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SEISMIC FRAGILITY OF NUCLEAR POWER PLANT COMPONENTS (PHASE II)

MOTOR CONTROL CENTER, SWITCHBOARD, PANELBOARD AND POWER SUPPLY

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December 1987

STRUCTURAL ANALYSIS DIVISION
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ABSTRACT

In Phase I of the Component Fragility Program, Brookhaven National Laboratory (BNL) has developed a procedure to establish the seismic fragility of nuclear power plant equipment by use of existing test data and demonstrated its application by considering two equipment pieces. In Phase II of the program, BNL has collected additional test data, and has further advanced and is applying the methodology to determine the fragility levels of selected essential equipment categories. The data evaluation of four equipment families, namely, motor control center, switchboard, panelboard and power supply has been completed. Fragility levels have been determined for various failure modes of each equipment class and the deterministic results are presented in terms of test response spectra. In addition, the test data have been analyzed for determination of the respective probabilistic fragility levels. To this end, a single g-value has been selected to approximately represent the test vibration level and a statistical analysis has been performed with the g-values corresponding to a particular failure mode. The zero period acceleration and the average spectral acceleration over a frequency range of interest are separately used as the single g-value. The resulting parameters are presented in terms of a median value, an uncertainty coefficient and a randomness coefficient. Ultimately, each fragility level is expressed in terms of a single descriptor called an HCLPF value corresponding to a high (95%) confidence of a low (5%) probability of failure. The important observations made in the process of data analysis are included in this report. For example, the lowest structural damage mode of an MCC is loosening of self-tapping screw connections followed by deformation and failure of the connections at the base at higher excitation levels. Recommendations for future research work in the fragility area are also included in this report. One of the important needs is to study the applicability of the fragility results to the earlier vintage equipment for which little or no test data exist.

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The guidance and recommendations provided by the Advisory Panel Members Drs. Robert Budnitz, Robert Kennedy and Paul Smith are gratefully acknowledged. The constant advice of Professor Mosanobu Shinozuka and assistance of Drs. Wei-Yann Tsai and Howard Hwang played an important role in the probabilistic analysis and their contribution is sincerely appreciated. The cooperation of Dr. George Sliter, EPRI and Mr. Kelly Merz of ANCO Engineers, Inc. is also sincerely acknowledged.

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EXECUTIVE SUMMARY

S.1 INTRODUCTION

This report presents the results of a study of the seismic fragility of nuclear power plant equipment as part of the BNL Component Fragility Research Program sponsored by the Nuclear Regulatory Commission. The essential objective of the program is to define and quantify the generic seismic fragility of safety-related equipment and to present the results in a format such that they can be readily used in margin studies and probabilistic risk assessments.

The BNL program was initiated in FY 1985. In Phase I, BNL collected and evaluated existing test data and developed a methodology to establish seismic fragility levels in terms of test response spectra. BNL applied this methodology on two equipment pieces and demonstrated the effectiveness of the use of existing test data in predicting the fragility level. The results were published in NUREG/CR-4659 [1].

S.2 COMPONENT FRAGILITY PROGRAM - PHASE II

In Phase II, BNL has collected additional test data for a group of electrical equipment[1] selected primarily from a previous prioritization study [3]. The test data for the following four equipment categories have been analyzed and the results are presented in this report:

1. Motor Control Center (including Interlock)
2. Switchboard
3. Panelboard
4. DC Power Supply

These equipment pieces belong to the group classified as "very important electrical equipment with low seismic capacity."

The fragility analysis methodology, developed in Phase I, has been refined and further advanced in Phase II. The fragility level for each major failure mode of an equipment is established both deterministically and probabilistically. Test response spectra are used as a measure of the deterministic fragility level and two indicators of the test response spectra are used as parameters of fragility functions specified in probabilistic terms.

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1 A complete list of the selected equipment is provided in Chapter 1, Section 1.2.

Zero period and average spectral accelerations are the two test response spectrum indicators. A statistical analysis is performed with each of these two indicators as inputs to obtain a median value, an uncertainty coefficient to include modeling uncertainties and a random coefficient to include performance randomness. These three parameters completely define the probabilistic fragility level expressed as HCLPF[1].

For each equipment, a description of the data base test programs, a summary of test results, a discussion of failure modes, a presentation of the fragility test response spectra and probabilistic fragility levels are all included in this report. A summary of the fragility analysis results is provided in Chapter 7, Table 7-1. The following are some of the generic observations made during the course of this research:

- The seismic test programs from which the data have been collected were conducted in the period 1975-1985.
- Electrical malfunctions and instrument accuracy problems occur at lower excitation levels than that required for a structural damage.
- Although minor structural problems, e.g. loosening of screws, did not pose a problem to the overall structural integrity of an equipment, in some instances, they triggered electrical malfunctions.
- Self-tapping screw connections and bolted connections at the base are structural weak links. Therefore, the structural capacity of an electrical panel, especially an MCC, can be raised by avoiding the use of self-tapping screw connections and by strengthening the bolted connections at the base.
- In some instances, the workmanship of solder joints for electrical devices and connections of panel structural members, especially for early products, controlled the fragility limit where apparently proper inspection had not been performed.
- Some products in an equipment category are capable of withstanding a seismic event significantly greater than that depicted by the lower-bound fragility limit presented in the report.
- At or close to the fragility level, the equipment performance varies and appears unpredictable.
- Since some relays apparently have very low fragility levels, they should be carefully screened for application of the results presented in this report.

1 High (95%) confidence of a low (5%) probability of failure.

- The natural frequency of a cabinet structure decreases with an increase of the vibration level.

S.3 CURRENT PROGRAM

The Component Fragility Program at BNL is continuing. Test data for other important equipment in the prioritized list are being collected and analyzed. The results will be published in future reports.

As part of the Fragility Program, BNL is also planning to test relays and motor starters in order to explore and generically quantify the influence of certain parameters in controlling their respective fragility levels.

