For example, $\frac{X_1}{X_{1\ (nominal)}} = 1.25$

Therefore,

$$\frac{\pi Xi}{\pi Xi\ (nominal)} = (1.25)(1.17)(1.44)$$

$\pi Xi = (1.25)(1.17)(1.44)\ \pi Xi\ (nominal)$

In these equations, π denotes "the product" of the variables X_i.

Now,

$$\begin{aligned} \ln X &= \ln (\pi Xi) \\ &= \ln (1.25) + \ln (1.17) + \ln (1.44) + \Sigma_i \ln Xi\ (nominal) \\ &= .223 + .157 + .365 + 0 \\ &= 0.745 \end{aligned}$$

The value of 0.745 measures the combined conservatism, that is, 0.745 away from the nominal (mean). To determine how many standard deviations away the following argument can be used. The standard deviation of ln X is

$$\begin{aligned} &\text{Std dev } (\ln X) \\ &= \text{std dev } (\ln X_1 + \ln X_2 + \ln X_3) \\ &= (.074^2 + .052^2 + .122^2)^{1/2} \\ &= 0.152 \end{aligned}$$

The ratio of 0.745 to 0.152 represents the degree of conservatism:

$$\frac{0.745}{0.152} = 4.91$$

In other words, this says that the value 0.745 is 4.91 standard deviations away from the nominal (mean). In terms of probability, the probability that a stress value will exceed its nominal strength is:

$Pr\ [Z > 4.91] \cong 4.6 \times 10^{-7}$

where Z is a standard normal random variate.

This derivation hasn't taken into account the conservatisms in strength. This is done below, using an argument similar to the one already presented.

The case of interest is the probability of $\frac{1}{X} > Y$, or, equivalently $\ln (XY) < o$.

Since,

$$\ln (XY) = \sum_i \ln Xi + \sum_j \ln Yj$$

For piping: $\ln (XY) = (.223 + .157 + .365) + [\ln (2.0) + \ln (1.2)]$
$= 0.745 + 0.875$
$= 1.620$

For supports: $\ln (XY) = (.223 + .157 + .365) + (\ln 1.43 + \ln 1.2)$

$= .745 + .540$
$= 1.285$

The standard derivation of ln XY is:

$$= (.074^2 + .052^2 + .122^2 + 0^2 + .061^2)^{1/2}$$
$$= 0.164$$

Therefore, the total conservatism for piping in units of std. deviations is:

$1.620/0.164 = 9.88$

and for supports:

$1.285/0.164 = 7.84$

The probability of stress exceeding strength is given by the tail probability of exceeding 9.88 std. deviations for piping and 7.84 for supports, and is equal to 2.5×10^{-23} and 2.3×10^{-15}, respectively. That is,

For piping: Pr [Stress > Strength] = 2.5×10^{-23}

For supports: Pr [Stress > Strength] = 2.3×10^{-15}

Higher Calculated Stress

If the calculated stress is increased above the nominal value due to new requirements, the probability of failure given the increase factor (IF) can be determined following the same formulation as previously given.

The actual stress is equal to $(\frac{IF.S_X}{X})$ and the probability expression is written as

$$\text{Pr [Stress > Strength]} = \Pr [\frac{IF}{X} > Y]$$
$$= \Pr [\ln IF - \ln X - \ln Y > 0]$$
$$= \Pr [\ln IF - \sum_i \ln X_i - \sum_j \ln Y_j > 0] \qquad (4)$$

Given in Table 1 is a summary of probabilities associated with different IF factors applicable to piping and supports. The corresponding standard deviations is 0.164 which is associated with the three standard deviations (3σ) criteria.

Given in Table 2 is a summary of probabilities associated with different IF factors applicable to piping and supports using a two standard deviations (2σ) criteria. Its corresponding standard deviation is 0.245.

TABLE 1

PROBABILITIES ASSOCIATED WITH STRESS INCREASE FACTORS USING A 3σ CRITERIA

TABLE 1A: PIPING

IF	Number of Standard Deviations from Mean	Probability
1.0	9.88	2.5×10^{-23}
1.1	9.30	7.0×10^{-21}
1.2	8.77	9.0×10^{-19}
1.3	8.28	6.2×10^{-17}
1.4	7.83	2.4×10^{-15}
1.5	7.41	6.3×10^{-14}
1.6	7.01	1.2×10^{-12}
1.7	6.64	1.6×10^{-11}
1.8	6.29	1.6×10^{-10}
1.9	5.96	1.3×10^{-9}
2.0	5.65	8.0×10^{-9}

TABLE 1B: SUPPORTS

IF	Number of Standard Deviations from Mean	Probability
1.0	7.84	2.3×10^{-15}
1.1	7.25	2.1×10^{-13}
1.2	6.72	9.1×10^{-12}
1.3	6.24	2.2×10^{-10}
1.4	5.78	3.8×10^{-9}
1.5	5.36	4.2×10^{-8}
1.6	4.97	3.4×10^{-7}
1.7	4.60	2.1×10^{-6}
1.8	4.25	1.1×10^{-5}
1.9	3.92	4.4×10^{-5}
2.0	3.61	1.5×10^{-4}

TABLE 2

PROBABILITIES ASSOCIATED WITH STRESS INCREASE FACTORS USING A 2σ CRITERIA

TABLE 2A: PIPING

IF	Number of Standard Deviations from Mean	Probability
1.0	6.61	1.9×10^{-11}
1.1	6.22	2.5×10^{-10}
1.2	5.87	2.2×10^{-9}
1.3	5.54	1.5×10^{-8}
1.4	5.24	8.0×10^{-8}
1.5	4.96	3.5×10^{-7}
1.6	4.69	1.4×10^{-6}
1.7	4.44	4.5×10^{-6}
1.8	4.21	1.3×10^{-5}
1.9	3.99	3.0×10^{-5}
2.0	3.78	7.9×10^{-5}

TABLE 2A: SUPPORTS

IF	Number of Standard Deviations from Mean	Probability
1.0	5.24	8.0×10^{-8}
1.1	4.85	6.2×10^{-7}
1.2	4.50	3.4×10^{-6}
1.3	4.17	1.5×10^{-5}
1.4	3.87	5.4×10^{-5}
1.5	3.59	1.7×10^{-4}
1.6	3.32	4.5×10^{-4}
1.7	3.07	1.1×10^{-3}
1.8	2.84	2.3×10^{-3}
1.9	2.62	4.4×10^{-3}
2.0	2.41	8.0×10^{-3}

APPLICATION

In the previous sections, the theoretical basis was given for using design margin factors to perform priority ranking or screening in a seismic reevaluation program. It is based on a statistical combination of a limited number of design margin factors. In this section the use of this method is demonstrated.

In Table 3 are given seismic reevaluation parameters for three hypothetical systems. Two critical piping lines and supports are identified

for each system. For each of these critical elements, stress level is given along with the acceleration increase defined for the location of the element in question. The increase factor (IF) is defined as the product of these two items. From Table 2, probabilities are obtained for the given increase factor. In the reevaluation program, three ranges of probabilities could be defined as part of a screening procedure to minimize the scope of work while highlighting the most important components:

1. No Reanalysis required for probabilities less than $7x10^{-7}$.

2. Reanalysis is required but not a priority for probabilities between $7x10^{-7}$ and $1.5x10^{-5}$.

3. Reanalysis is required for probabilities greater than $1.5x10^{-5}$.

Using this hypothetical criteria, the following conclusions can be made.

1. System B does not have to be included in the reanalysis program.

2. System C must be reevaluated, however, it can be addressed in a future phase of work.

3. System A must be included in the immediate reanalysis phase of work.

4. Supports are the critical elements in a piping system.

From the above example, it is seen that reserve margin (strength) as presented in this paper provides a viable simple method to categorize, prioritize, and minimize the scope of work in a PRA or seismic reevaluation program.

TABLE 3
SEISMIC REEVALUATION PARAMETERS

SYSTEM	ELEMENT	STRESS LEVEL	ACCELERATION INCREASE	INCREASE FACTOR	PROBABILITY
A	PIPE 1	0.9	2.1	1.9	$3.0x10^{-5}$
	PIPE 2	1.0	1.5	1.5	$3.5x10^{-7}$
	SUP 1	0.8	2.1	1.7	$1.1x10^{-3}$
	SUP 2	0.9	1.5	1.4	$5.4x10^{-5}$
B	PIPE 3	1.0	1.1	1.1	$2.5x10^{-10}$
	PIPE 4	0.9	1.1	1.0	$1.9x10^{-11}$
	SUP 3	0.9	1.1	1.0	$8.0x10^{-8}$
	SUP 4	1.0	1.1	1.1	$6.2x10^{-7}$
C	PIPE 5	1.0	1.4	1.4	$8.0x10^{-8}$
	PIPE 6	0.9	1.3	1.2	$2.2x10^{-8}$
	SUP 5	1.0	1.4	1.4	$5.4x10^{-5}$
	SUP 6	1.0	1.3	1.3	$1.5x10^{-5}$

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COMPONENT FRAGILITY AND ITS APPLICATION TO EQUIPMENT ASSEMBLIES

By

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ABSTRACT

This paper discusses some of the difficulties that may exist in the application of component fragility data when those components are part of a larger system. Large systems such as switchgear, motor control centers, and control panels modify the performance of individual components by introducing their own dynamic characteristics as well as non-linearities. Therefore, it is important that fragility data available for individual devices and components be supplemented by test information obtained for systems and assemblies.

The paper presents some examples from existing test data to demonstrate the effect of panel non-linearities on the performance of individual components in the systems. It further discusses various parameters such as frequency content of input motion, dynamic characteristics of panels, orientation and mounting of devices in the panel, and their effect on the applicability of fragility data of individual components.

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Recommendations are made to consolidate existing test data available for numerous assemblies and to obtain upper bound of test information. The paper discusses development of the generic fragility level from the available results. Also, components for which substantial margins exist between component capacity and seismic requirements are identified.

INTRODUCTION:

In the context of seismic qualification, fragility is defined as the maximum seismic motion that a given equipment can take before a seismically induced malfunction occurs. Equipment qualification data is mostly used to demonstrate that the components will perform satisfactorily when subjected to seismic motions determined by a plant-specific seismic environment. These seismic motions do not reflect the true fragilities of these components, but may be considered as conservative lower bound fragilities.

At present, true fragility data available for the components or assemblies used in nuclear power plants are very scarce and in most cases non-existent. Some manufacturers provide generic fragility data for some individual components and this information has been used, whenever possible, for the plant-specific qualification of such components. However, it is important to consider the method used to obtain the fragility data and to study the functional relationship between the component fragility and the system fragility before a component in the system is considered qualified.

COMPONENT FRAGILITY:

Component fragility is, in general, obtained by one of the following methods:

(1) Sine Beat Test: In this test the equipment is subjected to a single frequency transient excitation. The test is repeated for different pre-determined frequencies. The amplitude at each frequency is increased until malfunction occurs.

(2) Sine Sweep Test: In this test the equipment is subjected to continuous sinusoidal excitation in which frequency content is varied at a pre-defined sweep rate with constant input accelerations. The amplitude is increased from one test to other until malfunction occurs.

(3) Random Motion Test: In this test the equipment is subjected to a random multifrequency excitation. The spectra used envelops a pre-specified spectra. The spectra amplitudes are increased until malfunction occurs.

(4) Analysis: This method is generally used where equipment is simple enough to be represented by a mathematical model and the fragility is determined by the criteria of limiting stresses, strains, deformations and/or displacements.

The methods described above have their usefulness and limitation depending upon the system in which the components tested by these methods are used.

Single frequency tests such as sine beat tests and sine sweep tests have the advantage that they can cover various frequencies including resonant frequencies provided such frequencies can be pre-determined. For many components and devices it is difficult and in some cases even meaningless to determine the resonant frequencies because of the complexities of the internals of the components. The single frequency test also identifies the frequency at which malfunction occurs. This information is useful in extending the component fragility data to its use in a system or an assembly. However, the method fails to excite all frequencies simultaneously and also does not provide multiaxis response. It may also result in overtest, causing unwarranted fatigue.

Random motion tests have the advantage of being able to excite all fundamental frequencies simultaneously and can be multidirectional. They however, do not identify the frequency at which malfunction occurs and therefore, may have some limitations in the application of component fragility data to system fragility.

Qualification by analysis is generally used when structural integrity alone can be used as the criteria to assure the design-intended function. For this class of equipment code-limit fragility is relatively easy to determine, since one cycle of analysis can generally provide all the required information.

FACTORS AFFECTING COMPONENT FRAGILITY:

Most components, although often qualified separately, are part of a larger system like switchgears, motor control centers, control panels etc. The dynamic behavior of such systems will modify the response of individual components by introducing their own dynamic characteristics as well as non-linearities. Some of these factors are discussed below.

(a) Dynamic Characteristics of Assemblies

A base motion that is filtered through a cabinet or an assembly gets modified by the cabinet or assembly dynamic characteristics. Figure 1 shows a typical panel mounted on a shaker table for seismic testing. Figure 2 indicates the locations of various accelerometers mounted on the panel to monitor the seismic response at those locations due to the motion applied at the base. The resultant motion at a component location in an assembly could be a single frequency or a multifrequency motion depending upon the dynamic characteristics of the assembly. This in turn determines the applicability of component fragility data, obtained for example, through single frequency tests, to assembly fragility. Component fragility obtained by random motion test is

generally a broad-band spectra (See Fig. 3). Component location spectra, obtained through assembly testing, may have local peaks which exceed the broad band component fragility curve locally. Since a random motion test does not identify the frequency or frequencies at which component malfunction occurs, it is not conclusive as to whether these exceedances are acceptable or not.

(b) Non-Linearities of Assemblies

The resonance search for most assemblies is carried out through low amplitude tests, at which level the assemblies generally remain linear. However, when tests are carried out at the SSE level, many assemblies exhibit varying degrees of non-linear behavior such as shifts in the resonant frequencies as well as changes in damping of the system. Fig. 4 shows the results of a resonance search test of a Control Cabinet, which gives the first fundamental frequency of about 6Hz. The same cabinet when subjected to the SSE test shows that due to non-linearities of the cabinet, the frequency has shifted to about 3Hz (fig. 5). Thus, for the same cabinet, a given input motion will have amplifications at 6Hz if the cabinet is linear and at lower frequencies if the cabinet goes non-linear. Fragility performance of the component in this case, is thus, highly dependent on the system performance. Using the low level resonance search data alone to obtain component location spectra can be misleading.

Search for fragility data will mean subjecting the equipment to high level of seismic motions. This may cause non-linear behavior of the equipment, whereas equipment in the field may remain linear even under SSE loads. It will therefore, be necessary to have a careful correlation between two sets of data.

(c) Characteristics of Base Input Motion

Seismic response spectra at the component location of a given system is obtained either through direct test of the system with the responses measured at the component location or is obtained by performing the time history analysis of the system. In the test a seismic excitation represented by a test response spectra (TRS) is given at the base of the system. This TRS envelopes the required response spectra (RRS) at the base. Figure 6 shows a typical example of both RRS and TRS at the base of the equipment and the corresponding TRS test and RRS obtained through analysis at the component location. The equipment frequency in this case happens to be about 10Hz. It may be observed from the figure that, although at the base TRS envelopes RRS, amplifications for RRS at the component location may be higher than those for TRS. This emphasizes the need to ensure that motion content of TRS through all frequencies of interest for the equipment test does not fall below that of the RRS.

It should be noted that for the example shown, the analysis was based on linear behavior of the system, whereas actual test will include non-linear behavior of the system and component-system dynamic interaction. This variation in the component location spectra indicates the importance of testing components as part of an assembly so that their realistic functionality is ascertained. Otherwise, a careful interpretation of the component fragility data including the consideration of the system behavior is required when these are applied for plant-specific purposes.

COMPONENT FRAGILITY AS PART OF SYSTEM:

The previous discussions indicate some of the difficulties that exist in extending the fragility data for individual components to assemblies and systems. It is difficult to define a true fragility criteria. Individual components, when tested separately are performing in isolation under perhaps unrealistic seismic environments. The same component, when tested as part of the system will

experience seismic motion filtered through various substructures of the system. The anchorage and structural arrangement of the system, mounting of the component, interaction with other components and their mass distribution, location of the component within the system, all contribute to affect the performance of the component. It is therefore, felt that fragility data obtained for components, when tested as part of assemblies is more realistic and reliable than the data obtained for components tested individually.

CONSERVATIVE LOWER BOUND COMPONENT FRAGILITY:

Many components have been tested as part of assemblies for several nuclear projects with varying input motions and assembly characteristics. Such information can be compiled to obtain envelopes of all the spectra measured through tests at the component locations. Evidently this curve will not represent the true fragility of the component, but may be used to demonstrate a conservative lower bound of fragility. This information can be used to qualify any future replacement parts or to determine the qualification margin available for an already installed component. As more test data becomes available, the "Lower Bound" fragility curve can be upgraded to include new information.

INHERENTLY RUGGED COMPONENTS:

There are several components which have been used extensively in nuclear power plants, and have been found to be inherently rugged under seismic environment. Many types of valves, pumps and fans which are qualified either by test or analysis or combination of both have exhibited large margins between their test/analysis levels and the common seismic requirements. Table 1 lists some such components. Evidently, at the present time, there is no need to test these components all the way to their fragility levels. Existing information is considered to be adequate to provide lower bound of fragility data.

CONCLUSION AND RECOMMENDATIONS:

Based on the discussions above, it is seen that there are difficulties in extending individual component fragility data to determine an assembly fragility. Individual components tested in isolation may not experience the same seismic environment as that in an assembly. An effort should be made to conduct a comprehensive review of the existing data available for assembly testing. This data should be compiled to obtain a "Lower Bound" fragility base for individual components. This base can then be upgraded to include more information as it becomes available.

Fragility testing is expensive. Therefore, it is imperative that such a task be undertaken only after functional relationship between individual component fragility and assembly fragility is properly established. Existing information available through actual assembly testing can serve as a very useful fragility data base. Additionally, components which have consistently been found to be seismically rugged need not be tested or analyzed to obtain fragility data.

TABLE 1

EXAMPLES OF SEISMICALLY RUGGED SYSTEMS

EQUIPMENT	ACCESSORIES	REMARKS
Gate Valve Globe Valve Butterfly Valve Check Valves etc.	Motor operators (by Limitorque) Air operators (by Xomox, Hiller and Bettis) Limit Switches (by NAMCO) Solenoid Valves (by ASCO)	Accessories are tested by RIM* to a minimum of 4.5g. These accessories are used to operate any of the valves listed.
ASCO Pressure and Temperature Switches	---	RIM* tested to a minimum og 6.0g.
Crosby Safety Relief Valve (6"X6" Vacuum Relief Valve)	---	Rigid valve, sine beat test to 22.0g.

* RIM - REQUIRED INPUT MOTION

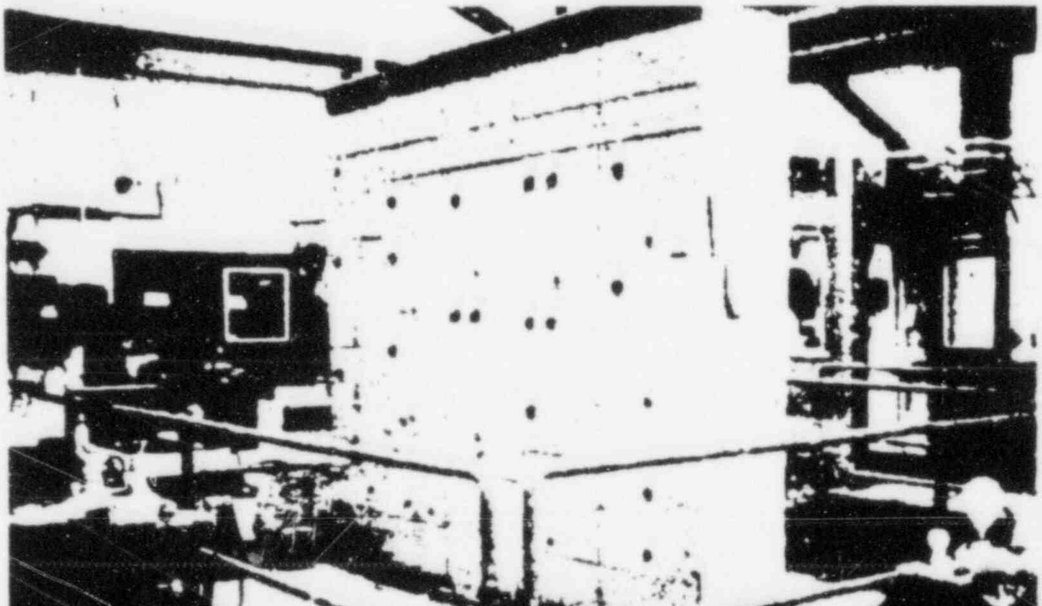

FIGURE 1 TYPICAL PANEL MOUNTED ON THE SHAKER TABLE

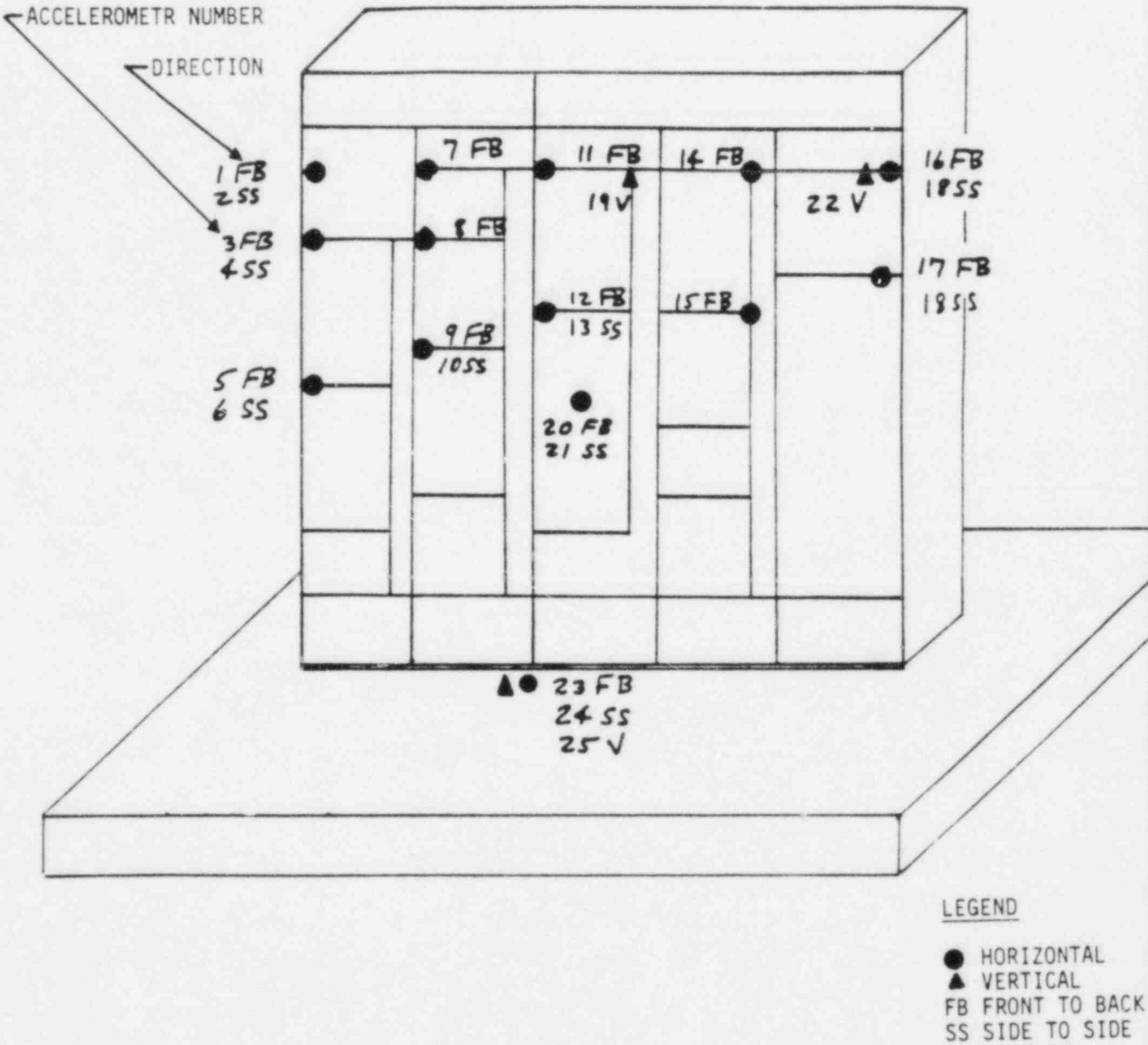

FIGURE 2 ACCELEROMETER LOCATION ON A TYPICAL PANEL

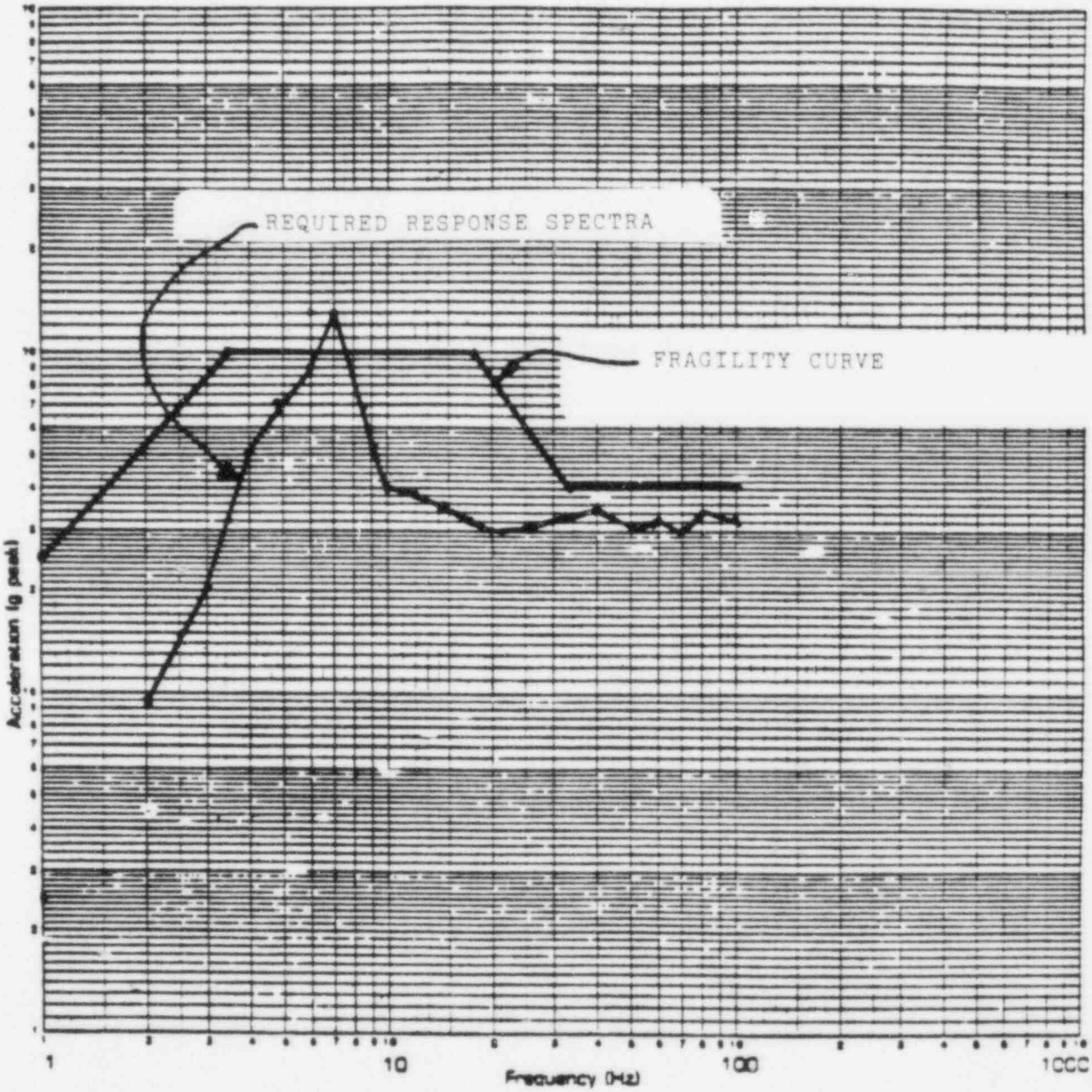

FIGURE 3   FRAGILITY CURVE VS. REQUIRED RESPONSE SPECTRA

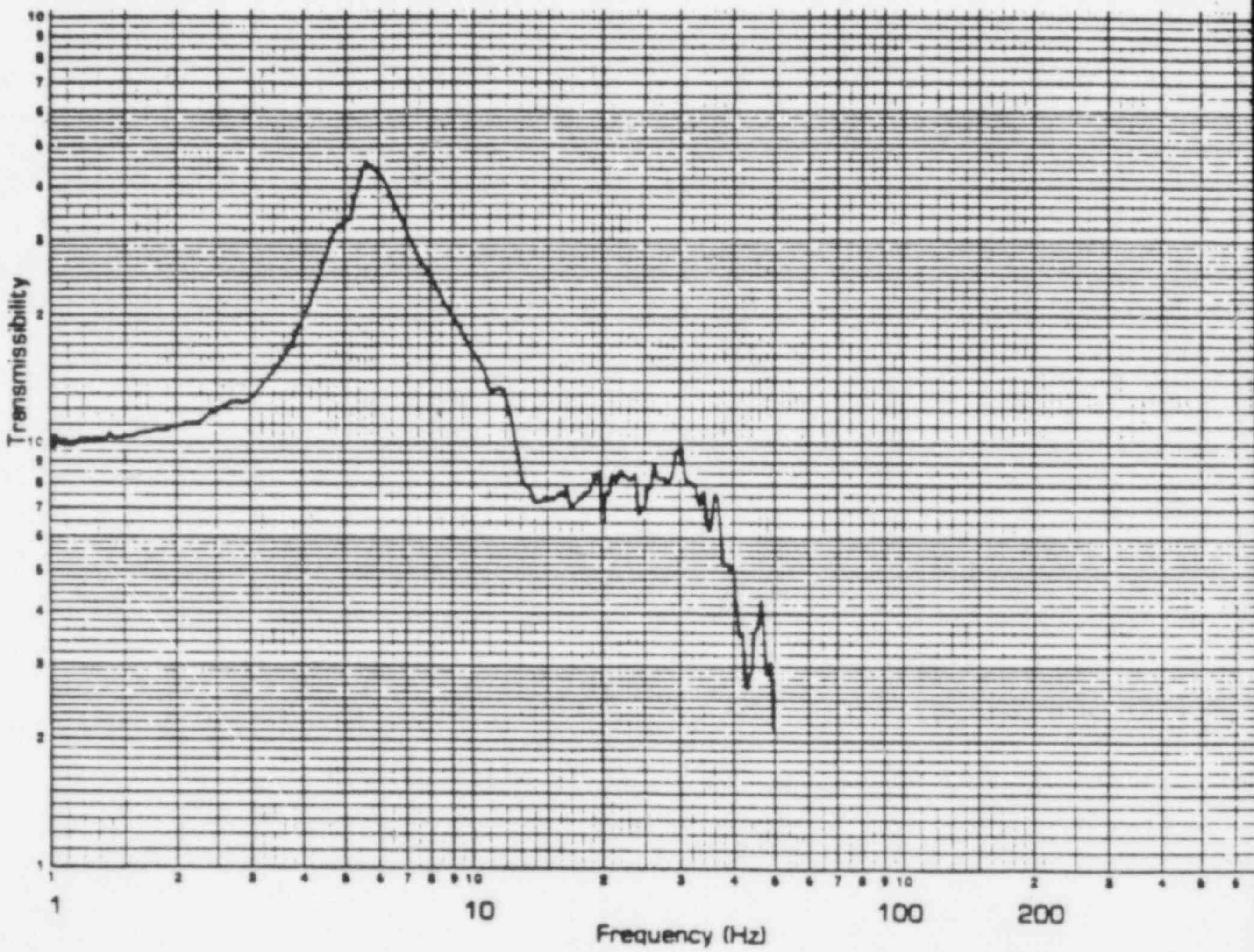

FIGURE 4 TRANSMISSIBILITY PLOT FOR A TYPICAL CONTROL PANEL

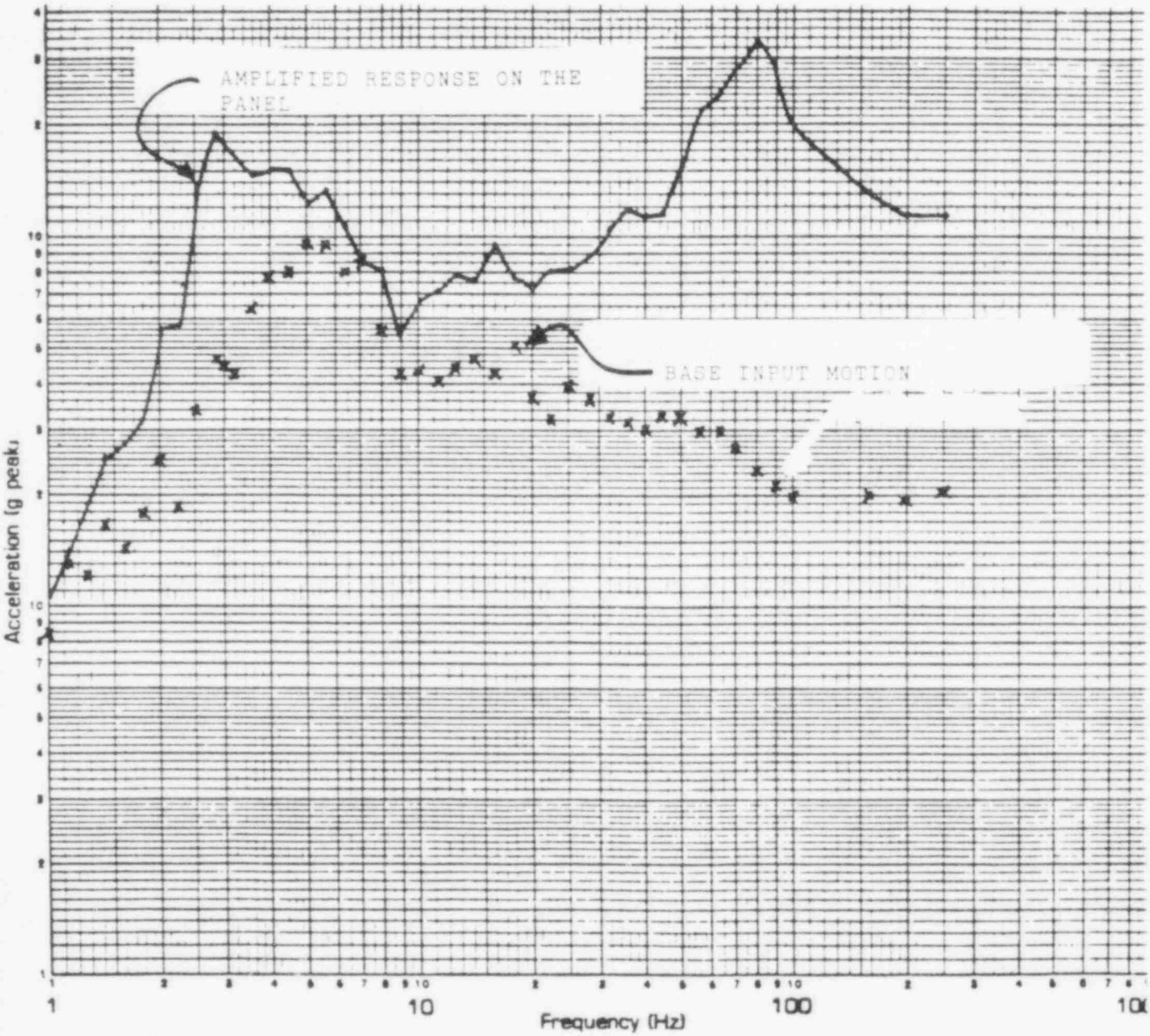

FIGURE 5 CONTROL PANEL RESPONSE UNDER SSE LOAD

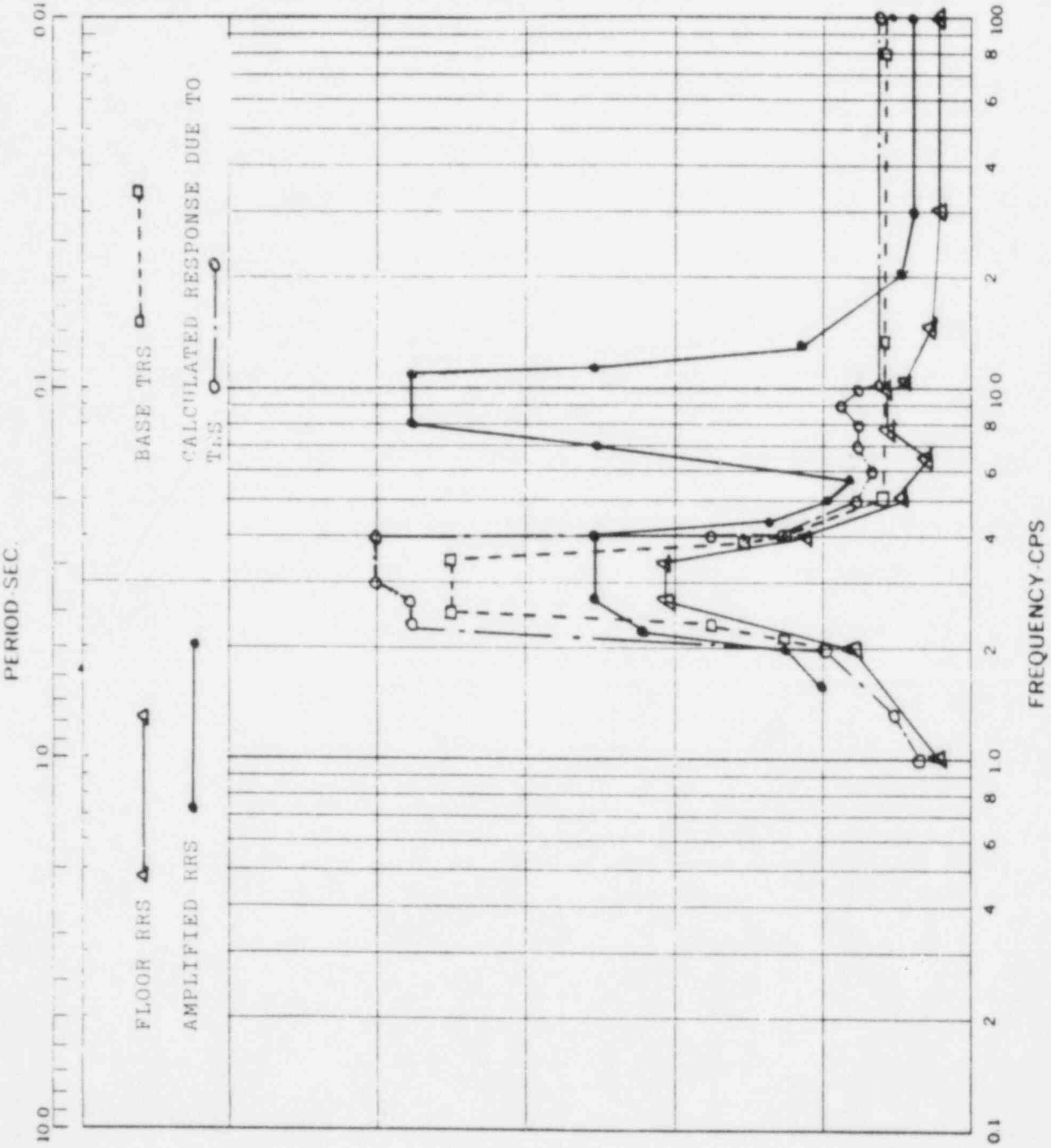

FIGURE 6. EFFECT OF BASE MOTION CHARACTERISTICS ON PANEL RESPONSE

SESSION V

EQUIPMENT REQUIRING FUTURE FRAGILITY TESTING

THE EFFECTS OF RELAY CHATTER IN SEISMIC PROBABILISTIC SAFETY ANALYSIS[1]

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ABSTRACT

In the Zion and Indian Point Probabilistic Safety Studies, relay chatter was dismissed as a credible event and hence was not formally included in the analyses. Although little discussion is given in the Zion and Indian Point PSA documentation concerning the basis for this decision, it has been expressed informally that it was assumed that the operators will be able to reset all relays in a timely manner. Currently, it is the opinion of many professionals that this may be an oversimplification.

The three basic areas which must be considered in addressing relay chatter include the fragility of the relays per se, the reliability of the operators to reset the relays and finally the systems response aspects. Each of these areas is reviewed and the implications for seismic PSA are discussed. Finally, recommendations for future research are given.

Relay chatter median capacity values have ranged from as low as 0.41g peak ground acceleration (pga), which was reported in the Seabrook PSA, to higher values in the range of 1.5g pga. The latter values were developed as part of the Limerick PRA in response to questions during the review process. Most relay chatter capacities used today find their origins in the Corps of Engineers shock test data; however, the Limerick data were based on plant-specific qualification data. The corresponding variability is large with logarithmic standard deviation values as high as 1.5 or more. Because relay chatter is a "brittle" phenomenon (i.e., there is no inherent material ductility) there is high associated variability which depends on the type of relays, the frequency content of motion, the amplitude of motion and

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[1] Work performed under the auspices of the U.S. Nuclear Regulatory Commission. Views expressed are not necessarily those of the U.S. Nuclear Regulatory Commission.

undoubtedly other factors which have not been considered. For example, relays have been found to chatter at a given motion amplitude only to stop chattering at a higher level of motion. The state-of-the-art of fragility values for relays is relatively weak.

Assuming relays chatter, the next level of concern is whether the plant operators are able to reset the relays and return the plant systems to the proper state. Very little experience and information is available to determine the reliability of plant operators under these circumstances. Some guesses have been made. For example, in the Limerick PRA, it was assumed that human failures would be 10 times greater during and immediately after a seismic event compared to non-seismic accident situations. As discussed below, the assumed recovery rate is an important contribution to the results of the seismic PSA.

The systems analyses of relay chatter also have not fully matured in seismic PSA. Even for cases where some attempt has been made to include relay chatter, it usually consists of single events and does not reflect the many relays which are present, the logical configurations and their interdependencies. Some sensitivity analyses have been performed to investigate the effects of relay chatter. As part of the review of the GESSAR II seismic PSA, it was found that reasonable assumptions on the fragility values and human recovery rates can change the mean frequency rate of core melt by a factor of 10.

Considerable research is needed to address the question of whether relay chatter is a significant contributor to risk in seismic PSA. This research should be directed to the capacities of relays (i.e., more fragility tests are needed), the human recovery aspects and the systems configuration of relays in relation to other safety-related components.

INTRODUCTION

Relay chatter recently has received attention as a potential failure mode which could lead to core melt. In the first probabilistic safety analyses (PSAs) conducted by utilities for Zion and Indian Point Nuclear Power Plants, relay chatter was dismissed as a credible event, and hence was not formally included in the analyses (Refs. 1 and 2). Although little discussion is given in the Zion and Indian Point PSA documentation concerning the basis for this decision, it has been expressed informally that it was assumed that the operators will be able to reset all relays in a timely manner. During the review of the Limerick Generating Station Severe Accident Risk Assessment (LGS-SARA) the issue of relay chatter was investigated, and it was concluded that the probability of failure on the part of the operator to reset was nonzero and would result in the equivalent of a relay failure (Ref. 3). Recently this issue has also been raised in the review of the General Electric Company GESSAR-II seismic PSA (Ref. 4). Finally, the issue of relay chatter as a potential contribution to seismic risk has been raised by the NRC Expert Panel on the Quantification of Seismic Margins of which the first author is a member (Ref. 5).

The three basic areas which must be considered in addressing relay chatter include the fragility of relays per se, the reliability of the operators to reset the relays and finally the systems response aspects. Each of these areas is discussed in the following sections. The results of a sensitivity analysis conducted for relay chatter during the review of the GESSAR-II PSA is presented next. Finally, recommendations to resolve the issue of whether relay chatter truly is a significant contributor to seismic risk and to provide data to rationally include the effects of relay chatter in a seismic PSA are given.

RELAY CHATTER CAPACITY

Although relay chatter has not been in the system analyses of previous PRAs, relay chatter fragility estimates have been calculated and published as part of the seismic fragility analysis. Relay chatter median capacities have been as low as 0.41g and 0.60g peak ground acceleration as reported in the Zion PSA (Ref. 1) and Seabrook PSA (Ref. 9), respectively. The basic data for relay chatter come from the Seismic Safety Margins Research Program (SSMRP) where test data from Corps of Engineers shock tests and expert opinion data were used (Ref. 6). A spectral acceleration capacity of 1.15g in the 5 to 10 Hz range with an associated total logarithmic standard deviation of 0.82 is reported in Reference 6 for relay chatter of instrument racks and panels. This capacity must be reduced for structure and cabinet dynamic amplification to an equivalent ground level capacity which is generally different for each panel.

A second set of fragility values is also given in Reference 6 for a generic relay category. A median value of 4.00g, spectral acceleration and a total logarithmic standard deviation of 0.89 are reported. In a recent personal communication with the principal author of Reference 6, it was learned that there is an error in the second set of fragility values given above. In future versions of Reference 6 the median value will be reported to be 1.66g spectral acceleration with a total logarithmic standard deviation of 1.20 instead of 4.00g and 0.89, respectively.

Recently, another draft report has been completed which addresses the effects of circuit breaker operation during earthquakes (Ref. 7). In Reference 7 a median spectral acceleration capacity of 2.59g and a logarithmic standard deviation value of 1.51 were assumed for relay chatter. These data apparently come from Reference 8 and represent data based fragility values. In terms of ground level acceleration capacity, the local component spectral acceleration value of 2.59g converts to approximately 0.8g peak ground acceleration for Zion. Although 0.8g is slightly higher than 0.60g, which was used in the utility-sponsored Zion PSA, the logarithmic standard deviation value of 1.51 is considerably larger than the corresponding Zion value of 0.67. In summary, the relay chatter capacity values used in Reference 7 produce much higher failure frequencies at lower ground acceleration values.

Except for the values used in the Seabrook and Zion PSAs, the various fragility values discussed above for relay chatter can be related. Table 1 summarizes the bases for the relay chatter values given above. As indicated in Table 1, values from various original sources were combined statistically to obtain the values reported above (Ref. 6). Included in both component cases listed in Table 1 are the spectral acceleration median and logarithmic standard deviation values of 2.59g and 1.51, respectively, which are based on the Corps of Engineers shock test data and analysis in Reference 8. These are the parameter values which were used in the recent study of circuit breaker operation (Ref. 7).

TABLE 1 ORIGIN OF RELAY CHATTER FRAGILITY VALUES

Components	Combined Spectral Acceleration Capacity Median (g)	β_c	Original Source (Ref. 5)		
			Spectral Acceleration Median (g)	β_c	Source
Instrument Racks and Panels	1.15	0.82	2.08	0.28	Expert opinion
			4.93	0.38	Expert opinion
			2.59*	1.51*	Relay chatter
			9.58	0.81	Relay trip
			18.20	0.88	Structure failure
Relays	4.00**	0.89**	5.67	1.16	Expert opinion
			2.59*	1.51*	Relay chatter

* These values are based on analysis of Corps of Engineers shock test data and can be obtained from Reference 8 by combining fragility and response parameter values for relay chatter from Tables 4-2 and 5-1, respectively.

** These values are apparently in error. Future versions of Reference 6 will report a median value of 1.66g with a logarithm standard deviation of 1.20.

The issue of relay chatter was raised during the review of the Limerick PRA (Ref. 3). Subsequently, qualification data were reviewed by the utility, and it was found that relay chatter median capacities for the critical relays could be defended to be about 1.5g pga, which is considerably higher than the generic-based values of 0.41g and 0.60g pga for Seabrook and Zion, respectively. Thus, median capacities obtained to date range between approximately 0.4g to 1.5g pga. However, there are many different types of relays with different relay chatter characteristics which need to be more reliably estimated.

Because relay chatter is a "brittle" phenomenon (i.e., there is no inherent material ductility), there is high associated variability in the capacity which depends on the type of relays, the frequency content of motion, the amplitude of motion and undoubtedly other factors which have not been considered. For example, relays have been found to chatter at a given motion amplitude only to stop chattering at a higher level of motion. The state-of-the-art of fragility values for relays is relatively weak.

Because relay chatter is a brittle phenomenon, it is important that the electrical cabinet doors be tightly secured. In a recent inspection of a nuclear power plant, the first author found several cabinet doors which were loose (the anchor screws apparently had not been tightened after the last entry to the cabinet). Motions during a large earthquake (greater than the SSE but important to the seismic PSA) could cause the cabinet doors to bang, inducing high frequency motions in the relays which could lead to relay chatter. There are likely other situations or variables which could also affect the relay chatter capacity.

RELIABILITY OF OPERATORS

In the Zion and Indian Point seismic PSAs, no random failures or operator errors were modeled. In contrast, these effects were included in the LGS-SARA where it was assumed that in the event of an earthquake the human error rate would increase by a factor of 10 to reflect increased stress. As pointed out in the review of the LGS-SARA, relay chatter should be modeled, and to be consistent, human responses to reset the relays should be treated similar to other required human actions (Ref. 3). Information on the issue of operator errors for internal events can be found in Reference 11.

It is not known how operators will respond to severe earthquakes (e.g., 2 to 4 times the SSE values). On one hand some say that the operators will "rise to the occasion" and perform creatively and successfully. On the other hand, the operators may become concerned about the status of their families or about their own well being. Thus, under stressed conditions they may perform below their capabilities. In some cases relays can be reset in the control room. For other situations, the operator may have to leave the control room, go to the electrical cabinet some distance away and reset the relays locally.