In another associated task, BNL is computing dynamic amplification factors for electrical panels by use of existing qualification and fragility level test data. The amplification factors are expected to provide a realistic correlation between the fragility level of a device and that of a panel which contains the device.

S.4 RECOMMENDATIONS FOR FUTURE RESEARCH

Based on the study performed to-date, some generic issues of great practical value are emerging and are therefore recommended for future research. A definition and description of some of these issues and some thoughts regarding how to address them are provided in Chapter 7, Section 7.5, a synopsis of which is presented in the following sub-sections.

S.4.1 Vintage

Among all the concerns in applying the fragility results, the vintage of the equipment is probably the most outstanding issue. For obvious reasons products of two manufacturers are not necessarily the same; similarly products of one manufacturer at different times are not necessarily the same. This is more so in the realm of seismic capacity of electrical equipment.

The use of the results presented in this report and those that will be presented in future BNL reports will be limited to recent plants unless further research is conducted to determine applicability of these results to earlier products. To this end, it is recommended that some or all of the following approaches be pursued to address the vintage issue:

- Search for early test data.
- Test some specimens from early vintage.
- Test new specimens by duplicating the old test procedure if the search for early test data becomes successful.

- Study the structural and electrical details of the products from early vintage.
- Select a small group of products, follow the trail of their design changes and estimate a variation of the capacity in that time domain.

S.4.2 Inconsistency of Results

At or close to the fragility level, the performance of an electrical component appears to be inconsistent. It is recommended that an in-depth study be performed to better understand the parameters, both the internal (i.e. component design) and the external (i.e. test input), that control the fragility and are the cause of such apparent inconsistencies of equipment performance. The study should concentrate on critical devices. Limited testing may be required.

S.4.3 Frequency-Dependent Fragility Level

It has been observed in the existing data base that the frequency content of the random excitation influences the functionality of an equipment. It is recommended that a study be performed for deriving the frequency-dependent fragility test response spectrum for equipment assemblies such that at any frequency the g-level depicted by the spectrum is the true fragility g-level at the particular frequency.

S.5 CONCLUSIONS

The approach to assess seismic fragility by use of existing data has emerged out of the initial demonstration stage. The probabilistic method has complemented and added strength to the deterministic approach. The outcome is a fragility test response spectrum for deterministic use and a single fragility descriptor along with other statistical parameters for use in margin studies and probabilistic risk assessments. The results are finding applications in different programs.

CHAPTER 1
INTRODUCTION

1.1 BACKGROUND

The Component Fragility Research Program is sponsored by the United States Nuclear Regulatory Commission (USNRC) and its essential objective is to establish the generic seismic fragility of nuclear power plant equipment and to present the result in a format such that it can be readily used in margin studies and probabilistic risk assessments.

The program was initiated in FY 1985. Two parallel approaches were considered to meet the objective - using existing test data and performing new tests. Brookhaven National Laboratory (BNL) was assigned the task of exploring the effectiveness of the use of existing test data in establishing the equipment fragility limit; whereas, Lawrence Livermore National Laboratory (LLNL) was assigned the task of performing a demonstration test and developing a priorization scheme.

In Phase I of the program, BNL collected seismic test data from various source organizations, evaluated the information and developed a methodology to establish fragility levels. BNL applied this methodology on two equipment pieces, switchgear and motor control center, and demonstrated the effectiveness of the use of existing test data in predicting the fragility level. The results were presented in terms of test response spectra and published in NUREG/CR-4659 [1]. LLNL performed a fragility demonstration test on a motor control center with various structural configurations and prioritized the nuclear power plant equipment categories based upon both their importance in performing safety functions and relative seismic capacities [2,3].

1.2 BNL's RESEARCH SCOPE IN PHASE II

In Phase II, more emphasis is given on the use of existing data. In the beginning of FY 1987, the following list of equipment was prepared for the purpose of the fragilty study primarily based upon the prioritization scheme developed by LLNL and the recommendations of an advisory panel:

Group A (very important electrical equipment with low seismic capacity)

1. Switchgear
2. Electrical Distribution Equipment (Panelboard)
3. Instrument and Control Panels and Racks
4. DC Distribution Switchboard
5. Local Instruments
6. Motor Control Center (including Interlock)
7. Relay
8. Power Supply

Group B (very important electrical and mechanical equipment with medium seismic capacity)

1. Transducer
2. Transformer
3. Auxiliary Relay Panel
4. ESF Sequencer
5. Circuit Breaker
6. Inverter
7. Bistable
8. Ion Chamber Electrical Connector
9. Batteries and Battery Racks (Documents available)
10. Small Valves
11. Fire Protection and Deluge Equipment
12. Bearing Cooling Equipment
13. CRD Equipment
14. Air Handling Units and Fans
15. Diesel Generator Peripherals

Group C (very important mechanical equipment with medium to high seismic capacity)

1. Air Compressor
2. Small MOV
3. Large MOV
4. Motor Driven Pump
5. Large Hydraulic and Air Actuated Valves
6. Large Relief, Manual and Check Valves
7. Miscellaneous Small Valves

BNL's research scope in Phase II is to evaluate the test data for these equipment categories with the understanding that Group A has the highest priority. This includes the following primary tasks:

1. Data Collection, Evaluation and Interpretation

   Both existing (as a result of Phase I effort) and new data sources will be used. The data will be stored on the BNL computerized data bank. Seismic fragilities will be developed and generic evaluations will be made on an equipment category basis.

2. Failure Modes Identification and Parameters

   Associated with the seismic fragility levels established in Task 1, BNL will indicate failure modes which control seismic fragility including both structural and functional failure modes. BNL will investigate the impact of equipment anchorage and other parameters on seismic fragility.

3. Development of Simplified Component Fragility Information for Seismic Margin Studies and Seismic PRAs

Fragility information from experimental sources is usually portrayed as test response spectra (TRS) from multifrequency inputs. Since such TRS usually do not provide frequency-dependent fragility response values, they are not readily useful to margin and PRA investigations. BNL will establish correlations between the TRS and more simplified fragility parameters (such as medians, coefficients of variation) and descriptors (such as HCLPF[1]) and make specific recommendations for each equipment category studied. The fragility descriptors must be sufficiently reliable such that NRC can use them to make decisions concerning seismic issues at nuclear power plants. Limitations on the use of these descriptors must be minimized without degrading realism. The fragility descriptors are the chief product of this effort.

A few other tasks have been added in FY 1987 and are not the subject matter of this report. However, they are briefy discussed as the current program in Section 7.4.

1.3 SUMMARY OF ACTIVITIES

BNL continued reviewing test reports and collecting data for the equipment categories listed above. The activities in performing the tasks listed above are summarized in the following paragraphs:

1. Additional data sources have been explored and contacted in FY 1987 and test data have been collected from both the existing and the new source organizations. Storing data on the BNL computerized data bank continued through FY 1987. The data evaluation has been completed for four equipment categories, namely, motor control center (including interlock), switchboard, panelboard and power supply. The generic seismic fragilities have been established for these equipment pieces[2] and are discussed in this report. The effort is continuing with other equipment pieces as discussed in Section 7.4.

2. The failure modes associated with the fragility levels have been identified. The various malfunctions which the equipment usually exhibited with a gradual increase of the vibration level have been listed. Moreover, electrical malfunctions have been separated wherever possible to identify those which continued to degrade the equipment even when the strong motion disappeared. Structural failure modes have been identified wherever applicable. The parameters controlling the equipment fragility have also been studied.

1 High confidence of a low probability of failure

2 Based upon the BNL data base

3. In order to obtain simplified fragility descriptors, statistical and probabilistic analyses have been performed for each of the four equipment categories mentioned above. The input data in the analyses are the zero period and average spectral accelerations from TRS for each significant failure mode. The outcome is the median fragility value with the associated uncertainty bands and a fragility descriptor (HCLPF). This information can readily be used in the current margin studies and PRA's.

4. In consultation with the NRC, BNL has formed an Advisory Panel comprising of the following experts:

   a. Dr. Robert Budnitz, Future Resources Associates, Inc.
   b. Dr. Robert Kennedy, Structural Mechanics Consulting, Inc.
   c. Dr. Paul Smith, EQE, Inc.

   Through three meetings in FY 1987 and numerous discussions and letters, the Panel provided guidance and recommendations for the BNL Component Fragility Program. The equipment prioritization list has been revised as a result of advice from these experts. In addition to the Panel Members, Professors Masanobu Shinozuka and Wei-Yann Tsai of Columbia University provided guidance in the probabilistic analysis of the data.

This report consists of seven chapters and three appendices. Chapter 2 contains the methodology used in compiling and evaluating the data. Since the same approach has been used in presenting the fragility results for each equipment, the presentation approach is discussed in chapter 2. Chapters 3 through 6 include the discussions on fragility evaluation and results of motor control center (including interlock), switchboard, panelboard and power supply, respectively - one chapter for each equipment. The size of the data base, description of the equipment test specimen, testing methods, test results, probabilistic analysis results and critical comments regarding equipment functionality are all provided for each equipment. The summary and conclusions are furnished in chapter 7. This includes discussions on the generic observations, the current program and the recommendations for future research.

Appendix A provides the details of the statistical methods used for probabilistic evaluation of the fragility descriptors. Appendix B contains the TRS curves at a 5% damping value for the corresponding curves provided in the text at a 2% damping value. Appendix C illustrates the presentation of dynamic amplification factors by use of existing test data.

CHAPTER 2
METHODOLOGY

2.0 INTRODUCTION

The methodology employed in compilation and evaluation of the test data and the procedure used in presentation of the results are discussed in this chapter. The test data have been collected, assembled and evaluated basically following the same approach used in Phase I of this program and described in NUREG/CR-4659, Volume 1[1]. Therefore, only a brief discussion is provided in the following sections on the methodology used in compiling the data and evaluating the deterministic fragility level. However, the statistical analysis of the test data in predicting the probabilistic fragility level is an important addition and that methodology is discussed in detail.

2.1 DATA COMPILATION

The collected data are the results of a wide variety of test programs and often require further processing before they can be compared with each other. In order to arrive at the generic fragility level from the individual test programs, each test report has been studied and the results have been analyzed by use of a uniform evaluation technique.

Variations in testing methods, vibration inputs and damping values of test response spectra (TRS) are the main obstacles for direct comparison of data. Random multifrequency biaxial vibration inputs and TRS at the 2% damping value have been considered standard in the BNL study, since a major portion of the collected data belongs to this group. Test data for different vibration inputs and/or different damping values are converted to the standard form by using a scaling factor.

For conversion of damping values, the following multiplying factors have been used [1]:

Conversion Damping Values	Frequency Range	Multiplying Factor
From 5% to 2%	1-12.5 Hz	1.4
	13-20 Hz	1.3
	21-31.5 Hz	1.2
From 3% to 2%	1-31.5 Hz	1.2
From 1% to 2%	1-19 Hz	0.77
	20-31.5 Hz	0.85

These factors have been used for conversion to 2% damping and are not recommended for a reverse operation (e.g. from 2% to 5%). It is recognized that the above factors are approximate and may be further refined.

Regarding variation of the test input, unless otherwise mentioned, a multiplying factor of 0.7 has been used over the entire frequency range to transform a narrowband (e.g. sine beat, sine dwell) or a single axis response to a standard response. A multiplying factor of 0.5 (i.e. 0.7 x 0.7) has been used when the input is both narrowband and single axis applied simultaneously. Engineering judgements have been used for conversion of other vibration conditions.