The success rate of operator interaction during and following earthquakes is not known at this time. There is no dispute that relays will chatter and cause breakers to trip. The concern is whether the plant operators can reset the relays in time to return the plant to a safe mode.

SYSTEMS ASPECTS

There are many relays which are part of the safety-related systems at a nuclear power plant. The relays are of different types, and they have different functions. In a recent study by Lambert, he focused on the loss of

offsite power transient caused by a strong-motion earthquake at the Zion Nuclear Power Plant and the operator action necessary to prevent core melt if circuit breaker failure modes occur simultaneously on three 4.16 kV buses (Ref. 7). He points out that numerous circuit breakers are important to plant safety such as the circuit breakers for the diesel generators and the engineered safety systems which must open and/or close during a loss of offsite power transient while the earthquake motion is occurring. He identifies the following two failure modes involving relay chatter which lead to circuit breaker malfunction and subsequent core melt if not recovered.

- Circuit breaker trip
- Seal-in of anti-pumping relays which prevent automatic closure of circuit breakers

It has been expressed by others that for relay chatter to be a problem, the relay must be part of a self-locking circuit which does not have any time delay protection. In this case the circuit could be locked into the wrong state due to the chattering of the relay contacts. For self-energizing circuits such as in load sequencers, relay chatter could cause the circuits to self-energize and lock the loads in.

There are many types of relays, both mechanical and solid state which have to be considered along with the different types of circuits. It is clear from the effort by Lambert, where nearly 500 electrical drawings were examined to address the earthquakes on only a few systems, that it is a complex task to model all safety-related systems in a nuclear power plant.

SENSITIVITY ANALYSIS

In the review of the GESSAR-II PSA, a sensitivity analysis was conducted to investigate the effects of different, but realistic, assumptions on relay chatter (Ref. 4). In this analysis the core melt system fragility curves were developed from event tree/fault tree logic, Boolean expressions and component fragilities. The mean fragility curve was integrated with the mean earthquake hazard curve which produces the mean core melt frequency. The electrical power (EP) train was modeled by the following Boolean expression:

EP = DGPANEL + 125BUS + DGHV + 480XFORM
+ 480SG + 4KVSG + RELAY * MANRESET

where:

DGPANEL = Diesel generator instrumentation panel
125BUS = 125V bus
DGHV = Diesel generator heat and vent
480XFORM = 480V transformer
480SG = 480V switchgear
4KVSG = 4KV switchgear
RELAY = Relay chatter
MANRESET = Manual reset of relay

The last term (RELAY * MANRESET) is relay chatter times manual reset, which is the single term used to represent relay chatter and potential reset by the plant operators. It is believed to be appropriate for the approximate sensitivity analysis which was conducted to introduce a single term (i.e., RELAY * MANRESET) where the chatter capacity is conservatively set low and to use structure failure capacities for the other six electrical components. This is in contrast to adding this term to each of the other six electrical component terms.

In reality there are many relays which are logically in series, each with a different relay chatter capacity. By choosing the lowest capacity to represent relay chatter, the resulting frequency of failure will be realistic unless there are several relays that also have the same low capacity which, if independent, could lead to slightly nonconservative results. By selecting a conservatively low capacity for the single term, realistic (or possibly even conservative) results can still be obtained.

As a note of reference, if there are N relays each with the same low relay chatter capacity, the mean frequency of failure can increase by no more than a factor of N and probably less because the results are diluted by other contributing terms which are not changed. Also any dependencies due to response (e.g., the relays are in the same cabinet or are located on the same floor) or capacity (e.g., the relays are the same manufacturer's model) will decrease the total contribution from N relays. If the relay fragilities are all perfectly dependent, the effect of N relays would be identically the same as one relay.

Table 2 demonstrates the influence of various assumptions for relay chatter and manual recovery on the mean frequency of core melt. The results were obtained using the GESSAR-II hazard curves and the fragility values developed in the review, except for changes in the relay chatter capacity and the manual reset failure frequency. The first four trials in Table 2 investigate changes in the manual reset failure frequency only (note that the relay capacity parameter values from the Zion PSA were used). Increasing the manual reset failure frequency from 0 to 0.5 and 1.0 leads to increases in the mean frequency of core melt by factors of 2.5 and 4.0, respectively. Note that since the relays are reset with certainty in trial 1, this case simulates the situation of no relay chatter problem.

TABLE 2 EFFECT OF ASSUMPTIONS ON RELAY CHATTER AND RECOVERY

Trail	Manual Reset (MANRESET) Failure Frequency	Relay Capacity $\check{A}$	β_c	Mean Core Melt Frequency (per year)
1	0	0.6g	0.67	2.67-5
2	0.1	0.6g	0.67	3.48-5
3	0.5	0.6g	0.67	6.64-5
4	1.0	0.6g	0.67	1.07-4
5	0.5	0.8g	1.50	2.54-4

In trial 5, the manual reset failure frequency is set at 0.5, but the median capacity is set equal to 0.8g with a logarithmic standard deviation of 1.50, which are the values based on the Lambert study. Relative to trial 1, where relay chatter is not a problem, the mean frequency of core melt for trial 5 is increased by a factor of 9.5. This is a significant variation.

The sensitivity results given in Table 1 are based on a simplified model of the potential relay chatter problem. A more detailed model which includes interactions between components and the various relays is needed to determine more realistically the true influence of relay chatter on the results of the seismic PRA. In addition, more reliable capacity values are needed for different classes of relays (the two sets of fragility values assumed in this analysis are generic and may or may not be applicable to GESSAR-II). The important conclusion which is obtained from Table 2 is the large variation of mean core melt frequency values which occur for relay chatter capacities and manual reset failure frequencies representative of the current state-of-the-art.

NEEDS FOR FUTURE RESEARCH

Relay chatter has been identified as a potential significant contributor to risk. It is clear that relays will chatter at accelerations important to the seismic PSA. It is not clear at this time whether relay chatter is a problem. There is a need for future research to address this concern in three areas.

First, tests should be conducted to determine the chatter fragility characteristics of different types of relays used in nuclear power plants. The absolute level of chatter should be determined, but also the different parameters which affect the relay chatter capacity should be determined and investigated. It may be possible to determine that certain types of relays have high enough capacity to not be a problem. This result would be useful

in the second area of research which is the systems aspects. More work along the direction of the Lambert study (Ref. 7) should be conducted to determine which systems and circuits require careful attention.

Finally, the issue of human response needs to be addressed. This is a difficult area because of the inherent psychological aspects which are present. Experiments should be developed to simulate the earthquake experience and the actions and errors of operators monitored and studied. Experience from past earthquakes and the responses of operators in fossil fuel plants and other industrial facilities should be studied. From these actual earthquake experiences, the integrated operator responses would provide evidence of what error rates can be expected in nuclear power plants.

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FORMULATION OF A FRAGILITY PROGRAM

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ABSTRACT

The formulation of a fragility test program should include the review of a series of questions and trade offs. The answers, or at least tentative answers, to these questions will guide the program approach. This paper will share with you the questions and the thinking that went into the formulation of a current test program.

Included in the questions are: 1) grouping and priority, 2) mounting and anchoring, 3) operation and functional anomalies, 4) instrumentation, 5) excitation waveforms, 6) test sequence and number of samples, and 7) data review and analysis. The approach selected for the demonstration program will be outlined.

INTRODUCTION

Wyle Laboratories and Lawrence Livermore National Laboratory are in the early stages of a fragility test program. There are a number of trade offs which must be evaluated to arrive at a reasonable approach to such a program. In this paper, I will share with you some of the thinking that has gone into formulating this program. The first phase of the program will include, in addition to overall program planning, a demonstration test program. The objectives and plans for this demonstration program will be included in this discussion.

To keep this discussion to a manageable complexity, it will focus primarily on electrical equipment. A discussion of mechanical equipment would include comparable issues and concerns.

GROUPING & PRIORITY

To facilitate the performance of a fragility program, and maximize the benefit/cost ratio, equipment should be prioritized and grouped into categories. Potential groupings are: 1) those which are most important to plant safety, 2) those expected to have high sensitivity to seismic motions, 3) those shown by PRA studies to be of concern, and 4) those

that can be tested in a similar manner. Another element of grouping is that of size. It may not be necessary to test all sizes of a device if one size can be shown to be representative of sizes somewhat larger and smaller than the one tested. Discussions are proceeding with respect to groupings for the later phases of this program.

Fragility tests could be performed on sub-systems, or components, or both. In the general case, it is prefereable to work with cabinets with devices installed rather than the devices themselves. It is difficult enough to work with spectrum shapes which are "representative" of floor motions, without trying to work with spectra which have added the complexities of various cabinet transfer functions. There are, of course, specific conditions where fragility testing of devices can be desirable, such as when the device environment is known.

MOUNTING - ANCHORING

The equipment in-structure dynamic environment can be materially affected by:

1. Mounting and anchoring rigidity. Different plants use different mounting configurations for the same equipment.

2. Local stiffness and strength of the equipment structure near the mounting. Different cabinets use different structural designs.

3. Mechanical interfaces such as conduits, cables, bus ducts, etc. Depending on structural details, top entry conduits or cables may act as stiffness or as mass loading.

Also one mounting or design approach may be good for a medium seismic zone, but another design is needed for a high seismic zone, so data on both may be significant for such variations. The vintage of equipment may be significant because of structural design improvements for later models. A fragility program should include a representative range of all such conditions. The demonstration test will account for four such potential variations. The demonstration will not consider the influence of top entry interfaces.

AGING

Some equipment must be aged to its end of qualified life prior to seismic qualification. There is now extensive data on which equipment items are sensitive to aging phenomena. When a fragility program is being performed on an item which is known to be sensitive to aging, then aging prior to the fragility test should be considered.

OPERATIONAL LOADS

The general seismic qualification requirement is to include operational loads. This can be interpreted to mean all such loads that have a potential for synergism with the seismic loads. For some devices that can mean current but not voltage, for another it could be the opposite. Clearly, it is a device specific question, and another of the parameters requiring proper consideration. Operational loads may be influenced some by monitoring techniques, e.g., if it is desired to observe the operation of a motor starter by using a motor as a load.

OPERATION AND FUNCTIONAL ANOMALIES

Here we need to clarify terminology. As I will be using it in this paper, the following applies. A f ilure mechanism is any kind of abnormal behavior of, or in, the equipment. It may be functional, or it may be structural. A failure mode is a failure mechanism which is unacceptable in the particular system in which the equipment is operating. That is any failure mechanism is a potential failure mode and is system dependent. In the general case, a fragility program cannot define a failure mode, but can define failure mechanisms. Since there is some lack of clarity of this, many engineers prefer to speak of failure mechanisms as functional anomalies, a less condemning phraseology, hence the terminology you see here.

There are a variety of anomalies which can limit the capability of equipment. The anomalies may be functional or structural. A particular equipment item may have several potential failure modes with the significant one being highly application or system dependent. To satisfy its safety function, a given equipment in one system may be required to perform an active function during the earthquake while in another system, it may be required only to survive (structural) to be able to operate after the earthquake. Potential anomalies include relay chatter of various durations under no load, and under load, change of state or other spurious operation without command, load current fluctuation, increase in stroke time, loss of function, and structural failure such as cracking and yielding. A fragility program then must look for multiple potential anomalies at progressively higher test levels because a given equipment may serve in several different systems. Relay pickup and drop out, or valve time might be critical which can suggest that function with under/over voltage may be a necessary data point as well.

We don't know all that we would like to know about functional anomalies, including what lévels they occur at, how they may interact, how similar are they, etc. The demonstration program will be looking at these questions.

INSTRUMENTATION

Instrumentation of a fragility program must be more comprehensive than a qualification program. The instrumentation needed for a qualification program is only that required to detect specific failure modes which are specific to the particular application. A fragility program must instrument to detect any potential functional anomaly. For example a relay should be monitored to detect different durations of chatter, at presumably successively higher levels of excitation. The operation of a motor starter may be observed by monitoring for chatter, by monitoring the current through one of the main contacts into an inductive load, or by operating an "off table" motor.

In addition to the normal test control accelerometers, accelerometers for in-structure response should be included, particularly at device mounting locations. Cross axis acceleration should be monitored for selected locations.

Stress levels will be appropriate for some items. Deflection measurements will be useful for some.

EXCITATION WAVEFORMS

The most common qualification waveform is random, so any fragility program must include random excitation. But what spectrum shape, or shapes, should be used? If it is appropriate and desirable to simulate typical locations in a plant structure, certain generalizations on frequencies and bandwidth can be made, e.g., low in the structure the frequency bandwidth will be wide, higher in the structure the frequency bandwidth usually narrows.

If devices are being tested, then a properly performed fragility test can be significantly more complex. The greater the variety of cabinets that a device can be mounted in, the greater the potential variation in frequency content. A given cabinet may act as a strong mechanical filter and reduce a broadband input into a narrow band, but amplified spectrum. It is even more likely to add higher frequencies due to rattling which is present in most cabinet structures.

On the other hand, what is the sensitivity of the equipment to frequency content? Some functional anomalies can be expected to be sensitive to frequency, others can be expected to respond only to acceleration level (ZPA). A given equipment item may include some sensitivity to both. Frequency search data may provide guidance for a specific case.

What upper frequency limit? For ordinary plants, at ground level, probably no higher than 33 Hz cutoff. Up in the building, the frequency

may drop off to perhaps 12 to 15 Hz cutoff. If hydrodynamic loads may apply, then maybe as high as 50 Hz.

In qualification testing the general requirement is to envelope an RRS, which usually means that as a practical matter, the TRS turns out to be some 25 percent higher than required in the amplified region, and as much as 2 to 4 times higher than the required ZPA. For fragility testing, I would suggest that the objective should be to achieve a flat spectrum (minimizing peaks and valleys) over the selected frequency range, and guide the overall level based on the ZPA level, letting the amplified level be as it will.

In light of the above, a fragility program should attempt a tailoring to the equipment being tested. Depending on the equipment dynamic response and its sensitivity to the ZPA, it may be sufficient to perform only wide band excitation. On the other hand, it may be desirable to also employ two, or more, narrow band spectra to probe frequency sensitivity. A given equipment, with multiple functional anomalies, could be sensitive in different ways to each of the above.

Amplitude steps. Getting a good definition of the fragility level would suggest increasing the spectrum level in relatively small steps. Minimizing fatigue effects, suggests reducing the number of steps, i.e., increasing the size. We intend to try a compromise with steps of 1.5 times. Another way of reducing the number of steps is to select the first one just below the lowest fragility level. If the anomaly at the lowest level is expected to be a malfunction then one can start higher, and simply back down, with no loss, if the first level turns out to be too high.

Another fatigue related parameter is duration of each test. If the expected anomalies are functional, and not fatigue related, then duration is less significant, and a duration of 10 seconds of strong motion would seem sufficient. For those mechanisms sensitive to low cycle fatigue, it may be desirable to use longer durations, but it will be necessary to account for the fatigue effects of all tests performed at lower level. It might be useful to use the lower level tests to show compliance to normal OBE criteria. The demonstration program will use 10 seconds of strong motion with a 2-3 second rise and a 3-4 second decay.

Some equipment can be reasonably expected to be very rugged and to successfully withstand quite high levels of excitation. There is no justification for continuing to increase the test levels for such equipment. It is reasonable to select a level, beyond which fragility data would have no real benefit, and adopt that as a limit for test purposes. The demonstration program has selected that level to be an in-structure spectrum with a ZPA of 2.5 g.

Tests should ordinarily be performed biaxially, to be compatible with the majority of qualification data.

Some equipment will be subjected to predominantly sinusoidal type motions which are conventionally represented by RIM requirements. These motions are conventionally simulated with single axis sine sweeps for the OBE's and continuous sine beats for the SSE. Avoiding fatique with this motion poses an even larger concern. Potential techniques include using sine sweeps instead of sine beats, or using a number of beats (perhaps 4) instead of using a 10-15 second time criteria. The technique used must be compatible with demonstrating operability during strong motion at various frequencies. This quickly becomes an equipment or device unique decision. A further discussion of the approach for this would be beyond the time allotted for this paper, so suffice it to say for now that it is anticipated that fatigue questions will be a much greater concern, and much more difficult to deal with for this type environment. Fragility data for this type of motion will not be included in the early stages of the current program.

TEST SEQUENCE

Generally the sequence should follow from the configuration which is least likely to cause a structural anomaly to that more likely to cause a structural anomaly. If various mounting configurations are to be tested, then the stiffest mounting should be tested first followed by the more flexible configurations.

NUMBER OF SAMPLES

How many samples should be tested in a fragility program? Fragility testing is not reliability testing, so a large number of samples is not required. Qualification testing is based on the common mode theory, which suggests that when a device fails, all such devices would fail in a similar manner, at similar seismic levels. Therefore, when a device passes the qualification level, it is OK. On the other hand, when a device fails, it can be asked if it was really a common mode failure, or was it instead a random failure? Does it then follow that two or three devices should be tested in a fragility program? The demonstration test is expected to include two each of several devices to acquire some data on this question.

DATA REVIEW AND ANALYSIS

It will be important to find ways of presenting the results in a form which gives the best understanding of the data obtained. This will depend on the equipment and on the anomalies detected. Potential items to be included are: Transmissibility plots from the resonance search data. These can be for various locations in the equipment, for various mounting configurations, and for various device locations. The plots can also show mode

shapes of the equipment structure.

Test response spectra for input, and selected locations on, and in, the equipment. TRS should be correlated to anomalies detected, and to the devices involved in the anomaly. They may show frequency sensitivity as well as amplitude sensitivity. The TRS for lower level runs before and after may show information on fatigue sensitivity.

Time history plots of the excitation may be correlated to anomalies in the time domain. It is possible that specific wave form characteristics can be correlated to an anomaly, e.g., relay chatter.

DEMONSTRATION PROGRAM OUTLINE

Purposes. The purpose of the demonstration is 1) to study various influences, such as mounting, operational loads, and spectrum shape, on seismic fragility levels, and 2) to show that meaningful and useful fragility results can be determined, analyzed, and characterized. It is not to focus on, or target, any specific item of equipment as being necessarily any more important than any other equipment. The details presented in this outline are somewhat tentative as not all details are yet finalized.

Test Item. The equipment to be tested consists of one motor control center composed of three 20" x 20" x 90" columns. The unit will include starters as follows: one size 2 FVNR, one size 2 FVR, two size 3 FVNR, and tow size 4 FVNR. The unit will also include several relay panels with 25 general purpose relays of different types, vendors, and sizes. The assembled weight is expected to be 2,000 lbs. The unit is expected to be structurally representative of that installed in the late 1970's.

Mounting. To gather data on the influence of anchoring and mounting, four mounting configurations are anticipated. They will represent four of the more or less conventional mounting practices employed by the various plants. These are expected to show first mode frequencies over the range of 6 to 15 Hz.

Instrumentation. Dynamic. Four accelerometers will be used to monitor and control the test input motions. Fifteen accelerometers will be used to monitor the response of the cabinet structure and major components. Electrical. Instrumentation channels will be provided to monitor contact chatter, variation in load current, relay change of state, and loss of continuity. All of the instrumentation will be recorded to permit post test analysis as might be desired.

Dynamic Excitation. As a simple method of monitoring cabinet deterioration due to multiple tests and possible fatigue, a static load/deflection test will be performed before and after the testing in each configuration. A routine resonance search will be performed in each of the three

principal directions. The seismic tests will be conducted biaxially with random motion which will be synthesized to meet the desired spectrum shape. Independent signal sources will be used for the horizontal and vertical axes. The duration will be a 2-3 second ramp up, a 10 second strong motion portion, followed by a 3-4 second decay. A limited amount of testing may be performed with spectra with different frequency bands. The maximum test level will be a spectrum with a 2.5 g ZPA.

Test Sequence. The test series will be performed in the stiffest orientations first, followed by successively more flexible orientations. The first spectrum level will be that estimated to be just below the first anomaly. Test levels will be increased in steps of 50 percent, until one, or more, anomalies are detected, or the maximum test level is reached. Strain gage data will be monitored to try to avoid unnecessary structural damage.

Functional Operation. All control circuits will be energized. Circuit breakers will be in the closed position. Tests will be performed with starters and relays in both energized and deenergized positions. Some devices will be commanded to change state during the excitation.

Data Review and Analysis. The data will be reviewed, analyzed, and presented as suggested in the earlier part of this paper.

Flexibility. One of the themes of the demonstration program will be flexibility, i.e., the program plan will have continuous review and flexibility built in, to permit variations which can take advantage of things learned as the program progresses. It will particularly look for other ways of presenting results to gain better understanding and correlation of any anomalies detected.

SESSION VI

USE OF FRAGILITY DATA IN PRA AND SEISMIC MARGIN STUDIES

WILL THE REAL FRAGILITY PLEASE STAND UP?

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ABSTRACT

This paper is written from the perspective of the author's experience with the Seismic Safety Margins Research Program (SSMRP). The SSMRP is the only seismic PRA (probabilistic risk assessment) that:

1. Was developed by a team that had all of the technical disciplines required to execute a seismic PRA within a single organization (Lawrence Livermore National Laboratory).

2. Was developed by a team that emphasized seismic rather than PRA considerations.

(1) provided a mechanism for numerous and frequent formal and informal interactions between the various technical disciplines. These interactions led to the identification of many issues, including issues on fragility, that are still not resolved (and perhaps never will be) and, in some cases, not even widely known. (2) means that when the SSMRP is described, the phrase should be "SEISMIC pra" not "seismic PRA", and also means that there are significant <u>seismic</u> issues related to PRAs that have not yet received sufficient attention, including issues on fragility.

Both (1) and (2) mean that the fragility perspective in this paper is:

- From the top down, rather than the bottom up.

- In the context of the overall objectives of the PRA.

- In the context of the calculational method that is used to assemble the input data (including fragility data).

- In the context of an examination of the sources, meaning, introduction, calculation and estimation of uncertainties, including uncertainty in fragility.

This paper also examines fragility in the context of the pervasiveness of "bottom-line disease" (an overemphasis on numerical PRA outputs such as the annual probability of core damage) and the congruence of the disease with seemingly unrelated topics, even when these topics are discussed by those who claim to abhor or disavow the disease.

The point is also made not only are all fragilities estimates, which require engineering judgment, but that this will always be the case, regardless of how large a fragility test program is carried out. Many current discussions on fragility appear to be based on an (implicit) assumption that judgment is avoidable.

The (log normal) form of a fragility function is examined and certain observations made on some of the current controversies (that actually miss the more important points).

Finally, the point is made that data on the performance of industrial facilities in past earthquakes have been largely overlooked in the current state-of-the-art of seismic fragility. These data are the closest available analogues to the reliability (or unreliability) data that are gathered and used in internal-initiated PRAs. They also provide a means to develop fragility estimates using a totally independent route and logic than are used in the current state-of-the-art for fragilities for seismic PRAs or studies on seismic design margins. Performance data are of interest because they:

- Provide a credible indication of the physical performance during and after an earthquake -- which is a major open issue related to the interface between failure, as defined by fragility analysts, and failure as defined by system analysts.

- Provide a means to address (at least partially) the effects of issues that are difficult to address otherwise, such as undetected adverse design and construction errors, aging, and the large variety and number of small subcomponents or peripheral attachments.

1. INTRODUCTION

It is important to carefully describe fragility. It is also easy to misinterpret fragilities -- since they are based on so few entirely appropriate experimental results. This paper describes basic concepts in fragility and common models used for fragility in the current state of the art. Simple examples are chosen to clarify the key points.

The starting point for our presentation on fragility is seismic PRAs -- specifically the Seismic Safety Margins Research Program (Smith, et al., 1978, 1981, and Bohn, et al., 1983). The perspective that is intended by the title of this paper is that fragility development should not be thought of as an art or science that should be performed without considering the intended use of fragility. This is because the intended use of fragility has (or should have) an impact on how fragility should be developed. When the intended use is a seismic PRA, or a seismic margin study, there are significant factors that should be considered (that may be different for a seismic PRA compared to a seismic margin study) if resources are to be allocated in the most appropriate way in the fragility development. If these factors are not considered, and if the proper decisions are not made

in the full light of what is known and unknown or what is achievable and what is not, the fragility product per resource unit is unlikely to be optimal and may not even be useful.

In short, what should be done in developing fragility can be dependent on:

- The overall objectives of the study of which fragility development is a part.

- The measures or figures of merit that will be used to make decisions based on the results of the study.

- The total uncertainty in these measures and how fragility contributes to it.

All these factors can vary from one study to another. Thus, how fragility is developed can also vary from one study to another.

There is a great deal of confusion about fragility, and some controversy. The confusion, at least in part, stems from the impetus given to fragility development by the SSMRP. As one of the developers of the SSMRP, I feel some obligation to at least try to eliminate some of the confusion we sowed. This is the purpose of this paper. The controversy is discussed below. It centers on how fragility should be interpreted or used.

2. DEFINITION OF FRAGILITY

The <u>fragility</u> of an element (structure, piping system, component, or item of equipment) within a plant (or even the entire plant) is defined as the conditional probability of the element (or plant) achieving some limit state, given an initiating force described in terms of "peak acceleration" (the mean of the two horizontal peak free-field accelerations) of the surface of the plant site.