2.2 DATA EVALUATION - DETERMINISTIC APPROACH

In a typical fragility test program, with a gradual increase of the vibration input, the equipment starts malfunctioning at a certain level which is defined in this report as the fragility level. The test response spectrum is used as a measure of the vibration input. An equipment exhibits various failure modes at various TRS levels and each such TRS level is termed a fragility limit associated with the corresponding malfunction. Once the fragility levels are thus established for a number of test specimens of the same equipment category, the lower-bound TRS data indicate the deterministic generic fragility level for the particular equipment.

In the test reports, the equipment performance under various electrical conditions are described and almost all the corresponding test vibration input data are included. However, for a limited number of data base test programs, although the malfunctions are clearly identified in the test reports, all the pertinent TRS data are not available. In such cases, an approximate TRS level has been obtained by judging all other available test run levels in the same program and by consulting with engineers from the manufacturing company.

2.3 DATA EVALUATION - PROBABILISTIC APPROACH

In addition to the deterministic assessment of the fragility level discussed above, the test data have also been analyzed to provide probabilistic results that can be readily used in margin studies and probabilistic risk assessments (PRA's) of nuclear plants. The fragility TRS data were obtained from multifrequency inputs and usually do not provide frequency-dependent response values. Since in their current forms, the margin studies and the PRA's do not accept the fragility level in terms of these TRS data and require a median g-value associated with the coefficients of variations or an HCLPF value, a further data reduction becomes necessary. To this end, a g-value is selected to represent the TRS data set. Thus, for an equipment category, the fragility level is now represented by a number of single g-values corresponding to all the fragility test runs. These g-values are then statistically analyzed for determination of the probabilistic fragility level. The selection of the single g-value and the details of the statistical analysis method are discussed in the following subsections.

2.3.1 TRS Indicator

In representing a TRS data set with a single parameter i.e. a g-value, the objective is to select that parameter which has most influence on the fragility phenomenon. The following candidates were suggested as a result of the BNL Phase I study [1]:

a. ZPA[1]
b. Spectral Acceleration
c. Equivalent ZPA

The ZPA being the peak acceleration of the test input is expected to be a good indicator of the time history. However, it fails to represent the frequency content of the input and, consequently, does not adequately represent the fragility of frequency-sensitive components.

On the other hand, the spectral acceleration is probably an excellent fragility indicator for a frequency-sensitive device. But, in a typical equipment assembly, there may be a number of devices with different sensitive frequencies. In addition, the equipment structure may have the fundamental frequency quite different from the frequencies to which various devices are sensitive. There can also be a variety of combinations of equipment natural frequencies and device-sensitive frequencies. Therefore, the question arises as to which frequency should be considered for determination of the spectral acceleration.

Alternately, an equivalent ZPA can be obtained either by judging the spectral values or by comparing the TRS with a reference spectrum. In either case, the result is expected to be influenced by subjective judgements.

It appears from the above discussion that one parameter may not be adequate to represent the TRS. Therefore, in this report two parameters have been used. They are as follows:

a) ZPA[1]
b) ASA (Average Spectral Acceleration)

Numerically, the ASA is obtained by dividing the area under a portion of the TRS curve (g-value vs. frequency in regular scale) by the corresponding frequency band which is the frequency range of interest for the particular equipment. In this report, a frequency range of 4-16 Hz has been considered for all equipment categories unless otherwise specified.

It should be noted that the parameter ASA incorporates the essence of the two parameters, spectral acceleration and equivalent ZPA, discussed earlier. Moreover, a combination of ZPA and ASA virtually depicts the TRS in the frequency range of interest. The choice of which of these two parameters should be selected is left to the user.

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1 The ZPA values reported in the available test documents are often filtered to remove high frequency contents.

2.3.2 Statistical Methods

The TRS indicators obtained from the TRS data as discussed above constitute the input data for the statistical analysis. In a typical data base fragility test program, several test runs can be judged to possess fragility level vibration inputs. For the deterministic evaluation, the lowest level is of primary interest. However, for statisical purposes, all the fragility test runs are of interest and each run provides two TRS indicators, i.e. ZPA and ASA, as input data for the analysis. A separate statistical analysis has been performed for each indicator. A lognormal distribution has been assumed for the data base.

The median fragility level and the total coefficient of variation (β_c) are computed from the entire data set for a particular equipment category. The deviation within the data set for a specimen provides the coefficient of variation for that specimen due to randomness. The randomness coefficient is calculated for each specimen separately. For the equipment category, the coefficient of variation due to randomness (β_r)[1] is obtained from a weighted average of the randomness coefficients for all specimens in the category. Since the total variation is a result of both the variation due to randomness and that due to uncertainties, the coefficient of variation due to uncertainties, β_u, is obtained from the following relationship:

$$\beta_u^2 = \beta_c^2 - \beta_r^2$$

The above fragility parameters, i.e. the median value along with the coefficients of variation, are computed by employing both the method of moments and the method of maximum likelihood. In the former method, only the fragility data are used as input; whereas, in the latter method both the fragility and the highest qualification data are used. A discussion on formulation of both methods is included in Appendix A.

By using these fragility parameters, one can estimate the probability of failure for the equipment. The result of special interest is the probability estimate allowing a high confidence of a low probability of failure (HCLPF). In this report, the 95% confidence level for not exceeding 5% probability of failure is considered as the HCLPF value and is calculated as follows [4]:

$$\text{HCLPF} = \text{Median} * \text{Exp}\,[-1.645\,(\beta_r + \beta_u)]$$

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1 By definition β_r represents only the variation of the input motion. It is recognized that the approach used in this report may allow β_r to be slightly influenced by the uncertainties. This deviation from the true definition has been judged acceptable for estimation of the fragility parameter in this project.

The HCLPF value is the single g-value that has been sought to describe the generic fragility level of the equipment category and, in this report, is referenced as the "fragility descriptor."[1]

The fragility parameters and the descriptor, HCLPF, are calculated for all significant failure modes of the equipment in terms of both ZPA and ASA. If the number of data points is inadequate for a statistical analysis some or all of the fragility parameters are estimated from the available information by use of judgement and the fragility descriptor is then computed from the estimated parametric values.

A sensitivity study has been conducted to determine the effect of high-valued data points on the fragility parameters and descriptors. Obviously, both the median and the coefficient of variation diminish with the removal of high data points. Since the HCLPF is directly proportional to the median and inversely influenced by the coefficient of variation, the resulting HCLPF value may remain unaltered or may increase or even decrease depending on the relative change of the median and the coefficient of variation. If a set contains a large number of data points, removal of a limited number of data does not appreciably change the fragility parameters. For example, removal of the highest ZPA value of 2.4g for the contact chatter mode in Table 3-3 changes the median or the HCLPF by less than 3%. On the other hand, if only a small amount of data is available in the set, the reduction of the median and increment of HCLPF may be appreciable. For example, if the ASA value of 6.9g is neglected for the unrecoverable mode in Table 5-3 and the method of moments is employed, the median value will decrease by 7% and the HCLPF will increase by 20%. Again in the same data set, if the qualification data are included and the method of maxiumum likelihood is employed, elimination of some of the high data points will reduce the median by up to 13% while the HCLPF will remain unaltered. Furthermore, elimination of additional high data points will reduce the median by up to 34% and increase the HCLPF by 9%. This is due to the limited amount of fragility data and the fair amount of qualification data available in the set.

In summary, although it is recognized that for a limited data base the elimination of some of the high-valued data points may significantly reduce the uncertainties and the median values and appreciably increase the HCLPF, the fragility parameters and the descriptors are calculated based on the entire data set rather than a part of it. It has been judged that the large uncertainty due to the presence of the high-valued data is an inherent characteristic of the equipment. However, the input data are included in the report and the user can seek other combinations of the available data if one so desires.

In addition to the calculated fragility values discussed above, a set of recommended values are also included in this report. The recommended values are based on evaluation of the results obtained from the statistical and probabilistic analyses including the aforementioned sensitivity study.

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1 The HCLPF value is used in the margin studies and the median along with the coefficients of variation is used in the PRA's.

2.4 PRESENTATION PROCEDURE

By applying the methodology discussed above, the test data of four equipment categories, namely, motor control center (including interlock), switchboard, panelboard and power supply, have been compiled and evaluated, and the results are presented in the following chapters. One chapter is devoted to each equipment. The procedure used in presenting the information is similar for each equipment and is described in the following paragraphs.

2.4.1 Data Base, Equipment and Test Description

For each equipment, the size of the data base and the vintage of the test specimens are specified. This information is essential to understand the limitation of the results presented in the report. A generic description of the data base equipment is provided including the geometric and structural data, a list of devices, electrical rating, etc. The techniques used in testing the data base specimens are also discussed for each equipment.

2.4.2 Test Results

The test results are discussed in general terms and many specific results are presented in tables. TRS plots are presented for the highest qualification level and for the deterministically obtained lower-bound fragility levels for significant failure modes of each of the equipment classes. The fundamental frequency range of the test specimens is also included in the text.

A summary of the results from significant test runs is provided in a tabular form for each test specimen. Typically, the highest qualification level and the fragility levels associated with significant failure modes are provided in terms of ZPA and ASA. If applicable and available, the results are presented for various electrical modes, e.g. energized, de-energized. Since the electrical monitoring procedure and criteria are not necessarily uniform in different test programs, such information is also included in the table. Unless otherwise mentioned, the g-levels listed in the table are in the weaker horizontal direction for a possible plant installation configuration.

As mentioned above, only the significant and bounding test runs are discussed in the summary table. If similar qualification and failure levels have been achieved more than once in the test program, such information is not repeated in the table. The g-levels used as input in the statistical analysis are listed separately as discussed in subsequent paragraphs.

2.4.3 Data Analysis

In addition to the summary of the test information, each chapter contains an analysis of the data and describes the important generic observations made in the process of reviewing the test results and evaluating the equipment

performance. The usual failure modes as they occur with a gradual increase of the excitation level are discussed. An attempt is made to group electrical failure modes into a few broad categories, e.g., recoverable, unrecoverable. Structural degradation is considered separately.

The test data for each broad failure mode are statistically analyzed by employing the method discussed in section 2.3 above. Both the input data and the probabilistic fragility results are separately presented in tabular forms. The input data are obtained from the test reports and are not necessarily limited to that listed in the test results summary table discussed in section 2.4.2 above. On the other hand, judgements are used for uniform sampling by excluding the data for certain specimens which do not conform to the same equipment category due to peculiar design characteristics or testing techniques. In any event, the input data table provides a final list of the data used in the statistical analysis.

The failure mode, the TRS indicator, the analysis method and the corresponding median fragility value, the coefficients of variation and the HCLPF value are all presented in the probabilistic fragility results table. If sufficient data are not available for a statistical analysis, judgement is used to arrive at one or more of the fragility parameters and it is so indicated in the table.

2.4.4 Limitations

The evaluation results, both deterministic and probabilistic, presented for each equipment have certain limitations due to vintage, sample size, testing technique and similar other reasons. Therefore, the results should be used with caution. For each equipment, a list of limitations is included for careful use of the information presented in this report.