It is necessary to discuss three aspects of the definition to assist in understanding it:

- A <u>limit state</u> is a generic term used to indicate a physical condition of the element that is of interest. It is used to indicate that the concept of fragility can be used in many ways beyond the usual view of fragility as a "failure." The definition of the limit state will depend on the purpose of the fragility analysis. Examples of ways to define the limit state include:

    - Code allowable stress* is achieved

    - Yield stress* or strain is achieved

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*Although stress is not measurable physically, it is sometimes used as a convenient parameter of interest.

- A certain deformation occurs

- "Failure" occurs in the sense of structural collapse or ceasing to operate

- A structure deforms sufficiently (but does not collapse) so that anchorage cannot be assured of equipment mounted or supported on the structure

- "Failure" occurs in the sense that the element can no longer perform its safety function

- Severe core damage occurs

The limit state describes a mode or set of physical conditions of the element.

- Defining fragility as a conditional probability is based on the view that the occurrence of the limit state is not certain, given some initiating force. Achievement of the limit state within an element given a peak acceleration level is unpredictable. The appropriate way to express the existence of a limit state is thus in terms of the probability (sometimes denoted "likelihood" or "frequency") of it being achieved. Fragility is conditional in the sense that it generally changes with the peak acceleration value. That is, it is a function of peak acceleration. For example, at low accelerations fragility is generally close to zero while for high accelerations a limit state (for example, failure) is almost always achieved and fragility is close to 1.0.

- Fragility is expressed as a function of peak acceleration at the ground level of the plant site. This implies the existence of some external source, for example, an earthquake, which can affect the element and initiate a process which could result in the achievement of the limit state within the element. It also assumes that the influence of the external source on the achievement of the limit state is adequately reflected in the value of peak acceleration. The choice of peak acceleration as the parameter (conditioning variable) of the fragility function will have an effect on the shape of the fragility function. This choice is made for various practical reasons, not the least of which is that fundamental relevant measured earthquake data are typically expressed in terms of acceleration.

A graphic description of a typical fragility function is given in Figure 1. The range of a fragility function is the interval (0,1), since fragility is a probability.

The reason acceleration is chosen as the conditioning variable for fragility is that in the data assembly process in a seismic PRA, the conditional probability of achieving the limit state described by the fragility function is integrated over the seismic hazard function to obtain the unconditional (annual) probability of achieving the limit state (Smith, et al., 1980) Hazard functions typically have acceleration as their conditioning variable. If the hazard function uses some other parameter (for example, velocity) so should fragility, or vice versa, if the fragility is intended for use in a seismic PRA. The choice of this parameter has important consequences on fragility development as will be seen below. This is the first example of how the use of fragility in a particular study (here a seismic PRA) has an impact on fragility development.

3. SIMPLE EXAMPLE

We introduce a simple example to clarify the key points. Assume that there is a single standard steel coupon somewhere in a plant that is a key element to the safety of the plant. If the steel coupon is subjected to sufficient tensile load and breaks, we assume that undesirable safety consequences result. Assume that a safety analysis of the plant is undertaken, thus the performance of the coupon is of interest. Finally, assume that the threat to the plant is an earthquake, thus peak acceleration is an appropriate fragility parameter in the safety analysis.

Different coupons will not break at the same tensile load or at the same overall elongation, even when the coupons are from the same batch of steel. This is well known from laboratory tests on steel coupons. One reason for this is the various uncontrollable factors in the manufacturing, rolling, machining, etc., process that produces the coupons. It is common to consider these uncontrollable factors as random. Thus, we also consider the tensile breaking load or elongation of the coupons, which depend upon the uncontrollable factors, as random variables. Although it might be possible to identify, and quantify or control the effects of <u>some</u> of the sources of variation, it is not feasible, economical, or necessarily desirable to do so. Rather, it is more practical to accept a certain inherent variability in tensile breaking load or elongation from one coupon to another. The only sure way to determine the precise breaking load or elongation is to test each coupon until it breaks, thus leaving no coupons to use. A more realistic approach is to consider each coupon or set of coupons as randomly selected from the collection of all such coupons. Then any property of the coupon can be treated as a random variable, for example, tensile break load or elongation.

This is the first reason fragility is defined as a probability and the fragility function, as shown in Figure 1, is not a step function (is not a vertical straight line at a single acceleration). The inherent variation in the breaking load of steel coupons, as observed in laboratory tests, is attributed to uncontrollable factors which cannot be characterized deterministically. The theory of probability is the appropriate

mathematical tool for describing such "random" variation, thus fragility is appropriately defined in terms of probability.

4. SIMPLE EXAMPLE EXTENDED

The variation in the tensile breaking load and elongation of coupons is only one reason for defining fragility in terms of probability. We extend the simple example to provide additional rationale for considering the attainment of a limit state within an element to be a random event and fragility to be appropriately defined as a probability.

Assume now that the steel coupon is an element of a simple linear elastic single degree of freedom structure (or simple harmonic oscillator) as shown in Figure 2. This simple structure is often used to explain response spectra.

It can be shown that if the simple structure in Figure 2 is subjected to a number of different real earthquakes, each with the same peak acceleration, the peak response (acceleration, velocity, displacement, strain, etc.) of the simple structure will not be the same for each earthquake. Shibata (1978) has essentially shown this using empirical data from earthquakes, for example. We assume that the peak response of the simple structure that is of interest is the peak displacement of the mass of the structure relative to a fixed point, which is also assumed to be the displacement imposed on the ends of the steel coupon. Thus the fragility of the steel coupon is characterized in terms of peak acceleration input to the simple structure. The simple structure translates the earthquake excitation into peak relative displacement of the coupon which then determines if the coupon experiences a tensile break. We assume that when the tensile break occurs it does not affect the dynamic response of the simple structure (this is inherent to the assumption that the simple structure responds in a linear manner).

Viewing the coupon in the context of a structural model provides insight into other sources of variation associated with the achievement of a limit state, that is, reaching the tensile breaking load or elongation of the coupon, and fragility. Given a specific earthquake, the ground motion at the base of the structure will initiate a structural dynamic response and hence some relative displacement of the ends of the coupon. However, as mentioned in the description above, if the same structure is subjected to different earthquakes, all with the same peak acceleration, the peak relative displacements will not be the same for all earthquakes. One reason for this is the fact that the way an earthquake affects a structure is not totally described by specification of peak acceleration as the excitation.

One way to see this is to consider a typical transfer function for the simple structure in Figure 2 (Figure 3). This function describes the relationship between the earthquake excitation (input) and the structural response (output), at any given frequency. As shown in Figure 3 the structure (with frequency f_n) responds to the frequency content in the

input motion (at frequency f) in different ways, depending on the frequencies f and f_n. For example, if the input frequency is one-half of the frequency of the structure ($f/f_n=0.5$) the structural response will be much different than if the input frequency is twice the frequency of the structure ($f/f_n=2$). Even when earthquakes all have the same peak acceleration, they typically do not have the same "frequency content" at any given frequency, in particular the frequency of our simple structure, f_n. Thus, the structural response will vary from one earthquake to another, even for earthquakes that have the same peak acceleration.

Imagine observing all possible earthquakes and grouping the earthquakes into classes of "equal" peak acceleration. For a fixed acceleration imagine observing the peak relative displacement of the ends of the coupon for all earthquakes with the same acceleration. As discussed above, we expect to observe a range of displacements. Similar to assessing the breaking load or elongation of a steel coupon, it is not feasible to measure the effect of all aspects of an earthquake. Thus, it is not feasible to predict precisely what any specific displacement would be (or will be for future unobserved earthquakes) based only on knowledge of the peak acceleration. Therefore, it is appropriate to accept this inherent variability in displacement, given peak acceleration, and include the variation as a source of variation in the existence of the limit state. That is, it is another factor in considering fragility a probability.

There is no loss of generality because the fragility is specified in terms of input (to the simple structure) peak <u>acceleration</u> and the tensile break of the steel coupon is assumed to be related to the peak relative <u>displacement</u> of the ends of the coupon. It can be shown that if the fragility of the coupon is specified in terms of input (to the simple structure) peak <u>displacement</u>, this variability still exists for the steel coupon example. Again, this is because peak displacement is an underspecification of the total effect of an earthquake on the structure. (This is actually the precise meaning of Figure 3, as far as the numerical gain and phase factors in Figure 3 are concerned.)

The variation in the fragility of an element due to the variation in how different earthquakes affect structures typically has a more profound effect than the inherent variation in material or operational properties of an element, at least for many elements. This can be demonstrated, but we will not do so here. However, heuristically, it is well-recognized that "loads" typically have the largest variation. We can consider an earthquake a generalized load. The greatest variability in the earthquake as a "load" is that associated with the size and frequency of future earthquakes. This is modeled in a seismic PRA by treating peak acceleration as random. (In a seismic margin study this variability is removed from impacting the results.) The next largest variation in the earthquake as a "load" is the variation due to the effect we have just discussed.

5. PARTIAL SUMMARY

There are two reasons so far that the function displayed in Figure 1 is not a vertical straight line (two reasons that the tensile break of the coupon cannot be characterized deterministically):

- Inherent variations in individual steel coupons that arise from normal variations in manufacturing, machining, and so forth.

- Variations in the dynamic response (for example, peak relative displacement) of a structure to different earthquakes, each with a specific peak acceleration.

There is the further assumption that the inherent "random" variations associated with the tensile break of the coupon in this model are adequately characterized by the theory of probability.

6. ADDITIONAL CONSIDERATIONS

There are additional factors which contribute to the variability in the existence of the limit state and treating fragility as probability. For example, the response of the simple structure in Figure 3 will depend on the structural damping of the structural motion initiated by the earthquake. Damping, as used here, describes the various energy loss mechanisms that exist within a structure, some of which are due to nonlinear phenomena.

If repeated tests could be carried out on a structure using the <u>same</u> input source (that is, same time history of input), some variation in inferred damping will be observed, but this will be relatively small, see Shibata (1978). This variation is typically due to inherent variations in excitations, or noise in the measurements. This is discussed by Gersch (1974).

If repeated physical tests are carried out on a structure using <u>different</u> time histories of input (each with the same peak acceleration) a larger variation in inferred damping (in terms of the assumed linear predictive model) will be observed from one test to another.

The reason the inferred damping will have a larger variation in the second case is that there is interaction between the different earthquakes and the nonlinear energy loss mechanisms that are reflected in the inferred damping. This interaction will vary from one input time history to another in terms of its observed effects on damping.

Not only does damping vary between different earthquakes, but it will also depend on the material properties of the structure, its design, as well as the construction process.

All of the these factors are unpredictable, thus it is appropriate to consider damping as a "random" variable which contributes to the uncertainty in the achievement of the limit state for a fixed peak acceleration.

Damping variability is thus a third factor, in addition to the inherent variation in the breaking load or elongation of the coupon and the variation in how earthquakes affect the system response, which influences the value of fragility.

There are additional factors, for example, other structural properties such as the structure frequency, which also contribute to the need to define fragility as a probability. It suffices to note that there are many factors which contribute to this randomness. There has not been sufficient research to quantify the effects of the various factors. It is generally agreed, however, that a factor that contributes significantly to the fragility or level of probability is the variation in the response due to the effects of different earthquakes, at least for many elements.

7. FRAGILITY MODEL

One question that needs to be addressed is: What is an appropriate model for the fragility function? Since fragility is a (conditional) probability which is a function of the fragility parameter, that is, peak acceleration, one class of functions which have been used are the cumulative distribution functions for some of the classical probability distributions.

Two distributions frequently considered are the normal and lognormal distributions. Smith et al. (1979, 1979a) and Bumpus et al. (1980) examined the validity of these. Generally, the lognormal distribution function has been used to model the fragility function. Without further comment on the choice of this function we simply explain the two parameters that specify it. These are the "median peak acceleration," A, and the lognormal standard deviation, β_R (see Figure 4). The "median", that is, the peak acceleration for which fragility is 0.5, describes the central tendency or location of the fragility function. The standard deviation, β_R, describes the "slope" of the fragility function. Roughly, as β_R increases, the "slope" of the function in Figure 4 decreases. That is, the range of peak accelerations over which the achievement of the limit state is not deterministic, that is, it is or is not achieved for certain, becomes wider with increase in β_R.

In terms of the steel coupon and the system in Figure 2, the assumption here is that the lognormal fragility model, as shown in Figure 4, adequately describes the fragility (the probability of tensile break of the steel coupon) as a function of peak acceleration. Generally, the two parameters, A and β_R, which characterize the model are unknown. It is then necessary to derive some estimates of these parameters. A variety of sources have been used as a source of estimates. These sources include, but are not restricted to, experimental test data, historical data,

empirical models, engineering judgments and expert opinions. Additional comments regarding estimating these characteristics are included in later sections.

Note that the lognormal distribution function is used differently as a fragility function than it is used in ordinary probability theory. Ordinarily, a distribution function describes the probability that a random variable does not exceed a value, written as a function of the value. That is, if X denotes the random variable, then the distribution function $F_X(\cdot)$ describes the probability that $X \leq x$, that is, $F_X(x) = P(X \leq x)$. On the other hand, a fragility function describes the probability of the event -- the limit state is achieved -- given a value of the fragility parameter, for example, peak acceleration, written as a function of the parameter. That is, if LS is some limit state of an element E, then the fragility function $F_E(\cdot)$ describes $F_E(a) = P$ (LS is achieved /a). That is, the fragility describes the conditional probability that the limit state is achieved given peak acceleration a. While the same mathematical function is used, for example, the lognormal distribution function, the meaning and interpretation is thus quite different in the two cases.

8. MORE THAN ONE FRAGILITY PARAMETER

Fragility could also be characterized in terms of more than a single parameter, at least in principle. Fragility could be characterized in terms of two or more variables: for example, "root mean square acceleration" and duration. This could lead to improved fragility predictions. However, in the current state of the art of fragility, construction of fragility functions with any degree of experimental accuracy is not well known. Until more definitive knowledge is acquired, it may not be practical to consider fragility to be a function of more than one variable. As a consequence, there may be greater uncertainty in the fragility analysis than is desired. This is discussed in more detail in Section 10. The alternatives are experimental programs, or more complex and perhaps nonlinear analysis, depending on the element of interest and its limit state(s).

9. FRAGILITY ANALYSIS

The discussion so far has concentrated on the definition of fragility and some motivation for treating fragility as probability. The discussion is based on the view that, within the context of our ability to observe and measure a limit state, there is inherent variability in the system (for example, variable properties of the element and structure and variable effects of the earthquakes) which lead us to use the theory of probability as the appropriate modeling tool. The discussion assumed that the sources of variation were well understood and adequately modeled so that the fragility function and its characteristics, for example, the (A, β_R) in the lognormal model, are known. Unfortunately, this is not the case, so that some analyses are necessary to develop <u>estimates</u> for fragilities. An analysis to estimate fragility functions involves several methodologies and sources of information, such as:

- use of experimental and test data to estimate "the tensile breaking load or elongation of a steel coupon"

- use of predictive mathematical models, for example, a linear response model, to estimate the response of a system to some input

- use of engineering judgments to estimate the values of appropriate model parameters

- use of expert opinions and historical data to model random phenomena and estimate model parameters.

All of these tools introduce some uncertainty into the fragility model. The mathematical models can only approximate reality, and test and historical data, engineering judgment(s) and expert opinion(s) are based on incomplete and imperfect information. Estimates of fragilities based on these tools and information can only be approximate. It is appropriate to associate some measure of uncertainty with fragility estimates, because of the uncertainties of the analysis.

10. RANDOM AND MODELING UNCERTAINTY

It is necessary to discuss some terminology before discussing uncertainties associated with estimating fragilities. In the previous discussion on the concept of fragility the variability (sometimes called uncertainty) referred to is called by many terms, for example:

- Random variation or variability

- Random uncertainty

- Variability

- Inherent or physical variability

- Randomness

Uncertainty associated with the process of analyzing and estimating fragility has also been denoted by several terms, for example:

- Statistical uncertainty

- Modeling uncertainty

- Analysis uncertainty

- Professional uncertainty

- Uncertainty

The terms "random variation" and "modeling uncertainty" are particularly descriptive and we use them in this paper to distinguish between the two concepts, see Smith and Dong (1980) for further discussion. Randomness and uncertainty are commonly used in the literature.

As a generalization, random variation is inherently associated with the physical environment and system and any measurements (within the limitations of the measurement system) derived from the system. It is irreducible (given the measurement system). Modeling uncertainty is associated with the analysis process necessary to model and derive estimates of fragility. The estimation process depends on multiple sources of information, each of which is incomplete and sometimes imperfect. In contrast to random variation, modeling uncertainty can be reduced through, for example, more extensive test programs, improved models, use of additional sources of information, more detailed analysis, nonlinear analysis, and so forth.

11. SOURCES OF MODELING UNCERTAINTY

Although modeling uncertainty has generally been treated as a singular concept, we now believe that it is more appropriate to differentiate between two "types" of modeling uncertainty:

- Uncertainty introduced by a choice of models (for example, choice of a linear response model to model system responses, or choice of parameters; for example, use of a linear damping parameter to represent nonlinear energy loss mechanisms within a structure) for use in the analysis and estimation of fragility. We call this modeling uncertainty of the first kind.

- Uncertainty due to our state of knowledge about the "true" values of model parameters and characteristics, for example, appropriate damping coefficient value, earthquake frequencies and magnitude distribution parameters. We call this modeling uncertainty of the second kind.

11.1. Modeling Uncertainty of the First Kind

One source of modeling uncertainty is due to the need to make choices with regard to appropriate models and parameters for use in a fragility analysis.

For example, we have chosen to use acceleration as the parameter of the fragility model. We could also have chosen velocity or displacement or some other parameter (limiting our discussion to a single parameter). However, while the use of velocity or displacement as the fragility parameter rather than acceleration might reduce the modeling uncertainty for some elements (and increase it for others), we should not expect the adoption of a single parameter to eliminate uncertainty.

Likewise, we choose to use a linear predictive model to estimate the dynamic response in our simple example. For certain levels of response of the structure (that is, for certain levels of input) the linear predictive model can provide a satisfactory (if not entirely accurate) estimate of the actual response. There may be technical, economic, or other reasons to choose the simple linear predictive model rather than a nonlinear one, for example. This choice of model then leads to observations that the damping and other parameters of the linear predictive model vary in an inexplicable (random) way from one earthquake excitation to another, even when the earthquakes all have the same peak acceleration. The reason that uncertainty enters the model is the choice not to model or characterize certain phenomena in terms that are most appropriate for the phenomena: for example, the use of a linear damping model to estimate energy losses that arise through nonlinear means. This choice is often dictated by economic considerations.

There is no loss in generality in the assumption of a linear rather than a nonlinear predictive model. Every predictive model, linear or otherwise, will have some limitation in that some physical phenomena will be explicitly or implicitly modeled in a somewhat arbitrary or possibly inconsistent way, or not modeled at all. In the above example linear predictive model, nonlinear energy loss mechanisms are modeled as linear damping. In other cases, the sources of apparent randomness may not be readily identified. However, in the end the question is not <u>whether</u> the choice of peak acceleration or linear predictive models lead to the introduction of uncertainty but rather <u>how much</u>. While better models (nonlinear, etc.) may reduce this uncertainty, we should not expect to eliminate it entirely. More importantly, the question of whether some uncertainty should be reduced or eliminated may ultimately be an economic and not just a safety or a technical question.

For some elements, empirical data lead to the inescapable conclusion that substantial seismic margin exists in nuclear plants (Smith et al., 1985 and EQE, 1985, 1985a, 1985b). That our current seismic PRA or margin analysis indicates that margin is relatively low for these elements is more a reflection of inadequacy in the fragility analysis rather than inadequacies in the actual margin. For these elements the question is economic: Is it more economical for a utility or NRC research organization to do research on fragility or for utilities to do refined plant-specific fragility reanalysis or is it more economical to retrofit the plant? (This is a question that should be answered given a clear definition of the costs of the various options.) For other elements there may be some safety issue. The technical difficulty is to know when the question is economic and when it may be safety. If a model is <u>adequate</u> (but not entirely <u>accurate</u>) the prudent choice may be to opt for the simple model and thus accept some uncertainty -- if the answer is reasonably consistent with other data and has no adverse economic impact.

There are still additional factors that introduce uncertainty into our fragility model such as the apparent variability that could be observed in the frequency of our simple model. In addition, Gersch (1974) provides a

perspective on frequency and damping uncertainty that arises due to noise and limitations in processing information. The discussion relative to our fragility model for all these additional factors is analogous to the above.

There are also additional factors that could arise as we increase the complexity of our simple model, for example:

- Uncertainty in modeling the damping and frequency of higher frequency modes as we increase the complexity of the linear predictive model.

- Uncertainty due to gross nonlinear response (not just nonlinearities due to relatively minor nonlinear energy loss mechanisms) of the soil-structure system.

- Uncertainty in modeling the interaction effects between the element and the structure as the element of interest grows in size to something like a reactor vessel/reactor coolant loops/steam generators/reactor coolant pumps/etc., system.

It suffices to note that there are many factors that can contribute to a need to include modeling uncertainty in the analysis of fragility. There has not been sufficient research to quantify the effects of the various factors.

The model and parameter choices discussed above illustrate how these choices will impact the estimate of fragility by either changing the slope of the fragility function or possibly altering the location, for example, median, of the function. Given that choices must be made, it should be recognized that whatever models or parameters are used only approximate the real situation. Thus some attempt should be made to quantify what the "range" of fragility functions would be if other formulations (for example, a more extensive response model, including nonlinearities) of the models were used. This type of modeling uncertainty has not always been included in previous attempts to quantify modeling uncertainty or estimate fragility.

11.2. Modeling Uncertainty of the Second Kind

Another source of modeling uncertainty is due to our lack of knowledge about model parameters, properties, and functional characteristics associated with a fragility analysis. For example, for the steel coupon illustration a basic variable is the tensile breaking load or elongation of a coupon. It was shown that it is appropriate to model this as a random variable. Thus, a description of breaking load or elongation would be given by a probability distribution. Generally, this distribution is unknown, hence it must be estimated from test data (from the same type of steel or similar steels) or, if no test data is available, based on judgments derived from experience with similar types of materials and elements. In any case, there is a "lack of knowledge" about the "true"

description of the random variation of breaking loads or elongations among steel coupons.

A similar state of "lack of knowledge" exists for other aspects of the fragility analyses. For example, structure damping and frequency are modeled as random variables. The distributions of these variables must often be based on judgments derived from experimental data, theory, and empirical evidence. Again, there is uncertainty because of this lack of knowledge.

Other examples can be presented and would include lack of knowledge about functional characteristics, properties, and effects of the earthquakes, soil, complex structures, nonlinearities and interactions (between different physical elements, between physical elements and input motion, etc.). Overall, it is necessary to recognize that we have a certain lack of knowledge which should be included as part of the fragility analysis.

12. USE OF MODELING UNCERTAINTY

Modeling uncertainty, due to choice of models and lack of knowledge, typically is included in fragility models, at least as they are used in seismic PRAs or margin studies for nuclear plants. Modeling uncertainty is also quantified. It is interesting to consider that this process, at least in part, attempts to "quantify lack of knowledge." This is somewhat different from some other more common situations. For example, the reduction of experimental data might be termed "quantify newly acquired knowledge" or, more specifically, "quantify observed variability."

There is a certain hopelessness about a process we describe as: "Quantify lack of knowledge." As illustrated by the above example, this is virtually the compliment of the ordinary experimental process. However, recall the objective of introducing the concept in the first place: We recognize and admit and even attempt to quantify the fact that our predictive models are not entirely accurate. At the very least this speaks of intellectual honesty.

13. MODELING UNCERTAINTY IN FRAGILITY AND HAZARD FUNCTIONS

It is interesting to compare the methods used to quantify modeling uncertainty in the seismic hazard and fragility areas.

In the seismic hazard area, modeling uncertainty is quantified formally through the elicitation of recommendations from several experts. These recommendations do not all agree, and this divergence of recommendations is used to characterize modeling uncertainty.

On the other hand, in the fragility area modeling uncertainty has been quantified more informally through the use of judgment. Furthermore, this judgment has been exercised by virtually only one firm, at least as it exists for the bulk of the available fragilities. It can be shown that

this is an advantage, not a disadvantage, at least at this stage of development of fragility analysis.

In the SSMRP, some attempt was made to develop fragility modeling uncertainty using several experts. However, this use of expert judgment was never carried through with the same formalism and care as is currently used in the hazard area. One reason for this difference was the perceived difference in effect that was expected in the hazard and fragility areas. That is, at that time it was believed that uncertainty in the hazard was much more important than uncertainty in fragility. Recent SSMRP results indicate that hazard and fragility are about equally important. This result was obtained in spite of the bias inherent in the above belief. At a minimum, this calls for a reexamination of how fragility should be developed for use in seismic PRAs. Consideration should be given to a formal procedure using several experts, if experimental programs or detailed and possibly nonlinear analysis is not an acceptable option.

14. MODELING UNCERTAINTY IN MARGIN STUDIES

More important, fragility, and especially modeling uncertainty in fragility, is much more important in margin studies than in seismic PRAs.

For example, in Section 11.1 uncertainty due to the choice of models and parameters is discussed. To the extent that this uncertainty is reducible (through the use of nonlinear models, for example) it will increase the estimate of the "high confidence low probability" value for peak acceleration (see Section 20) at least in the case where the median (see Section 16) is unchanged by the reduction in uncertainty. This increase leads to a technically justified case that the margin is actually higher than previously estimated. The reduction in uncertainty may also lead to an increase or decrease in the previous estimate of the median. Of course, whether the estimate of the margin is increased or decreased by a reduction in uncertainty cannot be predicted a priori. However, by definition, a reduction in uncertainty provides an improved estimate. This ultimately leads to a better distinction between real and apparent seismic margin issues.

This supports the need for, and importance of, a careful development of fragility in seismic margin studies.

In any event, discussions on random variation and modeling uncertainty will be with us for some time, as illustrated in the next paragraph.

15. POINT OF CONTROVERSY

While modeling uncertainty could be characterized in many ways, it typically is characterized using the theory of probability. This is a point of controversy. The reason for the controversy is discussed in Sections 17 and 19.

16. FUNCTION USED FOR MODELING UNCERTAINTY

Typically the lognormal distribution is used to characterize modeling uncertainty. Generally, this is modeled by treating the median as a "random" or "uncertain" variable. The distribution of the median is then of the same form as the one shown in Figure 4, but with somewhat different values for the parameters. The model used is shown in Figure 5, which does not explicitly display the lognormal function for modeling uncertainty.

17. GENERALIZED FRAGILITY MODEL

What is shown in Figure 5 is the fragility for any element -- no particular element (structure, piping, component, or equipment) is depicted. The central function, labeled "median function," represents the analyst's best estimate for the true fragility of the element. The central point is the so-called "median capacity," as labeled. The central function is a distribution, characterized by a lognormal function with median A and logarithmic standard deviation β_R which describes the random variation discussed in the earlier sections, and is the same as that shown in Figure 4. The value of A and β_R for the central function are the analyst's best estimates of these parameters.

The modeling uncertainty is exemplified in Figure 5 by the "5% function" and "95% function", as labeled. These "bounds" are based on the assumption that there is uncertainty in the median A characterized by a logarithmic standard deviation β_U. Given the assumptions of our model, the 5% and 95% fragility functions can be used to derive "bounds" for the fragility given a peak acceleration. We then can make a "confidence" statement of the type "we are 90% confident that the fragility at the specific peak acceleration of the element falls within these bounds."

The use of the term "confidence" in this context requires some discussion. The term confidence, as used in classical statistics, has a precise meaning which has its bases in random variation and probability theory. Confidence, as used to describe the uncertainties associated with fragility analyses, is not used in the same way. As discussed earlier, fragility estimates generally involve engineering judgments and expert opinions. Thus, the uncertainties in these judgments and opinions, although quantified by probability functions, are not based on any notion of randomness. Generally, the quantified modeling uncertainties associated with opinions and judgments attempt to reflect the adequacy of the information the analyst or expert uses to form their judgments or opinions. Measurement of adequacy is subjective. Thus, the "confidence" in a fragility analysis will generally have a subjective basis rather than "random" basis as is true in the statistical sense. The difference between the classical statistical situation and the fragility analysis situation is acknowledged by sometimes using the terminology "uncertainty interval for fragility" to describe the modeling uncertainty in fragility analysis. This is consistent in some sense in that for fragilities we are dealing with a "lack of knowledge." The 5% function and the 95% function represent approximate bounds on the analyst's ability to describe the fragility

function. Specifically, we have "95% confidence" that the median fragility is above the lower "bound," the 5% function. Likewise there is a "5% probability" that the median fragility is above the upper "bound," the 95% function. This is probably one of the simplest ways of characterizing modeling uncertainty in fragilities. As an alternative, for example, we might choose a model that would allow the various possible random fragility functions to cross one another. This is not possible in this simple model.

18. NUMERICAL CONFIDENCE LIMITS

As discussed before, the reader must be cautious to understand that nothing now achievable by fragility analysts can capture anything like the precision implied by using numerical values like "95% confidence" or "5% probability." There is simply not enough known, either through actual fragility data from experiments or real earthquakes, to allow a statement about fragilities or confidence to be made with the implied numerical precision. What is shown represents, and discussions need to emphasize the point, is only an estimate. However, this estimate can be extremely useful and present the most rational currently available broadfront attack on the basic issues of interest in seismic PRA or margin studies. Of course, it is also clear that fragility analysis is now entering its second major phase. The state of the art can be expected to advance rapidly.

19. REASON FOR CONTROVERSY

The controversy referred to above arises because modeling uncertainty is not admitted by all experts to be amenable to being characterized by the theory of probability. This is because expert judgment is not admitted to satisfy the axioms of this theory. However, modeling uncertainty typically is characterized using the theory of probability and, as noted above, by the lognormal density function. A simple alternative would be to use the uniform distribution, but this does not resolve the controversy. There is no single solution to this controversy that is acceptable to all parties.

20. FRAGILITY FORMULA

With these cautions out of the way, we provide the formula for some numerical values:

$$A_{.05} = A \exp(-1.65\ \beta_U)$$

$$A_{.95} = A \exp(1.65\ \beta_U)$$

Finally, the so-called high confidence, low probability (HCLP) peak acceleration value will be elucidated. This acceleration considers both random and modeling uncertainty, as discussed above, and is the peak acceleration value for which we have "95% confidence" that the probability of achieving a specified limit state is less than "5%." That is, it is an acceleration value for the element for which we are "highly" confident that given this level of peak acceleration there is only a "small" chance of achieving the limit state (yielding, failure, severe core damage, etc.).

This is a useful concept that may have important practical consequences in seismic margin studies in spite of the lack of precision or lack of knowledge that is admitted by the very concept of HCLP. Numerically, the HCLP value is obtained as follows:

$$A_{HCLP} = A \exp\left[-1.65(\beta_U + \beta_R)\right]$$

There are many other issues that could be discussed that are related to the basic theme here, but these will be covered in future efforts.

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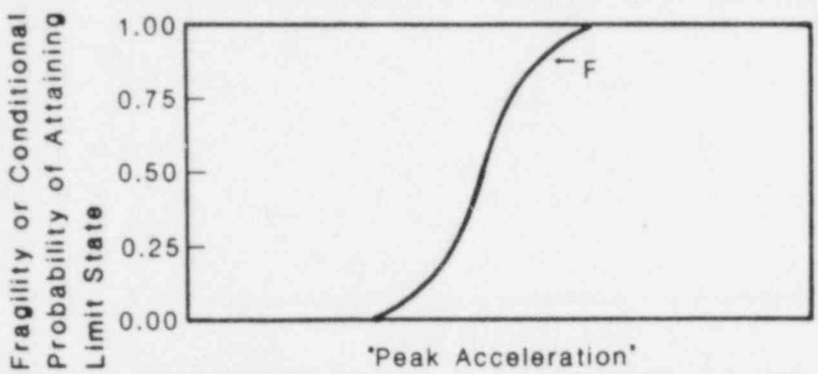

Figure 1: Stylized fragility function, F, for any element of a plant. "Peak acceleration" is further specified as follows: the average of the two horizontal earthquake peak accelerations at the ground surface at the nuclear plant site. For any "peak acceleration," a, the fragility function, F(·), describes the (conditional) probability of achieving the limit state of the element for which F is developed.

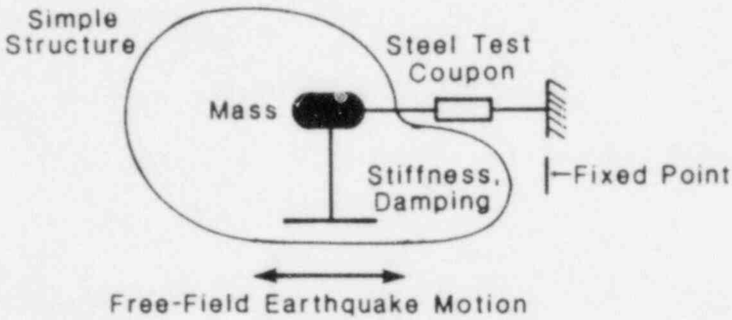

Figure 2: Simple example structure.

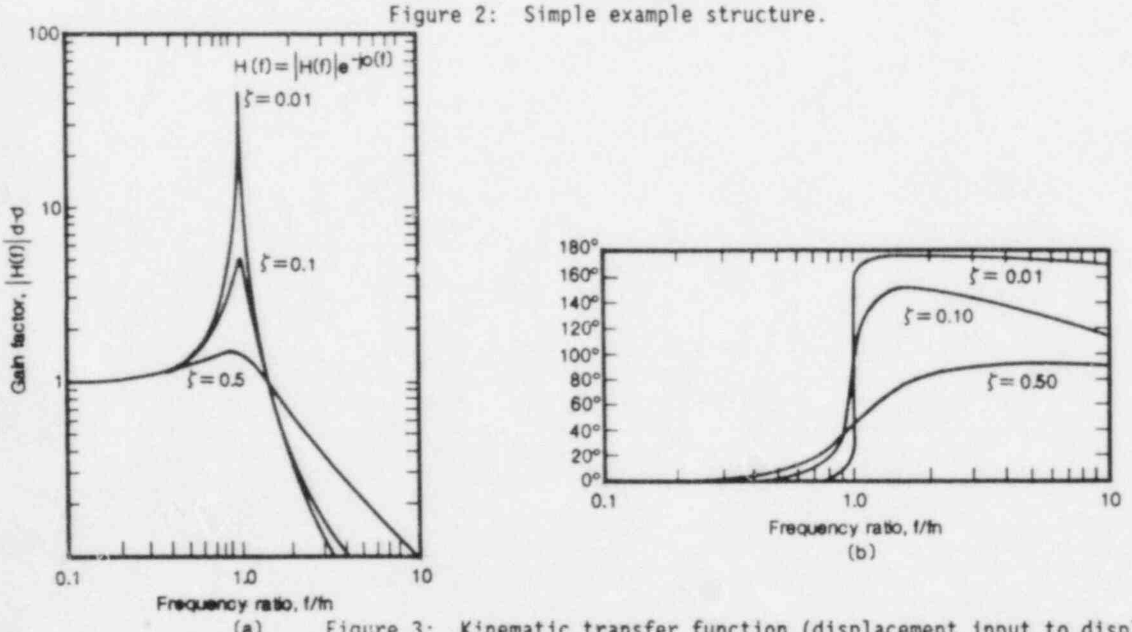

Figure 3: Kinematic transfer function (displacement input to displacement output, velocity input to velocity output, acceleration input to acceleration output) for a damped simple harmonic oscillator for damping values of 1%, 10%, and 50% of critical (a) Gain factor, (b) Phase factor.

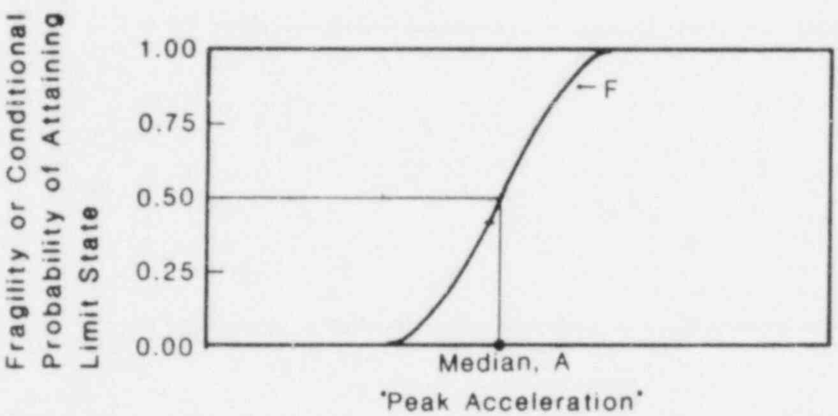

Figure 4: Stylized lognormal fragility function for any element of a plant. "Peak acceleration" is defined in Figure 1.

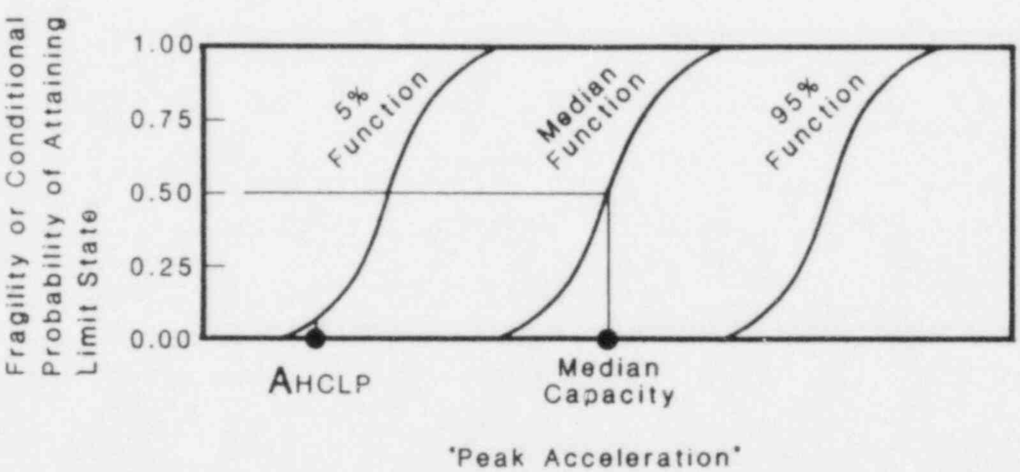

Figure 5: Stylized lognormal fragility function for any element of a plant. "Peak acceleration" is defined in Figure 1. The three lognormal functions are lognormal display of the modeling uncertainty discussed in the text, as is the "high confidence, low probability acceleration," A_{HCLP}.

REVIEW OF SEISMIC PROBABILISTIC RISK ASSESSMENT AND THE USE OF SENSITIVITY ANALYSIS*

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ABSTRACT

This paper presents results of sensitivity reviews performed to address a range of questions which arise in the context of seismic probabilistic risk assessment (PRA). These questions are the subject of this paper. A seismic PRA involves evaluation of seismic hazard, component fragilities, and system responses. They are combined in an integrated analysis to obtain various risk measures, such as frequency of plant damage states. Calculation of these measures depends on combination of non-linear functions based on a number of parameters and assumptions used in the quantification process. Therefore, it is often difficult to examine seismic PRA results and derive useful insights from them if detailed sensitivity studies are absent.

In a seismic PRA, sensitivity evaluations can be divided into three areas: hazard, fragility, and system modeling. As a part of the review of a standard boiling water reactor seismic PRA which was performed by General Electric (GE), a reassessment of the plant damage states frequency and a detailed sensitivity analysis were conducted at Brookhaven National Laboratory. The rationale for such an undertaking is that in this case: 1) the standard plant may be sited anywhere in the eastern U.S. (i.e., in regions with safety shutdown earthquake [SSE] values equal to or less than 0.3g peak ground acceleration), 2) it may have equipment whose fragility values could vary over a wide range, 3) there are variations in system designs outside the original defined scope.

Seismic event trees and fault trees were developed to model the different system and plant accident sequences. Hazard curves which represent

*Work performed under the auspices of the U.S. Nuclear Regulatory Commission.
Views expressed are not necessarily those of the Nuclear Regulatory Commission.

various sites on the east coast were obtained; alternate structure and equipment fragility data were postulated. Various combinations of hazard and fragility data were analyzed. In addition, system modeling was perturbed to examine the impact upon the final results. Orders of magnitude variation were observed in the plant damage state frequency among the different cases.

Several conclusions can be drawn from the results of the reassessment and the sensitivity analyses. First, it is clear that in order to gain useful insights from a seismic PRA, systematic and rigorous sensitivity studies are necessary. Back-of-the-envelope calculations or crude estimates often are found to be wrong, or at best, misleading due to the highly non-linear nature of the problem. Findings from the sensitivity studies also may not be intuitively obvious. Second, perturbation of the hazard curves yields significant changes in the final results. This is so dominant that fragility data and system model appear to be of secondary importance. Third, the percentage of contribution to plant damage state frequency from low ground accelerations can be dominated by the characterization of the left-hand-tail of the fragility curve.

INTRODUCTION

A number of seismic probabilistic risk assessment (PRA) studies for nuclear power plants have been published in the past few years.[1,2,3] All of these studies involve the evaluation of seismic hazard of a particular site location, component and structural fragilities, and system responses. Results of these considerations are presented in terms of some types of risk measures, such as core damage frequency or offsite consequences. It is a rather common practice within the nuclear industry to report these results of a single analysis. In many respects, this has limited the usefulness of the seismic PRA. Numerical results are, to some professionals, the least valuable part of the PRA. It has been suggested by others that the process of performing a seismic PRA and the insights derived by studying the effects on the power plant of the various safety related structures and equipment failure are more meaningful. It is often difficult to take the published seismic PRA results and to uncover the useful insights which are provided by the analysis without a detailed sensitivity study.

As part of the review[4] of the GESSAR-II seismic PRA[5] which was performed by General Electric Company (GE), the entire analysis was scrutinized in great detail. The justification for this effort was in part due to the fact that the GESSAR-II plant may be sited anywhere in the eastern U.S. (i.e., in regions with SSE values equal to or less than 0.3g peak ground acceleration), and only single representative analysis was performed.

New seismic event trees and fault trees were developed in the review to represent the GESSAR-II systems and plant accident sequences. Hazard curves which represent various sites on the east coast of the U.S. were obtained[6] and alternate structure and equipment fragility data were postulated. Various combinations of the hazard and fragility data were analyzed. In addition, system modeling was perturbed to examine impact on the core damage frequency.

Table 1 Alternate Fragility Parameter Values

Structure/Component	Alternate Parameter Values			
	Case 1		Case 2	
	Median (g)	β_c	Median (g)	β_c
Ceramic Insulator	0.20	0.32	0.20	0.32
Pump	1.81	0.61	1.81	0.61
Piping	(1)	(1)	(1)	(1)
Heat Exchanger	1.09	0.47	1.09	0.47
Valve (Hydraulic or Air)	(1)	(1)	(1)	(1)
Valve (Check or Spring)	(1)	(1)	(1)	(1)
Shroud Support	0.67	0.43	0.67	0.49
CRD Guide Tube	1.37	0.45	1.37	0.48
Hydraulic Control Unit	1.24	0.63	1.24	0.63
SLC Tank	1.33	0.33	1.33	0.33
RPV	1.25	0.40	1.25	0.59
Auxiliary Building	1.50	0.50	1.50	0.41
Drywell	1.50	0.50	1.50	0.50
Containment	1.50	0.50	1.50	0.50
Shield Building	1.50	0.50	1.50	0.50
Control Building	1.50	0.50	1.50	0.40
Diesel Generator Building	1.50	0.50	1.50	0.50
Diesel Generator Panel	1.56	0.52	1.50	0.67
125-V DC Bus	1.49	0.56	1.49	0.56
Diesel Generator Heat & Vent	1.55	0.51	1.50	0.65
480-V Transformer	1.49	0.56	1.39	0.66
480-V Switchgear	1.46	0.58	1.46	0.58
4-kV Switchgear	1.46	0.58	1.46	0.58
Water Service System	1.50	0.45	1.50	0.79
Condensate Storage Tank	0.80	0.39	0.24	0.39
Relay Chatter	0.60	0.67	0.60	0.67
Diesel Generator Structural	1.50	0.50	0.91	0.49

(1) Not included in systems analysis since capacities are relatively high.

As a result of this exercise, two areas have been identified from the results of this assessment and of the sensitivity analyses which warrant some discussion. The first area pertains to the effects of the hazard curve on core damage frequency. The second area deals with the contribution to core damage frequency from low ground acceleration earthquakes.

Impact of Hazard Curves and Fragility Curves

Owing to the fact that the GESSAR-II plant may be located anywhere in the Eastern U.S. where the SSE value does not exceed 0.3 pga, various hazard curves for different sites were obtained from a study sponsored by the U.S. NRC.[5] A selection of these curves are presented in Figure 1. A general observation of these curves is that there is a large variation in the annual frequency of exceedance for all the curves in general and even for those curves characterizing the same site; for instance, curves 2, 3, and 4 are generated by different experts for the Zion site, whereas curves 8 and 9 are for the Limerick site. The GESSAR-II curve has been omitted from the figure because of GE's claim of proprietary information. It lies approximately in the middle of these curves. In the sensitivity analyses, three hazard curves were selected; they are curve 14 for the Watts Bar site calculated by Lawrence Livermore National Laboratory, curve 4 of the Zion site by Dames and Moore, and the GESSAR-II curve. The GESSAR-II curve was chosen because it lies between the two extreme cases.

Using the BNL system model and the fragility values tabulated in Table 1, core damage frequency for the different cases was calculated; results are presented in Table 2.

Table 2 Core Damage Frequency (Events/year)

Hazard Curve	Case 1	Case 2
Zion	9.29(-6)	1.35(-5)*
GESSAR-II	6.64(-5)	9.68(-5)
Watt Bar	7.31(-4)	1.00(-3)

*1.35(-5) = 1.35×10^{-5}

It can be seen from Table 1 that the changes in median capacity values from Case 1 to Case 2 occur mainly with the electrical components, and the changes are typically a few percent. The two major changes come from the condensate storage tank and the diesel generator structural. In addition to the median capacity values, the β_c are also changed. By and large, β_c values are those used for Case 1 with a slight increase for some components and structures. The most significant ones are the diesel generator panel and the diesel generator heat and vent.

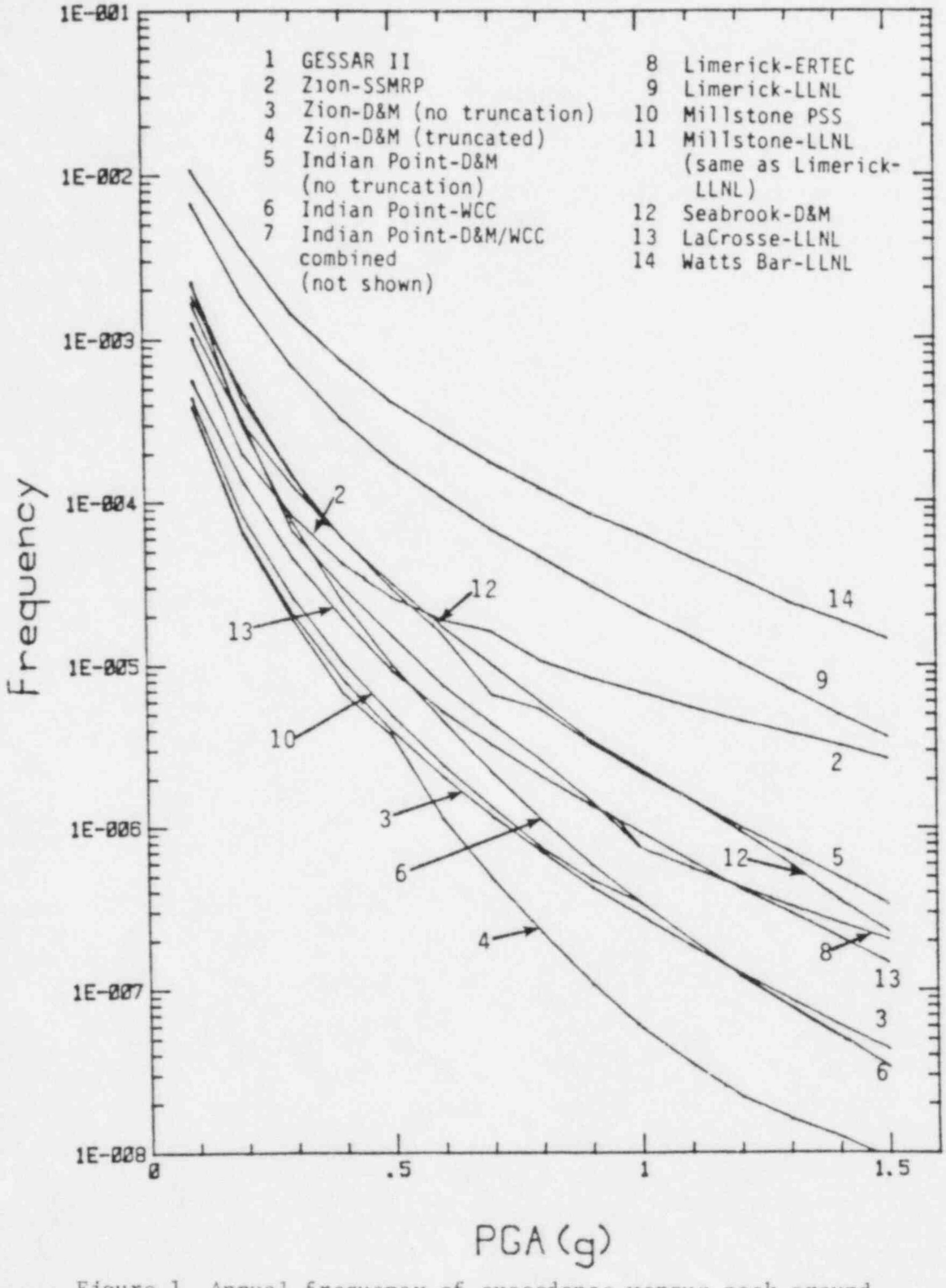

Figure 1 Annual frequency of exceedance versus peak ground accelerations for different sites.