CHAPTER 3
MOTOR CONTROL CENTER

3.1 INTRODUCTION

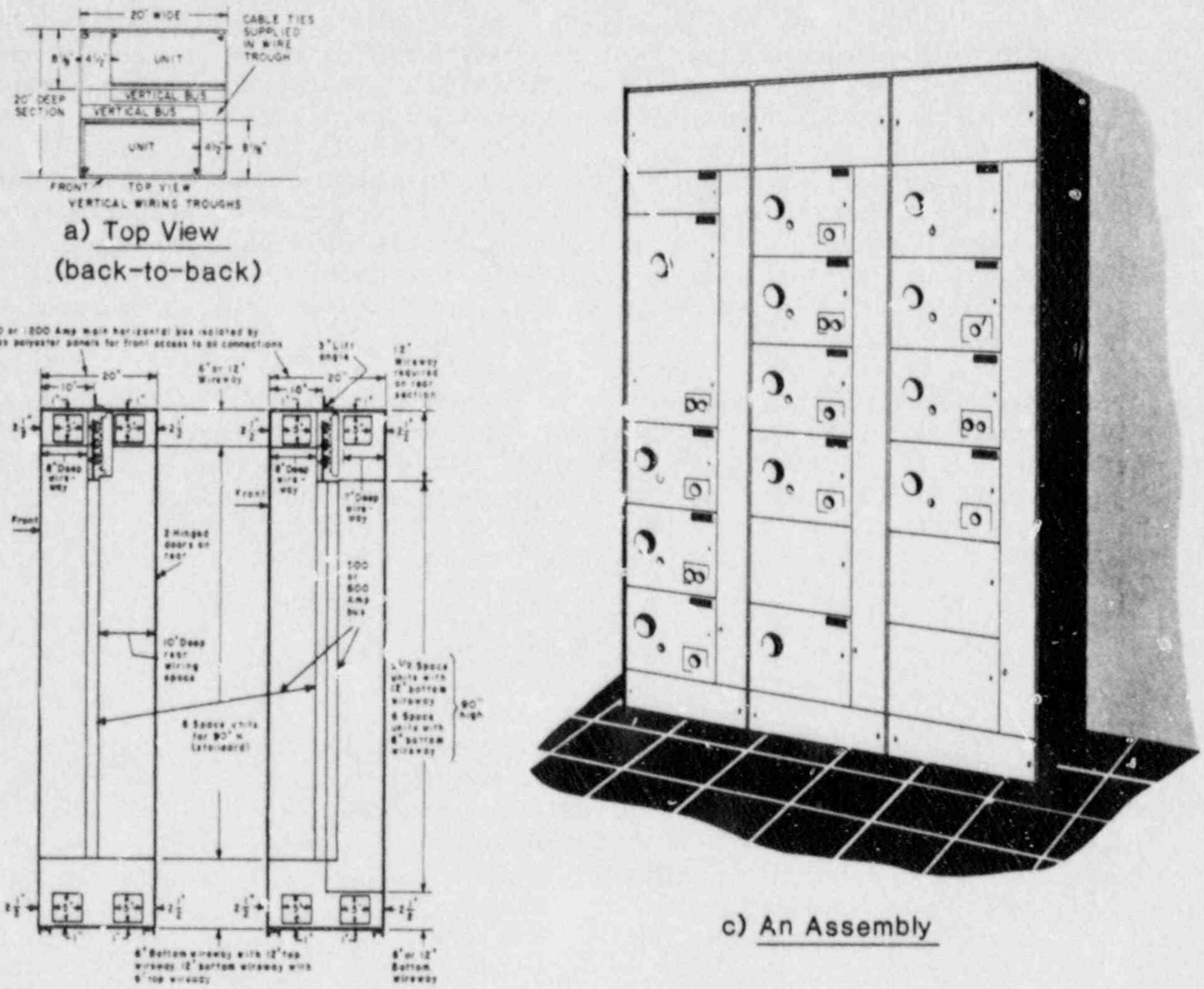
The motor control center, popularly abbreviated as MCC, is a floor-mounted electrical panel used for starting and controlling numerous safety-related equipment. It provides a convenient and economical method of grouping electric motor control, power distribution and other related devices in a centralized location. The cabinet steel structure is pre-engineered to provide modular unit compartments and a great flexibility in the arrangement and type of equipment that can be accomodated. The structure incorporates bus bars, horizontal and vertical wireways, withdrawable plug-in drawer units and necessary incoming and outgoing line facilities. An AC MCC supplies 480V to feed the 480V loads and also has a 480V/120-208V 3-phase transformer and a distribution panel with molded case circuit breakers for supplying power to small 208V and 120V loads. The fragility analysis of the MCC was initiated in Phase I of the Component Fragility Program and the data from several test programs were discussed in the Phase I report [1]. Since then additional test data have been collected in Phase II of this program. The new information has been assembled with the Phase I data and the fragility analysis based on this combined data base is presented in this chapter. The data analysis follows the methodology discussed in Chapter 2.

3.2 DATA BASE

The data base covers test results of nineteen MCC specimens manufactured by five major suppliers (as mentioned above, this includes the data presented in the Phase I report). Eighteen of the specimens were rated 480 VAC, although one of these was tested by use of a 120 VAC power source. The remaining test specimen was rated 250 VDC and for actuation, was powered with either the rated voltage or 120 VDC depending on the component involved. The data base test programs were conducted in the period 1977-85.

3.3 EQUIPMENT DESCRIPTION

A typical bay (also referred to as a frame or a vertical section) measures 90 inches high, 20 24 inches wide and 20 inches deep. Several such bays are attached side-by-side in a typical application to form an MCC assembly (Figure 3-1). Although most data base test specimens consisted of either two or three bays, there are one five-bay, two four-bay and two one-bay specimens in the data base. The usual weight of an MCC is 600-700 pounds per bay including standard devices. However, the data base includes specimens as heavy as 1000 pounds per bay and as light as 1080 pounds for a three-bay cabinet.



a) Top View (back-to-back)

b) Side Views of two designs:
Left: 20" deep section (front mounted)
Right: 20" deep section (back-to-back)

c) An Assembly

Figure 3-1 A Motor Control Center Unit and Assembly

Typically, the structural framework is made of formed steel channels. The sub-frames for the front and rear of each structure are welded. These sub-frames are then bolted to longitudinal members to form the complete frame. Side, rear and roof sheets are mounted with screw fasteners for easy removal. Latchable steel doors providing access to the electrical devices complete the enclosure. The more recent products were strengthened by means of seismic angle and plate stiffeners mostly attached near the base. The MCC in its application is either bolted or welded to the floor through a mounting sill.