Results from Table 2 indicate that if one keeps the fragility values and the system model constant, changing the hazard curves yields an order of magnitude change in core damage frequency. This is evident from either Case 1 or Case 2 results. For instance, the core damage frequency calculated for Case 1 using the Zion curve is 9.29(-6); if the GESSAR-II hazard curve is used instead, the core damage frequency is increased to 6.64(-5). Examination of the three hazard curves shows that they differ from each other by about an order of magnitude, especially in the low acceleration region. This sensitivity analysis shows that the core damage frequency is sensitive to the hazard curve definition, and in this example the change in core damage frequency is approximately proportional to the change in hazard frequency.

If one examines the results from Case 1 and Case 2, the core damage frequency is seen to change by less than a factor of 2. On one hand, this reveals that the final results are also sensitive to fragility changes; however, component fragilities do not vary by orders of magnitude, whereas hazard curves do. Therefore, the effect of the fragility variation is substantially less significant than the effect of the hazard frequency variation.

Contribution from Low Ground Acceleration

A cumulative core damage curve as a function of peak ground acceleration for Case 1 is depicted in Figure 2. It represents the conditional probability of core damage given that an earthquake of a particular peak ground acceleration occurs. For instance, given the occurrence of a seismic event of 0.5g peak ground acceleration, there is a 60 percent probability that there would be a core damage event. Similarly, 1.0g, the conditional probability of core damage given an earthquake of that magnitude is unity. It is interesting to note that the left hand tail of this curve slowly approaches zero at low acceleration. At 0.3g, which is the SSE value for the GESSAR-II plant, the conditional probability of core damage is about 10%.

Furthermore, if this cumulative curve is combined with the hazard curve, the following will result (see Table 3). This table shows that for the Zion hazard curve, 25 percent of the core damage frequency comes from peak ground acceleration below 0.19g, 50 percent from below 0.28g, and 75 percent from below 0.41g. Similarly, if the Watts Bar hazard curve is used, 25 percent of the core damage frequency can be ascribed to accelerations below 0.29g. The GESSAR-II hazard curve yields results that are between the two cases.

The major reason that the core damage results show a much higher contribution from low acceleration events than the conditional probability curve of Figure 2 is the shape of the hazard curves. Low acceleration frequency of exceedance ($< 0.15g$) is one to two orders of magnitude greater than that of higher accelerations ($> 0.3g$). This tends to amplify the sensitive portion of the fragility curve (i.e., the left hand tail) where not a great deal of data is available. For example, for the Zion-Dames and Moore hazard curve about 50 percent of the core damage frequency is accumulated between 0 and 0.3g; however, from Figure 2 the conditional core damage probability is only 10 percent at 0.3g acceleration.

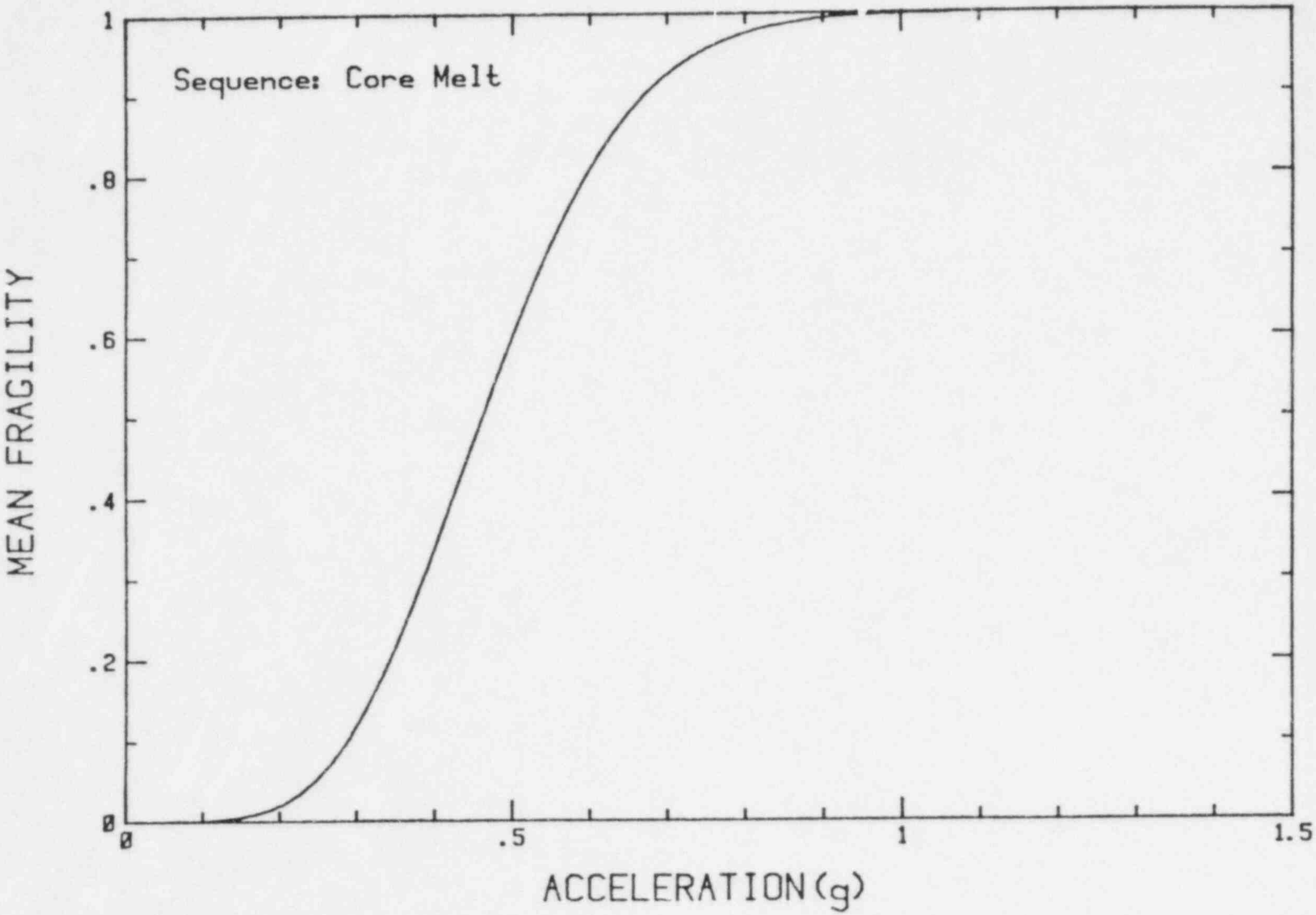

Figure 2 Conditional probability of core damage given the occurrence of an earthquake.

Table 3 Accelerations Contributing to the Mean Frequency of Core Melt for the Case 1 Alternate Fragilities

Hazard Curve	Percent of Total Core Melt 25	50	75
Zion - Dames & Moore (truncated)	0.19g	0.28g	0.41g
GESSAR-II	0.22g	0.31g	0.44g
Watts Bar--LLNL	0.29g	0.45g	0.66g

This type of results raises one important question: How credible is the seismic core damage result in view of the contributions from low ground accelerations? If the results are reasonable, what is the ramification for the current SSE requirement for nuclear power plants?

In general, it is believed that within the context of PRA for earthquakes below the SSE, there is a non-zero probability that a core damage accident may occur; however, a 25 to 30 percent contribution violates expectations based on deterministic review. The intricacy of this question lies with the definition of component or structural fragility curves at low ground acceleration and the amplifying effect of the hazard curve. Little can be done about the latter effect, but with regard to the former one, it is questioned whether fragility curves should be defined in such a way that the left hand tail extends to zero at zero acceleration. It has been suggested that at low ground accelerations component failure mode may become different and other considerations, such as fatigue failure, may become important. Others have suggested that below a certain ground acceleration, no failure would occur. In other words, a slight vibration is not expected to fail a component. In this case, the fragility curve would be truncated at the left hand tail to describe the threshold effect. However, the question still remains: if indeed there is a threshold, how can it be determined?

It is the belief of the authors that a lower bound cut-off exists for structure and component capacities; however, additional data is required to quantify this belief. For the case considered in this paper, the relay chatter capacity is an important contributor to the core damage fragility curve. Relay chatter has generally been considered to be recoverable in past seismic PRAs, and thus has not dominated the results. For the results reported in this paper, a 50 percent chance of recovery was used.

FUTURE RESEARCH

This paper reports the findings of a seismic PRA review and the sensitivity analyses. Two particular areas are discussed where further refinements would enable better quantification of core damage frequency for nuclear power plants.

First, the definition of hazard curves is found to greatly effect the results of a seismic PRA. It is an area where expert opinion plays an important role and consequently large differences may exist in the hazard results. This difference in the definition of the hazard curve could significantly alter and influence how the risk measure, such as core damage frequency, is calculated, and hence it would affect the interpretation of the PRA results. It has become more evident that there is an increased tendency to use seismic PRA to support nuclear power plant design modification decisions. Therefore, efforts to improve the definition of hazard curves, especially at low ground acceleration, should be conducted.

The second point pertains to the definition of fragility for components. The final results are also sensitive to them. There is in general a lack of realistic information for the different power plant components. It is important to acquire actual test data for these components if seismic PRA is to be meaningful. Moreover, additional work is required to better define the left hand tail of the fragility curves in order to provide a more realistic model of component failures for PRA analysis.

CONCLUSION

Several conclusions can be drawn from the results of the reassessment and the sensitivity analyses. First, it is clear that in order to gain useful insights from a seismic PRA, systematic and rigorous sensitivity studies are necessary. Back-of-the-envelope calculations or crude estimates often are found to be wrong, or at best, misleading due to the highly non-linear nature of the problem. Findings from the sensitivity studies also may not be intuitively obvious. Second, perturbation of the hazard curves yields significant changes in the final results. This is so dominant that fragility data and system model appear to be of secondary importance. Third, the percentage of contribution to plant damage state frequency from low ground accelerations can be dominated by the characterization of the left-hand-tail of the fragility curve.

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SIGNIFICANCE OF THE ANALYTICAL FORMS OF FRAGILITY CURVES

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ABSTRACT

Sensitivity analysis of the core melt probability to the analytical forms of the plant fragility is provided. Major parameters of the fragility curve affecting the core damage probability are discussed. Using algebra of fragilities it is demonstrated how analytical forms of component fragilities shape up the plant fragility and determine its parameters.

INTRODUCTION

The purpose of this analysis is to demonstrate how different analytical forms of component fragilities affect the core melt probability. The analysis is conducted in two stages. At the first stage a sensitivity analysis of the core damage probability to the different parameters of the plant fragility is conducted. At the second stage a sensitivity analysis of the plant fragility to different analytical forms of component fragilities is provided. A two-stage approach makes it easy to understand the final result.

In this analysis we limit ourselves to one-mode failures and select the simplest global failure indicator - a peak ground acceleration, a. The fragility density function is denoted as f(a) and the corresponding cumulative function or fragility, as F(a). We also use the conventional "probability-of-frequency" risk format [1].

MAJOR PARAMETERS OF THE FRAGILITY CURVE

The analytical expression for a fragility density function can be described with two groups of parameters:

(1) location parameters
(2) shape parameters

Examples of location parameters are mean $\bar{a}$, median A, and mode M. For the normal distribution all three location parameters coincide. For skew distributions they are different. However, we can express them through each other using different shape parameters. Therefore, there is only one independent location parameter. In our study, the median is selected as an independent location parameter because it is less subjective to tail or shape influences.

The following shape parameters are considered:

(a) range, L,
(b) spread, S,
(c) asymmetry coefficient, η,
(d) spread ratio, R.

Range is the mathematical domain of the definition of the fragility density function f(a). It could be infinite (normal distribution), half infinite (lognormal distribution) and finite (Johnson distribution). Sometimes, a mathematical range may not coincide with a technically justifiable range. On such occasions we have to truncate the density function or choose another one with the proper range.

Spread is an interval of the failure indicator within a given range where failure is more likely. We may quantify the notion of spread by using a confidence interval. It is convenient to select a 50 percent confidence interval. The length of such interval is less sensitive to tail behavior and it is the smallest confidence interval which always contains the median within itself. To make our definition single-valued we select the best (i.e., shortest) 50 percent confidence interval (see Fig. 1) [2].

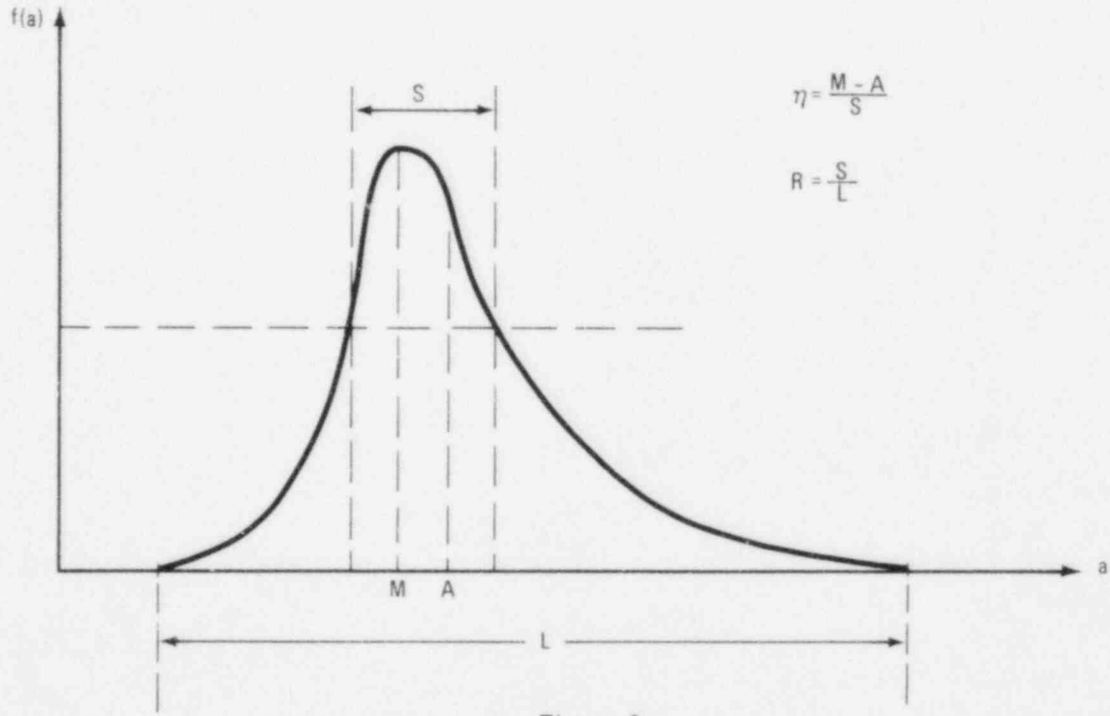

Figure 1
PARAMETERS OF THE FRAGILITY CURVE

The asymmetry coefficient, η, can be determined according to the formula:

$$\eta = \frac{M-A}{S} \tag{1}$$

Because mode M and median A are always within a spread then the asymmetry coefficient η is always less then unity. The asymmetry coefficient η is positive if $M > A$ and negative if $M < A$.

The spread ratio, R, is a ratio of some parameter associated with spread to another parameter associated with range. In case of the finite range we can adopt the definition:

$$R = \frac{S}{L} \tag{2}$$

In the case of infinite or half-infinite ranges we should modify formula (2). A practical technical range is always finite. A lower bound for A cannot be less than zero and an upper bound is proportional to A. Spread is proportional to standard deviation σ. Therefore, a proper substitute for formula (2) in cases of infinite and half-infinite ranges is:

$$R' = \frac{\sigma}{A} \tag{3}$$

The choice of Equation 3 in lieu of the classical coefficient of variation is a direct result of the exact analytical expression for fragility spread factor K in cases of normal and lognormal distributions. In any event these ratios are proportional.

It is easy to see that according to the definition of the spread ratio R the following inequality is true:

$$R < \frac{1}{2} \tag{4}$$

There is no such limitations on R' because R' is just proportional but not equal to R.

Among four shape parameters L, S, η and R, only three are independent due to formula (2). In this paper we select the following three parameters: spread S, asymmetry coefficient η, and spread ratio R.

SENSITIVITY OF THE CORE MELT PROBABILITY TO PARAMETERS OF THE PLANT FRAGILITY

The core melt probability, P, can be determined according to the formula [3]:

$$P = \int_{o}^{\infty} h(a)F(a)da \qquad (5)$$

where F(a) is a plant fragility and h(a) is a hazard density function related to hazard function H(a) according to formula:

$$H(a) = \int_{a}^{\infty} h(a')da' \qquad (6)$$

If the plant fragility F(a) has no randomness then the "deterministic" fragility, $F_D(a)$, can be presented in the form:

$$F_D(a) = \begin{cases} 0, & a < A \\ .5, & a = A \\ 1, & a > A \end{cases} \qquad (7)$$

The corresponding core melt probability, P_D, is:

$$P_D = H(A) \qquad (8)$$

For the fragility F(a) with randomness, the corresponding core melt probability, P, differs from the expression (8) by the fragility spread factor K [4]:

$$P = K\ (\lambda S,\ \eta,\ R) \cdot H(A) \qquad (9)$$

where:

H(A) = hazard function at the median point A of the plant fragility curve;

$K(\lambda S,\ \eta,\ R)$ = fragility spread factor

and parameter λ is defined as:

$$\lambda = \frac{H'(A)}{H(A)} \qquad (10)$$

where H' is the derivative of H(A) with respect to a.

The fragility spread factor is a lumped correction factor and the study of its behavior is extremely useful.

H(A) in Equation 9 is the major contributor to the core melt probability; shape parameters S, η, R determine the correction factor K.

As shown in Figs. 2-4, the fragility spread factor K increases exponentially with increasing of spread S. Parameters η and R accelerate or decelerate this trend. The positive asymmetry coefficient η increases the fragility spread factor relative to the negative asymmetry coefficient. It is to be noticed that the use of the lognormal over the normal distribution invariably would reduce the value of the fragility spread factor, K. However, this difference depends on the spread ratio R. When the spread ratio R tends to 1/2, this difference disappears.

For a small spread ratio and a large negative asymmetry coefficient the fragility spread factor can be even less than unity. For example, for $\lambda S = .5$ and $\eta = -.5$, $K = .77$. However, usually $K > 1$, and for a spread typical to current seismic PRA studies the fragility spread coefficient, K, is about 10.

To understand how component fragilities affect the core melt probability we have to learn how they shape up the plant fragility.

SENSITIVITY OF PLANT FRAGILITY PARAMETERS TO THE ANALYTICAL FORM AND PARAMETERS OF COMPONENT FRAGILITIES

The plant fragility can be assembled from component fragility with the help of several simple rules which are referred to here as algebra of fragilities. These rules follow from the fault tree analysis. For example, for the system of sequential components the system fragility F(a) can be expressed through component fragilities $F_i(a)$ according to formula:

$$F(a) = 1 - \prod_{i=1}^{n} \left[1 - F_i(a)\right] \tag{11}$$

For the system of independent redundant components we have:

$$F(a) = \prod_{i=1}^{n} F_i(a) \tag{12}$$

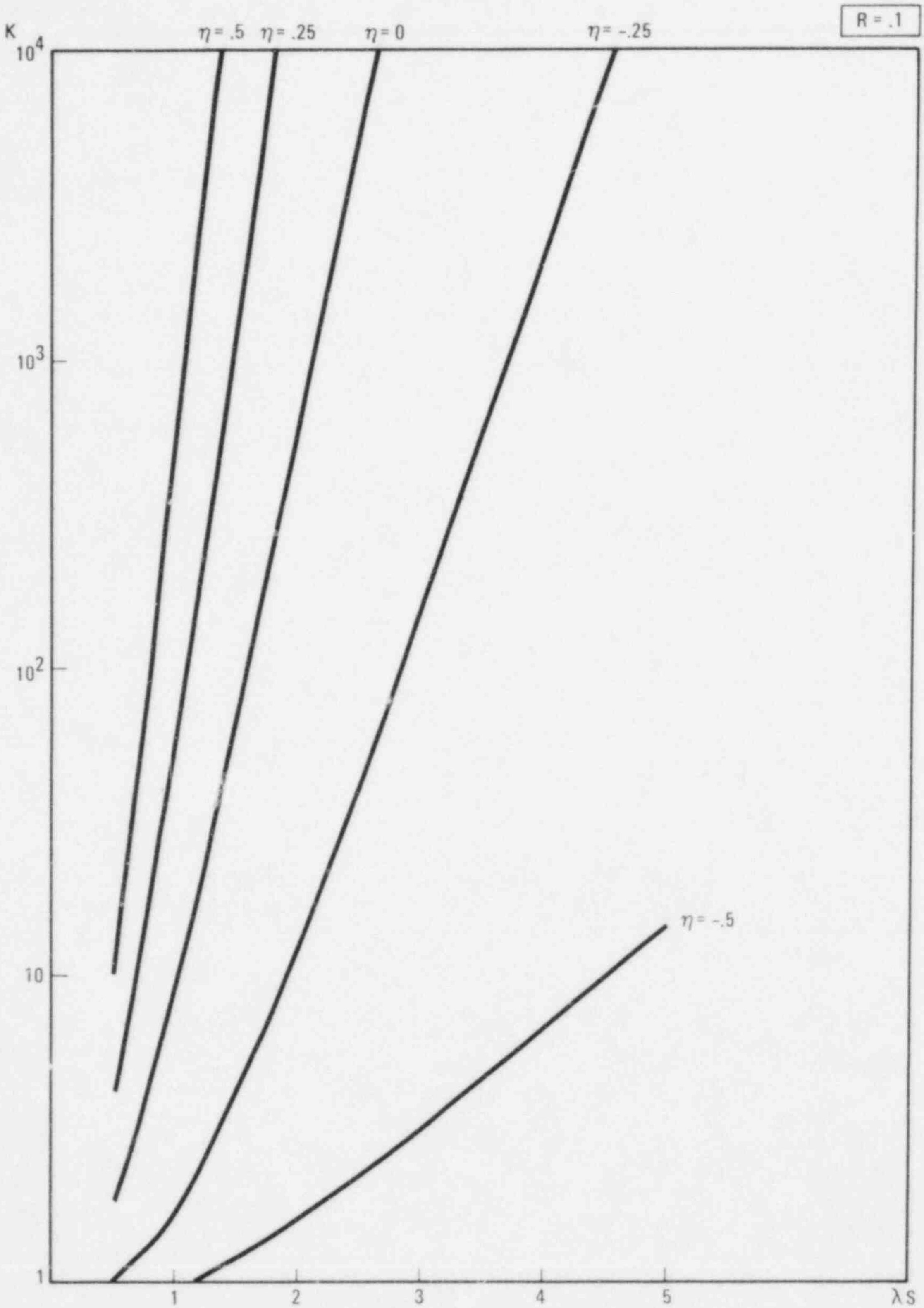

Figure 2
FRAGILITY SPREAD FACTOR FOR R = .1

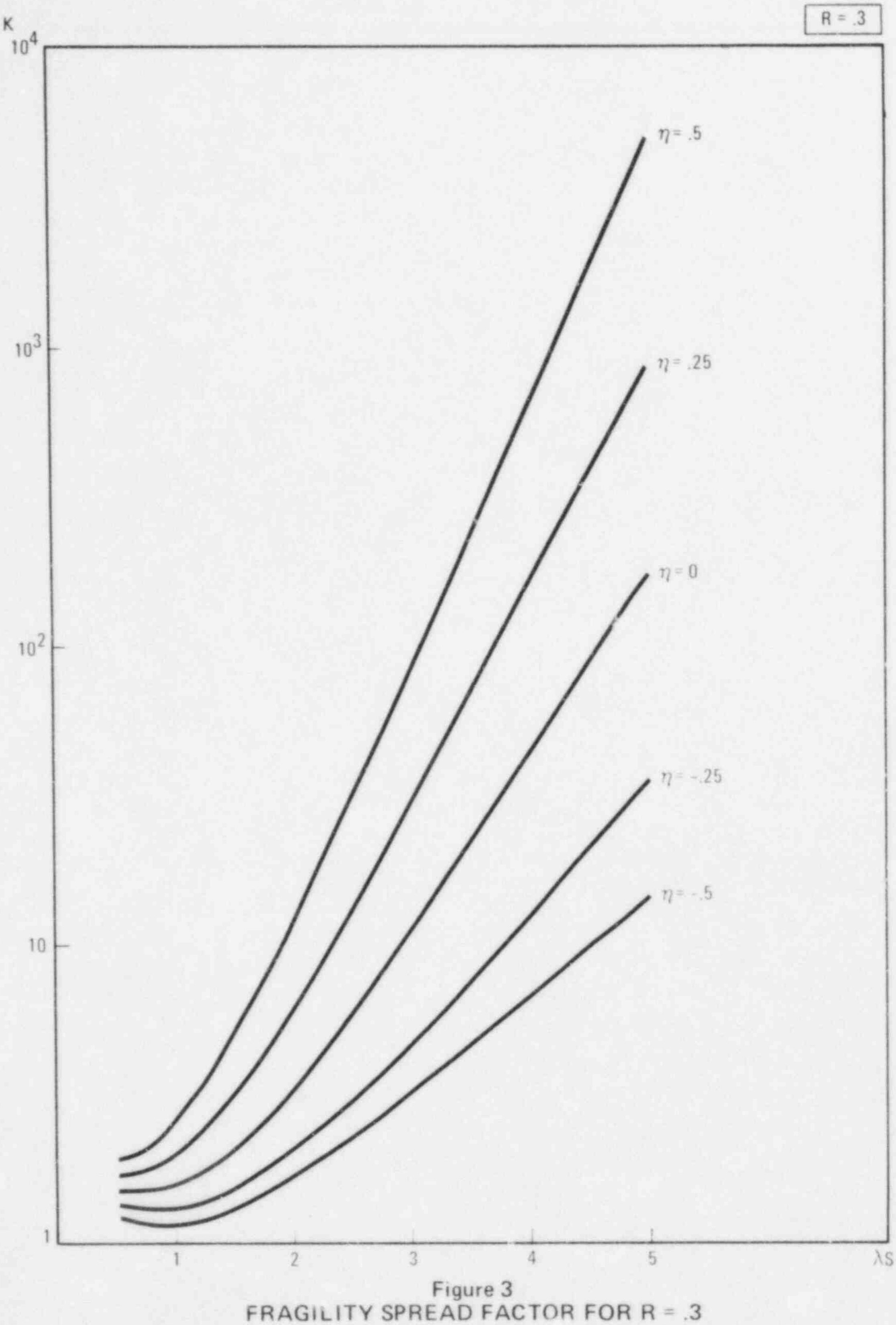

Figure 3
FRAGILITY SPREAD FACTOR FOR R = .3

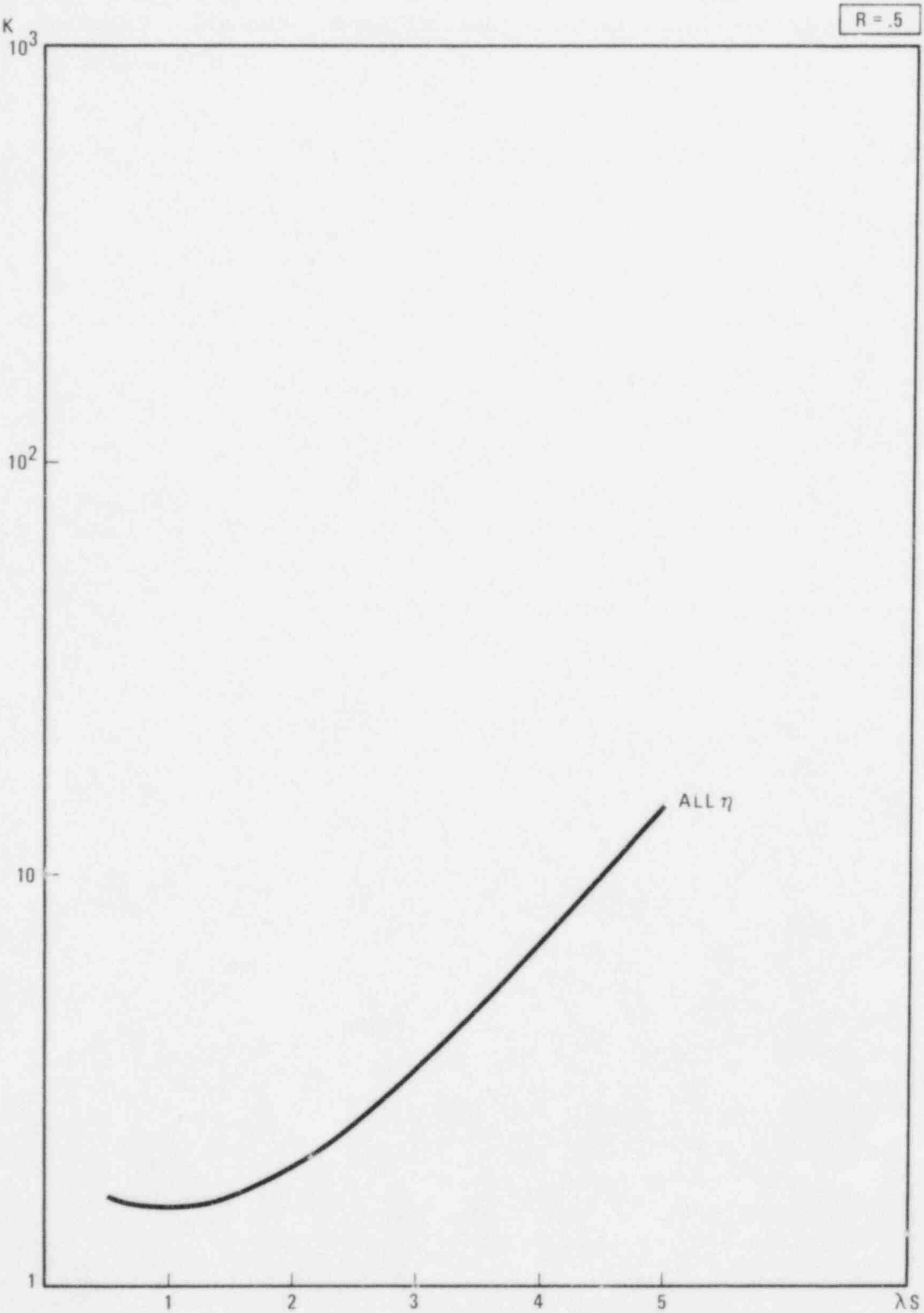

Figure 4
FRAGILITY SPREAD FACTOR FOR R = .5

Using sequentially formulas (11) and (12) we can calculate the plant fragility.

The behavior of the plant fragility depends drastically on chosen analytical forms of component fragilities. The crucial parameter is the fragility range. If ranges of all fragilities are finite then only several key components determine the plant fragility. Otherwise, all components presented in the fault tree will contribute to the plant fragility.

In the case of the finite range we denote the end points of the i^{th} component range as $a_{min}^{(i)}$ and $a_{max}^{(i)}$. The plant fragility range (a_{min}, a_{max}) can be found according to following simple rules [5] applied from the bottom to the top of the fault tree.

<u>OR-Gate rule</u>. The range $\left(a_{min}^{(OR)}, a_{max}^{(OR)}\right)$ of the fragility which is a Boolean sum of component fragilities can be found as:

$$a_{min}^{(OR)} = \min \left\{a_{min}^{(1)}, a_{min}^{(2)}, \ldots a_{min}^{(n)}\right\} \tag{13}$$

$$a_{max}^{(OR)} = \min \left\{a_{max}^{(1)}, a_{max}^{(2)}, \ldots a_{max}^{(n)}\right\} \tag{14}$$

<u>AND-gate rule</u>. The range $\left(a_{min}^{(AND)}, a_{max}^{(AND)}\right)$ of the fragility which is a Boolean multiplication of component fragilities can be found as:

$$a_{min}^{(AND)} = \max \left\{a_{min}^{(1)}, a_{min}^{(2)}, \ldots a_{min}^{(n)}\right\} \tag{15}$$

$$a_{max}^{(AND)} = \max \left\{a_{max}^{(1)}, a_{max}^{(2)}, \ldots a_{max}^{(n)}\right\} \tag{16}$$

Therefore, the plant fragility range (a_{min}, a_{max}) is determined by the range of the one key component. All other parameters depend on how many components and how much overlap there is with the key component. Overlapping component fragilities push the median of the plant fragility to lower values (see Fig. 5). However, because the number of overlapping component fragilities is limited the reduction of the plant fragility mean relative to the key component fragility mean cannot be too much. Usually, it is within a range from 10 to 20 percent.

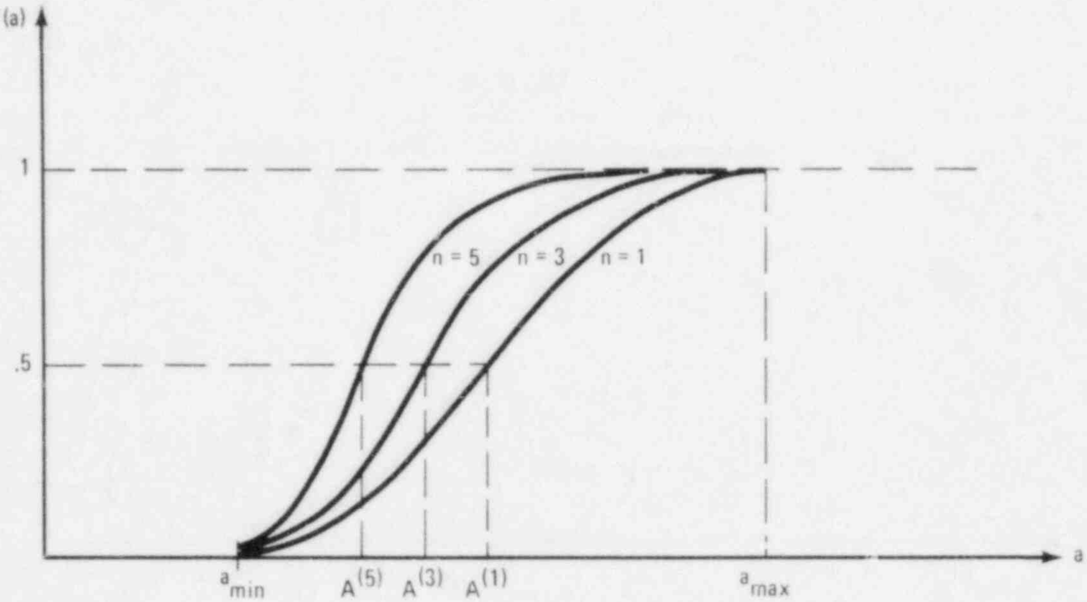

Figure 5
PLANT FRAGILITY FOR n OVERLAPING COMPONENT FRAGILITY

In the case of infinite or half-infinite ranges, all component fragilities overlap. Therefore, the reduction in the plant fragility is unlimited. In the current seismic PRAs the plant fragility is determined by the overall number of dominant components rather than several key components. Thus increasing the number of dominant components (i.e., the number of components identified with the fault tree analysis) will reduce the median plant fragility and increase the probability of core melt. Therefore, the analysis is very sensitive to the number of identified contributors; even if their medians are well above of SSE.

We illustrate these conclusions by comparison of medians for three different distributions applied to a system of three sequential components. The components are taken from Zion PRA study [6]. Three distributions are selected: normal, lognormal and Johnson [7]. Medians and spreads for all three component distributions are taken the same. Because of uncertainty we obtain the system distributions for medians presented in Table 1 and Fig. 6.

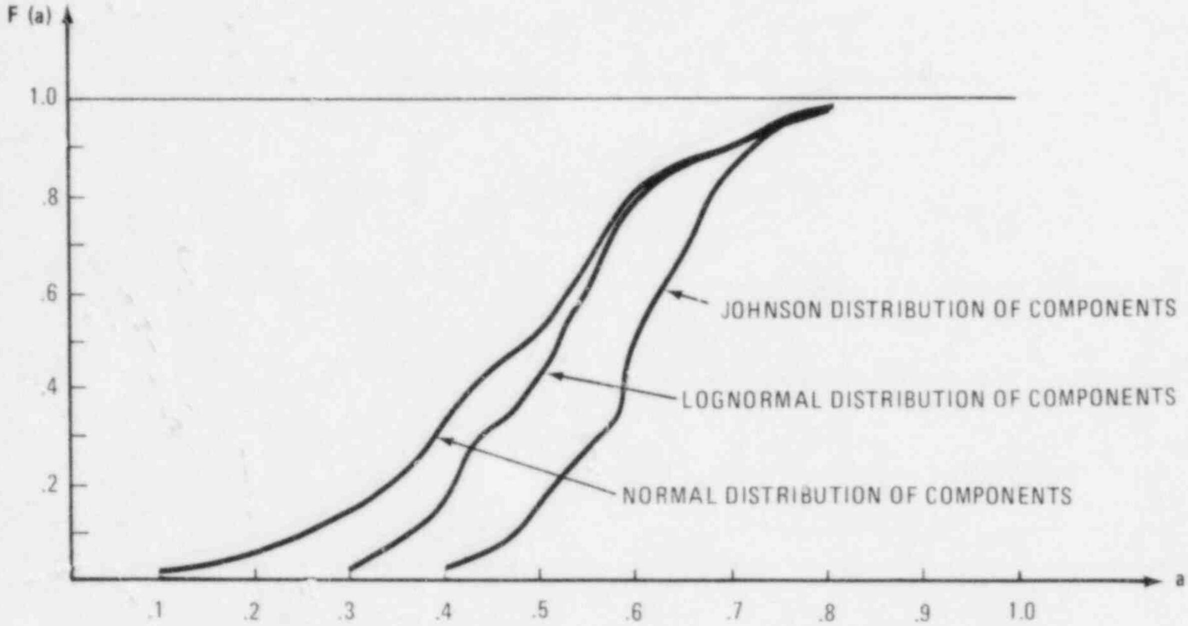

Figure 6
COMPARISON OF THE SYSTEM FRAGILITY WITH DIFFERENT ANALYTICAL FORMS OF COMPONENT FRAGILITY

We can see that upper estimates for medians are about the same. The difference between "best" estimate for medians will result in a substantial difference in the core melt probability. For example, the core melt probability at Zion with the Johnson distribution for component fragility is more than three times less than with the normal distribution. The most drastic difference is for "worse" estimates for medians. This difference may change the entire perception about seismic safety of a plant. The larger randomness and uncertainty the larger is the difference in the core melt probability due to using different analytical forms for component fragility.

Table 1

Comparison of Median Fragilities of the System
For Different Distributions (in g's)

Percentile	Normal	Lognormal	Johnson
5	.18	.33	.43
10	.24	.36	.48
15	.30	.39	.49
20	.34	.41	.51
25	.37	.43	.54
30	.38	.43	.56
35	.40	.46	.57
40	.43	.48	.59
45	.47	.51	.59
50	.49	.52	.60
55	.51	.54	.61
60	.53	.55	.63
65	.55	.56	.64
70	.55	.57	.65
75	.57	.58	.67
80	.59	.60	.67
85	.61	.61	.69
90	.68	.68	.72
95	.72	.73	.75
Mean	.471	.516	.60
Ratio of Upper and Lower Limits	4.0	2.2	1.74

CONCLUSION

The choice of analytical forms for component fragility is very important for seismic PRAs as well as other seismic safety evaluation methods. For example, analytical distributions with a finite range result in sensitivity of the core melt to only several key components. It allows, after preliminary screening, to concentrate efforts on a few of them to increase accuracy and reduce the cost of the analysis. Additionally, the use of a finite range distribution is consistent with the safety margin approach of the seismic analysis.

Analytical distributions with infinite or half-infinite ranges are sensitive to the total number of components with medians within certain ranges. It means that the core melt probability is sensitive, not to exact locations of component fragility curves, but to the number of components having medians of fragilities within every specified interval. Therefore, the result of the analysis is not stable: increasing the number of nonsignificant components makes the result look worse. Thus, the final result depends on the scope of the analysis.

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SEISMIC/DYNAMIC FRAGILITY
AND
SYSTEMS INTERACTION STUDY AT INDIAN POINT - 3

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ABSTRACT

Systems Interaction (SI) Study for Indian Point Nuclear Power Plant, Unit No. 3 was undertaken per advice of the Advisory Committee on Reactor Safeguards (ACRS) primarily to determine the effect of failure of non safety-related components and systems on safety-related items and plant safety itself.

In the present paper it is shown that a predominant number (95%+) of "postulated" SI's attributed to a seismic event equivalent to SSE, have extremely low probabilities of occurrence if seismic/dynamic fragilities of the components/systems were taken into consideration.

INTRODUCTION

Interactions between systems may be intentionally provided for in the design for proper functioning of the plant or unintended. USI A-17 is concerned with the later, specifically, non-safety-related-to-safety-related-interactions due to the functional, spatial or induced human error coupling. Relevant to present discussion are the spatially coupled systems interactions (SI) caused by external events like i) earthquake up to and including SSE, ii) pipe failure (whip), iii) physical impact (missiles), iv) flooding (tank failure), v) tornado depressurization or overpressurization, iv) LOCA or main steam line break and vii) fire. Of these, earthquake of maximum acceleration equivalent to SSE (0.15g) caused almost all SI's (1). Interestingly, contributions to two of the major risks from nuclear power plants, e.g., core-melt and off-site radioactive release, by seismic events of same magnitude are only 2% and 4% respectively (2). These facts do not contradict each other. Because, SI study was performed on the purely deterministic premises that systems, structures or components not designed seismically shall <u>fail</u> during an SSE

and so cause postulated SI's, irrespective of seismic safety margins inherent in them. On the contrary, for safety analysis or probabilistic risk assessment analysis (PRA), probabilistic estimates of ground motions are coupled with stochastically determined structural reliability of systems and components. Any event with probability of occurrence less than 1×10^{-7} per reactor year is not considered contributing to overall risk.

METHODOLOGY FOR POSTULATING SI

All spatial interactions caused by earthquake are source/target type impact. Sources can be completely detached from supporting structures and travel some distance in space before collision (missiles) or partially detached - pipe support failure. As a result of the impact the targets "fail" i.e., become overstressed (beyond yield stress), inoperable etc. Pipes with adjacent unidirectional restraints (hangers) were assumed to fail because displacements of these supports overstressed the pipes beyond code specified allowables. Interaction influence zones were established by engineering judgement alone.

RESOLUTION OF "FEASIBIBLE" INTERACTIONS

The three classical methods of seismically qualifying an equipment or component are i) Analysis, ii) Testing and iii) Demonstration. For resolution of SI's or "closing" an "open" interaction, analyses and testing or combination of them were utilized. Demonstration of behavior of same (or similar) components or equipment in past earthquake was prohibited on the ground that it would violate licensing criteria of the plant. Conservatively, the stresses in reanalysis were limited to 0.9 fy. Testing was performed by applying an equivalent static load to sources like lighting fixtures, PA system and conduits. Testing was adopted only when unknown material properties made an analysis impossible. Modifications to many components were done mostly in the form of additional supports to piping systems and redundant-hold-down devices to other sources.

LESSONS LEARNED AND GUIDANCE FOR FUTURE SI STUDIES

Following is a summary of lessons learned and what could be done in future SI studies regarding seismically induced spatial interactions.

1. Probabilistic not Deterministic Analysis:
   Prof. Newmark stated

[3] It is advisable to apply the theory of probability and optimization techniques... . The traditional deterministic disguise will do less well in earthquake engineering.

This is so true for the uncertainties like (a) although an earthquake affects the entire plant simultaneously, whether a single SSE can cause failure of all non-cat-1 components or equipment is unknown. Also, an SSE is nothing but the maximum rock acceleration (4) with a probability of exceedance of 0.5% in 50 years. This itself calls for probabilistic analysis (b) magnitude of rock/ground acceleration required to fail a component "C" is not known precisely; because component "C" is not defined completely. In PRA analysis a log normal curve with median (acceleration) and standard deviation (random variation parameter) is given (c) impact between source and target must be determined probabilistically since in the three dimensional space defined to be interaction soundry, source-target contact is not definite (d) perfect mathematical modelling of targets is not possible just as is not possible for sources; probabilistic approach is the only way to arrive at a reliable model and (e) role of the failed component or target in the system to which it belongs and that of the system to safety connot be determined definitely also.

Assigning probabilities to items (a) thru (e), even conservatively, leads to total probability of each of the postulated spatial SI's to $\lesssim 1 \times 10^{-7}$. Of course, if the argument is that assigning numbers to life safety probability is not an acceptable approach, almost every industrial facility may require to be closed down!

2. Elasto-plastic not Elastic Analysis:
   Failure analyses of sources and targets should not be on the same basis as design analyses of components. Since material for most sources and targets alike are structural steel, with ductility ratios nearly 20, local yielding must be allowed as long as collapse is not evident. Until further results are available through extensive analysis or experimental research of the cyclic hysterical behavior of structural steel, the following stress levels are considered useful (5) for SI studies.

   Bending: $1.70 F_b \leq F_y$
   Axial Compression: $1.70 F_a \leq F_y$
   Shear: $0.6 F_y$
   Bolts and Welds: 1.7x AISC ALLOWABLES
   Expansion Anchors: $(P/P_a)^{5/3} + (V/V_a)^{5/3} \leq 1.0$

3. Utilization of Experience Data:

Behavior of components or equipment in past earthquakes must be considered as "demonstration" and utilized on equal footing as testing. This is now acceptable to the NRC for equipment qualification (6) in operating plants. During reanalysis at Indian Point SI-study most "span evaluations" of piping system failed because of the currently advocated philosophy that restraints must be added until inertia stresses are below allowables. Experience data show quite contrary (7). During future spatial interaction study this deserves consideration!

4. SSE and LOCA combined:

The extremely conservative criterion in postulating interactions was to combine SSE and LOCA simultaneously. Probabilistic estimates of this extreme load combination may prove that probability is very negligible. In future SI-studies this consideration should be eliminated.

Note: The technical opinions expressed in this article are those of the Author only and those of his employer.

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APPENDIX A

DEVELOPMENT OF EQUIPMENT ANCHORAGE GUIDELINES

presented to

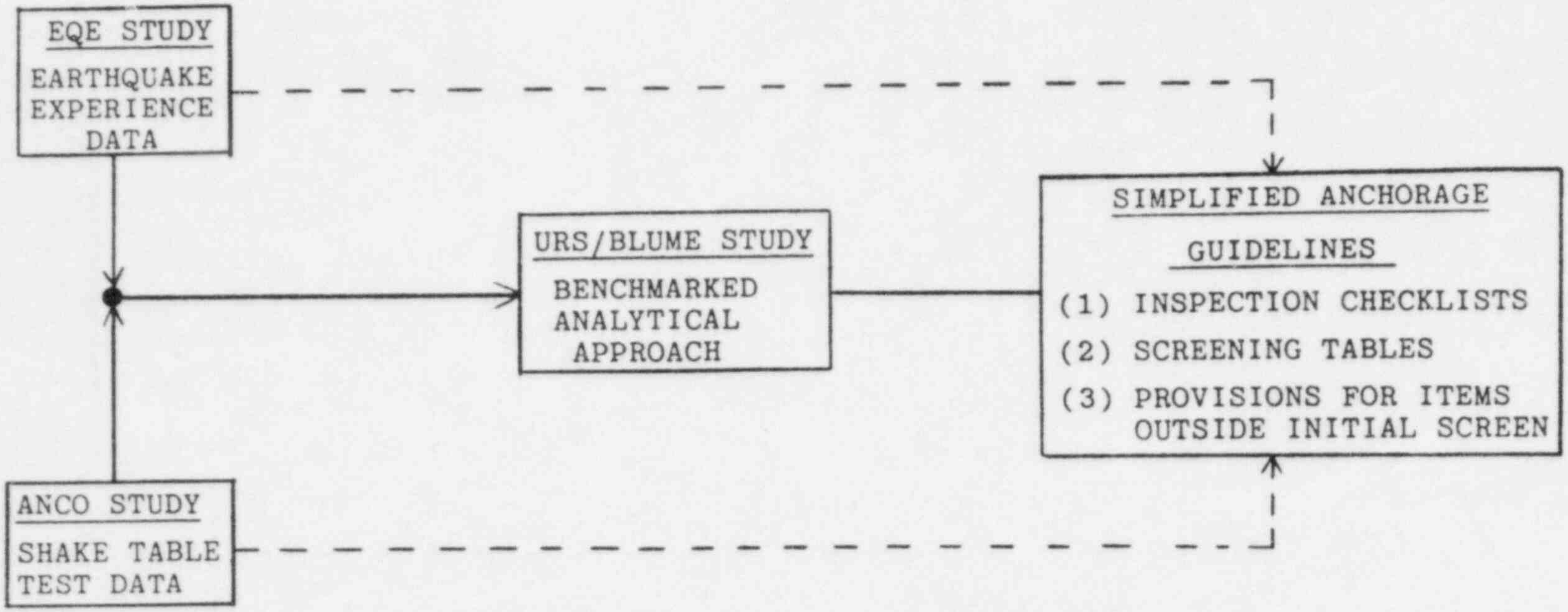
WORKSHOP ON SEISMIC AND DYNAMIC FRAGILITY
OF NUCLEAR POWER PLANT COMPONENTS

BROOKHAVEN NATIONAL LABORATORY

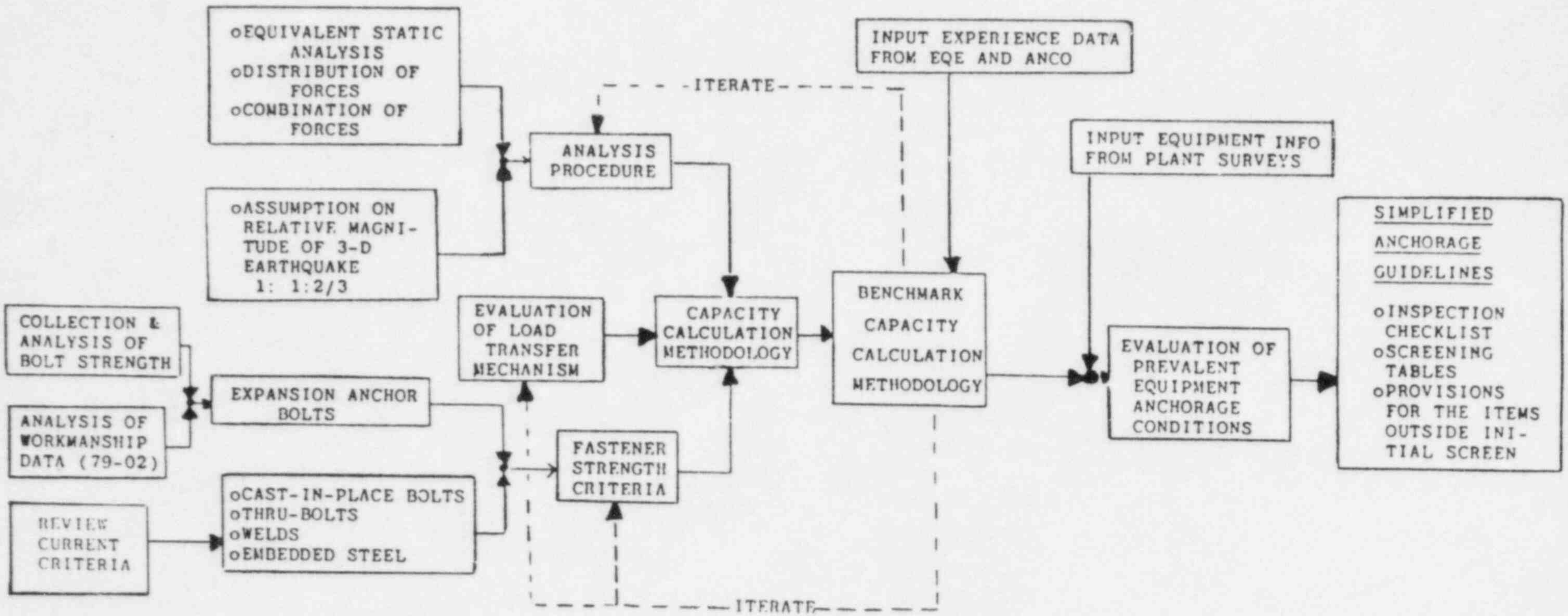
JUNE 5, 1985

presented by

R. MARTIN CZARNECKI
URS/JOHN A. BLUME & ASSOCIATES, ENGINEERS
WEST PEABODY, MA.



INTERACTION OF THREE MAIN COMPONENTS OF EPRI ANCHORAGE STUDY



PROJECT OVERVIEW

FASTENER STRENGTH CRITERIA

- EXPANSION ANCHOR BOLTS
  - COMPILED AVAILABLE TEST DATA
  - 2881 TENSION TESTS
  - 1611 SHEAR TESTS
  - PERFORMED STATISTICAL ANALYSIS OF STRENGTH
  - DEVELOPED OPTIONS FOR STRENGTH CRITERIA AND INSPECTION PROCEDURES
- OTHER FASTENER TYPES
  - REVIEW CURRENT CRITERIA
  - ELIMINATE UNNECESSARY CONSERVATISM