In a standard 90-inch structural height, 9 to 12-inch spaces are available at both top and bottom for wiring. The balance of the vertical compartment, 66 to 72 inches, is available for mounting of control devices. Access to the devices and to the wiring system is typically via doors on the front of each plug-in drawer unit, and via removable panels at the top, bottom and rear of the MCC assembly.

Motor starters with interlocks (also referred to as auxiliary contacts) and circuit breakers or fusible switches, all of various combinations, are the essential devices in an MCC. Typically an MCC contains some or all of the following additional devices:

Relays
Breaker Panels
Power Distribution Transformers
Selector Switches
Pushbutton Operators
Indicating Lights
Current Transformers
Current Transducers
Fuse Blocks
Current Limiters
Reset Assembly
Terminal Blocks
Terminal Boards
Stab Assembly
Door Interlock

3.4 TEST DESCRIPTION

Biaxial multifrequency vibration inputs were applied for fifteen specimens in the data base; triaxial inputs were used for the remaining four. The MCC specimens were mounted on the shake table and connected only at the base except for two specimens which were supported both at the base and on top. Most test specimens were mounted with four bolts per bay; others were welded. One specimen was tested with 2 bolts per bay. The minimum bolt diameter was 1/2 inch. The electrical cable entrance was simulated at least in one test program.

Representative devices were installed in all test specimens. Selective devices were monitored for ascertaining electrical continuity and detecting change of state and contact chatter. Although for most specimens, the contact chatter was monitored for a duration of 2 milliseconds (ms) or greater, for some specimens in the data base, the limiting duration varied from 1/2 ms to 20 ms. The devices were monitored for electrically energized (E), de-energized (DE) and transition (E-DE, E-DE-E, DE-E-DE) states.

3.5 TEST RESULTS

The fundamental frequencies in both the horizontal directions at a sine sweep level of approximately 0.2g were observed to be in the range of 4-9 Hz for welded or bolted (with 4 bolts per bay) floor-mounted cabinets. With the addition of bays, the frequency in the side-to-side (SS) direction increased, although the front-to-back (FB) frequency remained almost unaffected. Only one specimen in the data base exhibited an FB frequency as high as 10-11 Hz. The FB frequency of a cabinet decreased from 5 Hz to 3.5 Hz when the number of mounting bolts were changed from four to two per bay. As expected, the top support increased the natural frequency sub-stantially, namely from 5 Hz to 12 Hz for one specimen.

The lower-bound horizontal TRS plots are shown in Figure 3-2. Curve 2A represents the lower-bound envelope of the highest qualification levels in the horizontal direction. The test data indicate that at about the same acceleration level, the auxiliary contact of a starter and the relays exhibited contact chatter such that curve 2A can also be considered as the lower-bound fragility level. The lowest vibration level at which an auxiliary contact changed state is slightly above curve 2A. However, the starter main contact did not change state below the vibration level corresponding to curve 2B. Breaking of base metal, mounting bolts and/or mounting welds initiated at the level of curve 2C for a regular seismically designed MCC cabinet. The corresponding level for a cabinet strengthened with seismic plate and angle stiffeners is represented by curve 2D. The vertical TRS plots are shown in Figure 3-3. A summary of the test results including the highest qualification levels and the fragility information is presented in Table 3-1.

3.6 DATA ANALYSIS

The test data discussed above and summarized in Table 3-1 have been evaluated based upon the available information in the test reports and discussions with experts from the manufacturing companies. The results are presented in the following subsections.

3.6.1 Natural Frequency

The frequency data discussed in section 3.5 are the fundamental frequencies of the overall MCC structures which can be considered as vertical column members. However, the various structural elements in an MCC, such as sheet