GROUND RULES FOR STATISTICAL ANALYSIS OF EXPANSION BOLTS

- STRENGTH CRITERION APPLICABLE TO ALL BOLTS REGARDLESS OF MANUFACTURE OR TYPE

- USE LOGNORMAL DISTRIBUTION FOR STRENGTH

- CONSIDER CONCRETE STRENGTH $f'_c \geq 3500$

- CONSIDER BOLTS WITH MINIMUM EMBEDMENT

TABLE 1

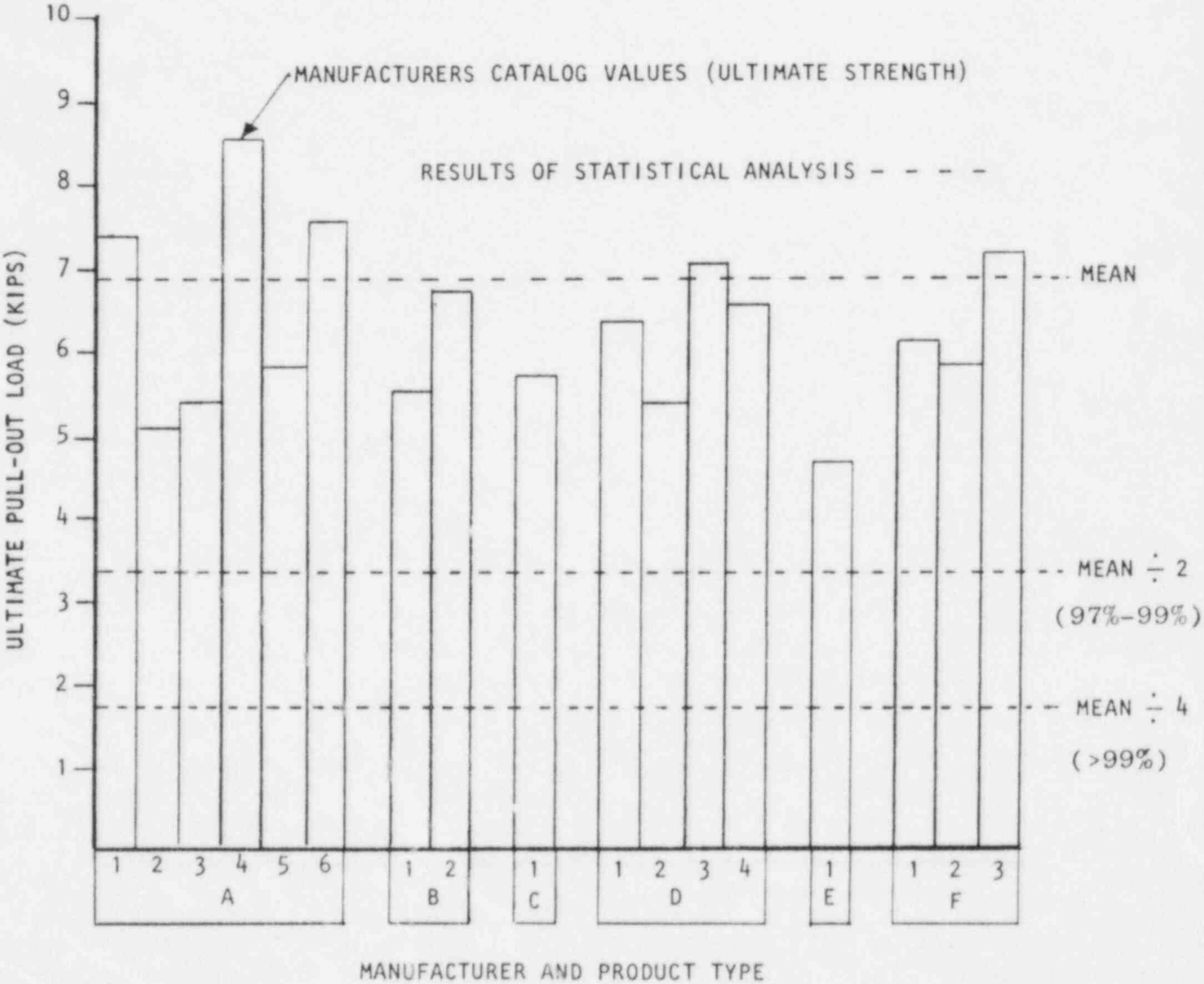
SUMMARY OF EXPANSION BOLT ANALYSIS

BOLTS WITH MINIMUM EMBEDMENT IN

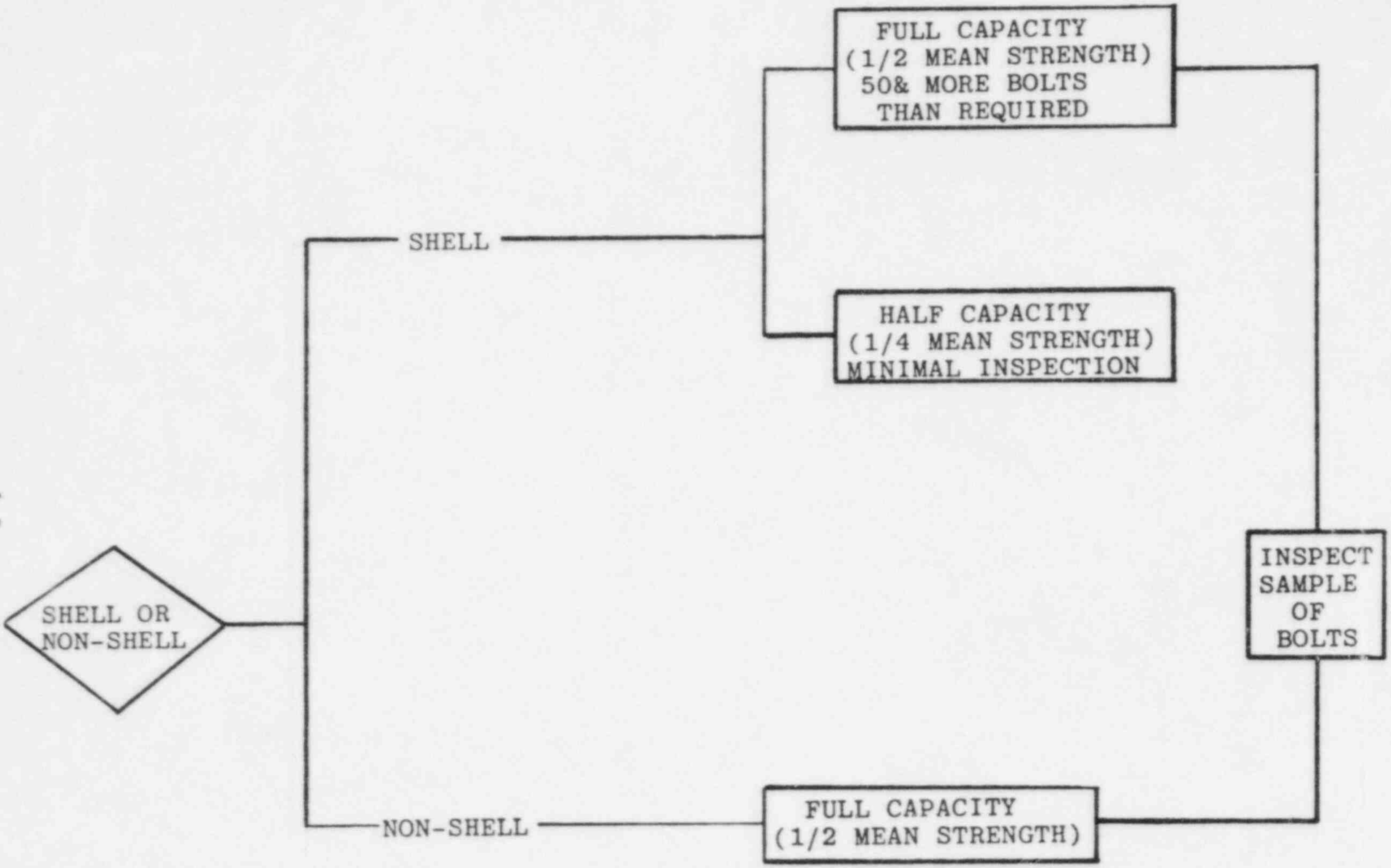
CONCRETE WITH $f'_c \geq 3500$ psi

Bolt Diameter (inch)	Pullout(P) or Shear(S)	Mean Strength $\overline{Y}$ (kip)	Variance σ^2	Probability of Not Exceeding Mean Strength Divided by 2	Mean Strength Divided by 2
3/8	P	4.20	2.08	2.4	2.1
	S	4.15	1.75	2.0	2.1
1/2	P	6.81	3.07	0.5	3.4
	S	6.92	3.32	0.6	3.5
5/8	P	9.27	8.67	2.0	4.6
	S	10.96	6.64	0.3	5.5
3/4	P	13.50	21.09	2.7	6.8
	S	15.85	15.48	0.4	7.9
7/8	P	18.27	16.51	0.1	9.1
	S	23.11	37.15	0.6	11.6
1	P	20.85	15.26	.01	10.4
	S	28.58	64.98	.9	14.3

COMPARISON FOR 1/2" DIAMETER BOLTS

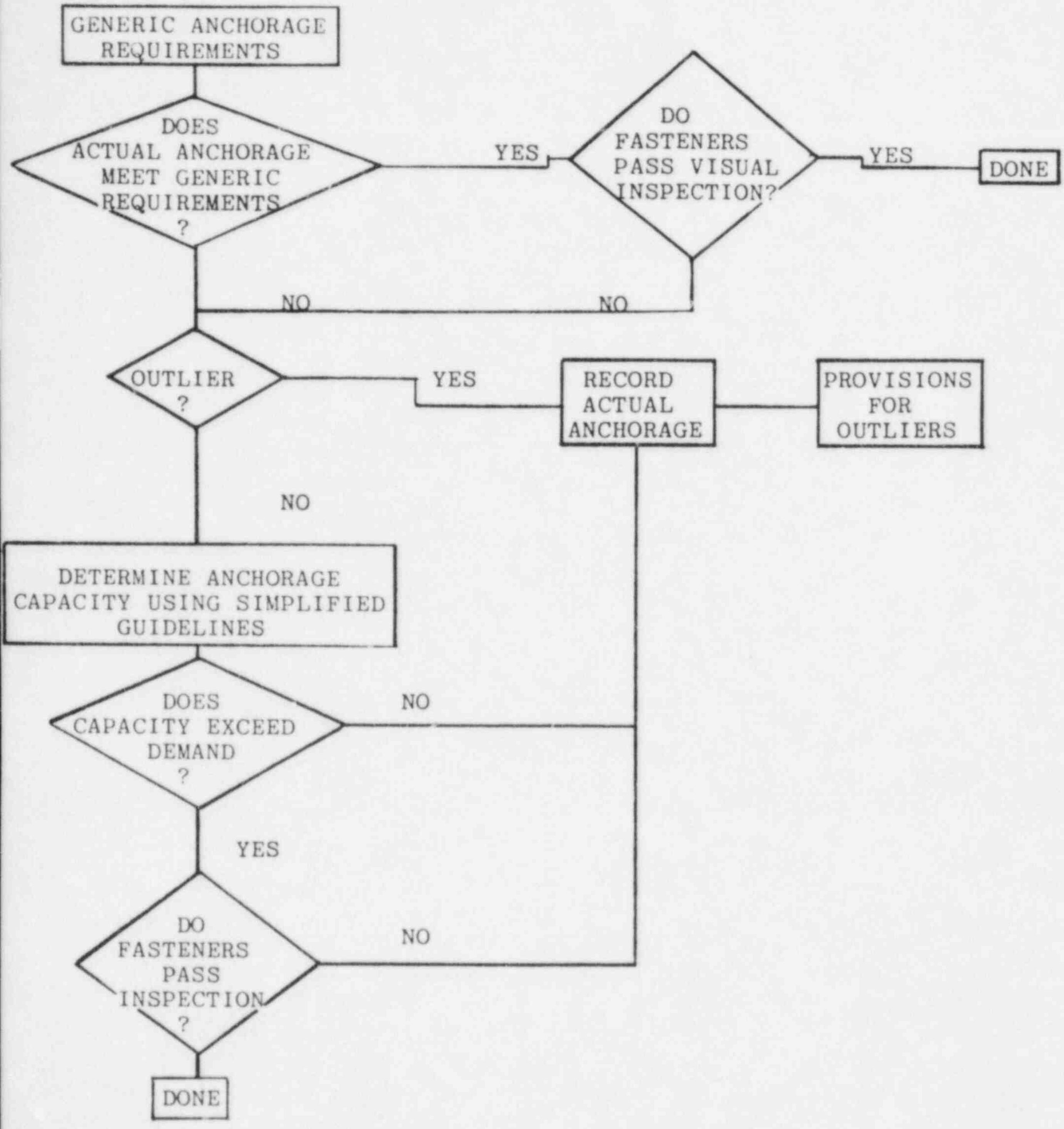


COMPARISON OF MANUFACTURER'S CATALOG STRENGTH
WITH RESULTS OF STATISTICAL ANALYSIS


SHELL OR NON-SHELL
SHELL
NON-SHELL
FULL CAPACITY (1/2 MEAN STRENGTH) 50& MORE BOLTS THAN REQUIRED
HALF CAPACITY (1/4 MEAN STRENGTH) MINIMAL INSPECTION
FULL CAPACITY (1/2 MEAN STRENGTH)
INSPECT SAMPLE OF BOLTS

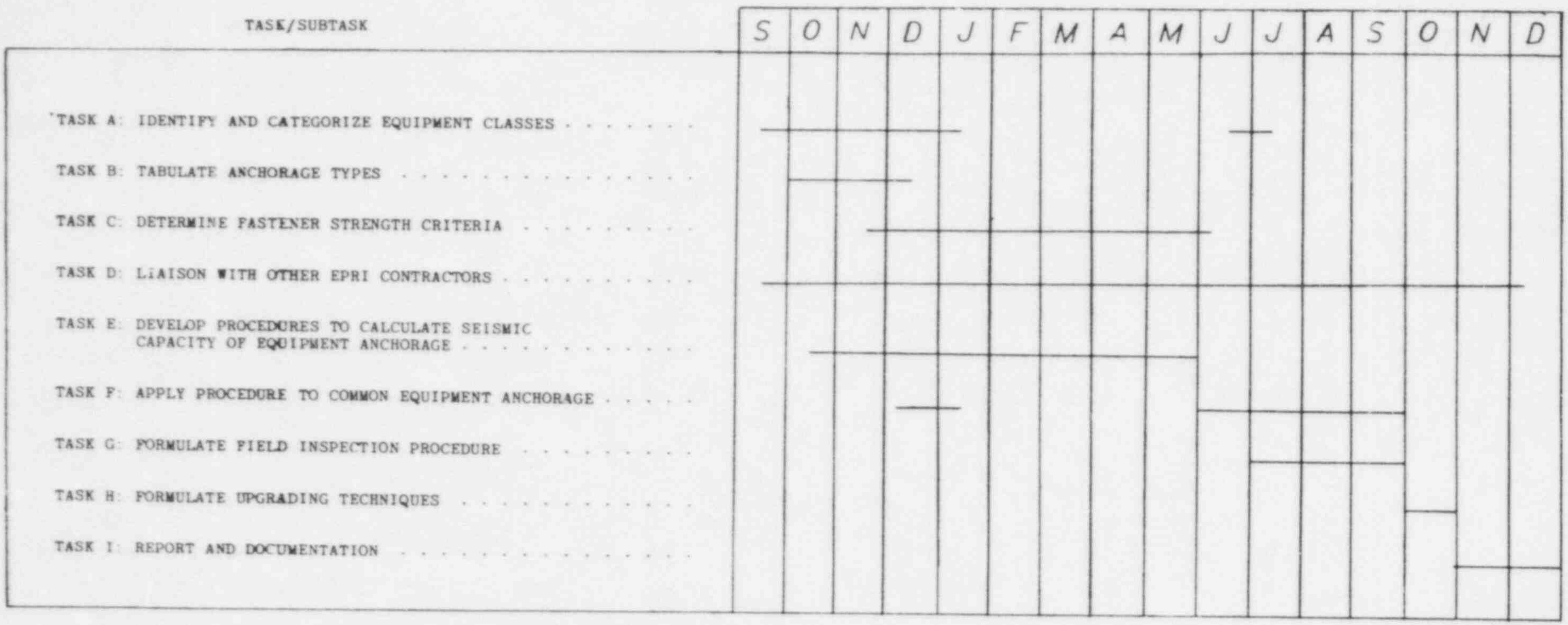
BENCHMARKING STUDIES

- o ANCHORAGE EVALUATION OF EQUIPMENT WHICH HAS GONE THROUGH EARTHQUAKES
- o FOR EQUIPMENT WITHOUT DAMAGE ANALYSIS PROCEDURE PREDICTS NO DAMAGE
- o FOR EQUIPMENT WITH DAMAGE
  - o EQUIPMENT WITH DAMAGE HAD NON-STANDARD ANCHORAGE
  - o MORE FAILURE DATA BEING COLLECTED



EQUIPMENT ANCHORAGE EVALUATION

FIELD WORK



REVISED PROJECT SCHEDULE

APPENDIX B

ESTIMATED COSTS OF NUCLEAR POWER PLANTS

PRESENTED TO

WORKSHOP ON SEISMIC AND DYNAMIC FRAGILTY
OF NUCLEAR POWER PLANT COMPONENTS

BROOKHAVEN NATIONAL LABORATORY

June 7, 1985

Presented by

John D. Stevenson
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Table 1

ESTIMATED COST OF ONE
1200MWe DOMESTIC UNITED STATES LWR NUCLEAR POWER PLANT,
MILLIONS OF DOLLARS*

Direct Costs	
Land and land rights	4
Physical plant	
Structures and site facilities	201
Reactor plant equipment	260
Turbine plant equipment	203
Electric plant equipment	74
Miscellaneous plant equipment	25
Main heat rejective system	39
Subtotal (physical plant)	806
Indirect costs	
Construction services	130
Home office engineering services	243
Field office engineering services	135
Other costs	86
Subtotal (indirect costs)	594
Total direct and indirect	1400
Interest during construction	1068
Escalation during construction	823
Total cost at commercial operation (September 1991	3291 ($2743 per kW)

With a 132-month project schedule from January 1985 (decision to build) to commercial operation in January 1996 (January 1985 dollars).

Table 2

APPROXIMATE INCREMENTAL COST (1/1985 $)
FOR SEISMIC CONSTRUCTION OF A DOMESTIC 1200 MWe LWR
FOR A NOMINAL 0.2g - SSE ZPGA SITE
MILLIONS OF DOLLARS

Item	Direct(1)	Indirect(2)	Overhead(3)	Total
Foundation*	2.0	1.5	4.8	8.3
Building Structure	2.1	1.6	5.1	8.9
Auxiliary Components	4.2	3.1	10.0	17.3
NSSS	2.1	1.6	5.1	8.8
Distribution Systems				
(a) Piping	17.0	13.5	41.9	72.4
(b) Raceway Ducts	5.0	3.5	11.0	19.5
Turbine Hall	1.0	0.6	2.2	3.8
Seismology & Siting	-	3.2	4.1	7.3
Engineering	-	66.0	90.8	156.8
Administration	-	8.5	11.7	20.2
TOTAL	34.4	103.1	186.7	324.2

Total Cost = Direct + Indirect + Overhead

* Assumes site is not subject to liquification.

(1) Direct costs include the cost of land and physical quantities and items delivered to the job site plus direct labor of installation.

(2) Indirect costs include construction services and miscellaneous services which include licensing, quality assurance, and direct supervision. As a separate line item engineering and administration are included.

(3) Overhead costs include interest and escalation assuming a 132 month project schedule.

It should be understood that these cost estimates are for new construction and cannot be applied to a backfit situation because congestion and radiological work areas increase unit installation costs by factors of 4 to 8 over new construction unit cost

Table 3 Summary Estimate of Extreme Load Differential Costs for Nuclear Power Plants
Percent of Plant Cost

Extreme Load	France	Japan[1]	Federal Republic of Germany	U.S.	Remarks
A. Seismic					
(1) SSE-S2	3[2]	2[1]	3[2]	4[3]	
(2) OBE-S1	-	5	2	5	
B. Extreme Wind					
(1) 100 Mile Wind	>>1	>>1	>>1	-	
(2) Tornado	-	-	-	1.5	Cost mainly in engineering and increased wall thickness as missile shield
C. Flooding	>>1	>>1	>>1	>>1	
D. DBA-LOCA	2	1	1	2	
E. Pipe Break	1	1	1	3.5	
F. Airplane Crash	2	-	10	-	
G. Blast Wave	-	-	2	-	
H. Plant Missiles	>>1	>>1	>>1	>>1	
I. Equipment Extreme Environment Qualification	>>1	1	1	1	
TOTAL	9.0	10.0	20.0	18.0	

Notes:

(1) Assumes a 0.3 g S_1 and 0.45 g S_2 for Japan ZPGA
(2) Assumes a 0.15 g for SSE equivalent ZPGA
(3) Assumes a 0.2 g for SSE and 0.10 g for OBE ZPGA

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The Workshop on Seismic and Dynamic Fragility of Nuclear Power Plant Components was held at Brookhaven National Laboratory (BNL) on June 5-7, 1985. The purpose of the workshop was to provide a forum for exchanging concepts, information and experiences on the fragility of electrical, control and mechanical equipment used in nuclear power plants when subjected to seismic and other dynamic environments. The workshop was divided into six sessions which included discussions on definition, uses and importance of component fragility; parameters affecting component fragility; categorizing equipment and existing test results; methodology and application of fragility data to equipment assemblies; equipment requiring future fragility testing; and, use of fragility data in PRA and Seismic Margin studies. The proceedings represent the compilation of the papers presented at the workshop.

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