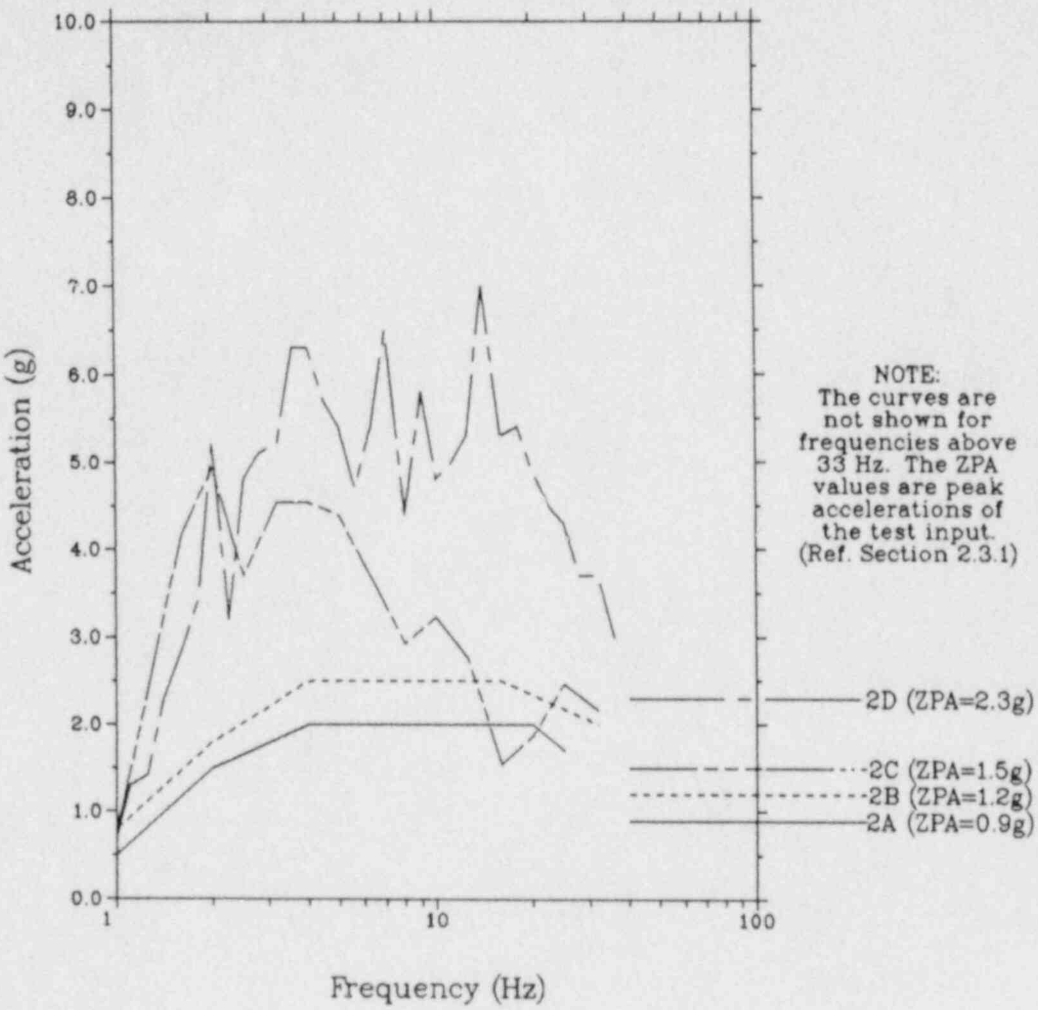


Fig. 3-2 Horizontal TRS @ 2% Damping – Motor Control Center

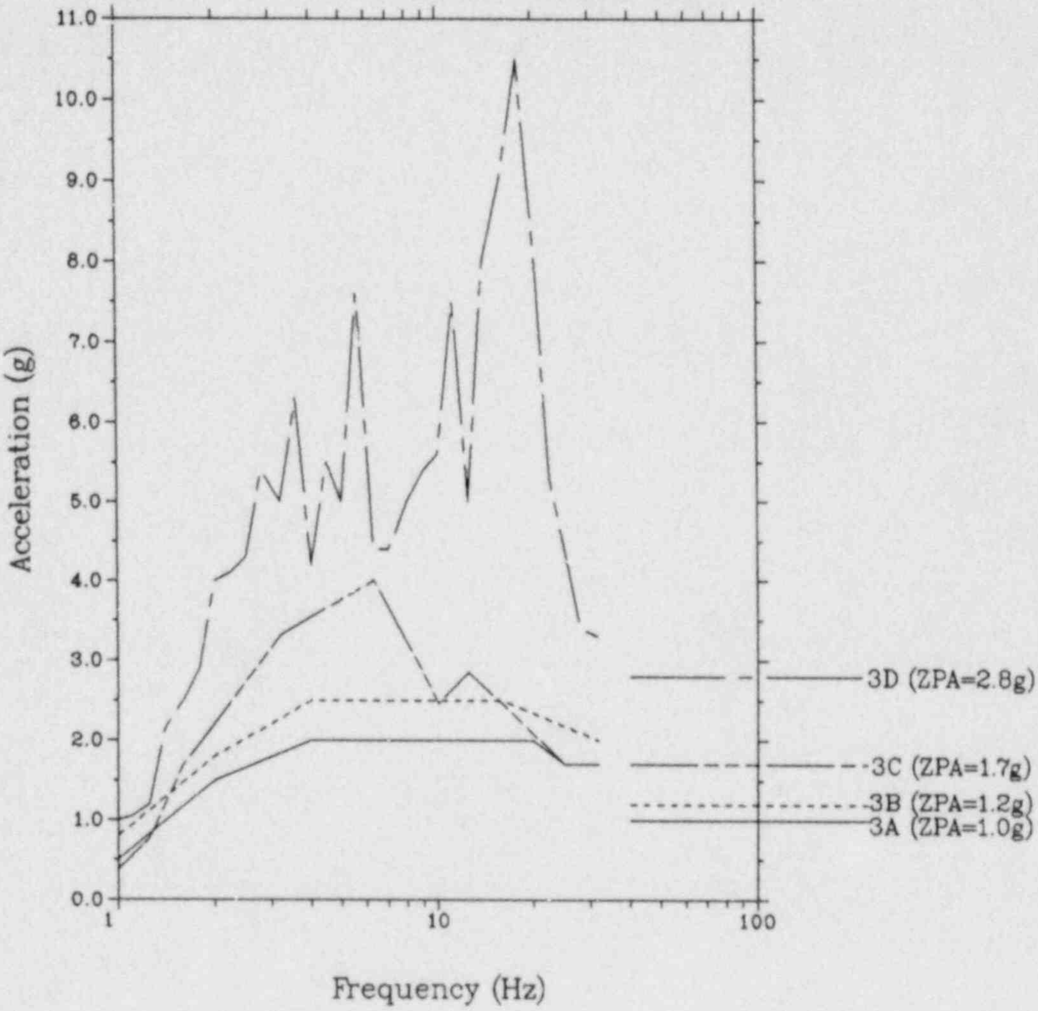


Fig. 3–3 Vertical TRS @ 2% Damping – Motor Control Center

TABLE 3-1
Summary of Motor Control Center Test Results

Test Specimen No.	Electrical Functions Monitored	ZPA in "g"	ASA @ 2% in "g"	Electrical State	Test Results
1	change of state contact chatter	1.0	2.1	DE	Starter chatter 60ms*, relay chatter > 0.5ms
		1.0	2.0	E	Note 1
		1.3	3.4	DE	Notes 1 and 2
2	change of state contact chatter > 1ms	1.5	3.3	E	No malfunction
		1.1	3.2	DE	Starter chatter up to 30 ms*
3	change of state contact chatter > 5ms	2.1	5.6	E and DE	Some faulty devices were replaced (before this test); assembly weld cracked
4	change of state contact chatter	1.0	2.1	DE	Starter chatter 17ms*
		1.0	2.1	E	Starter chatter > 0.5ms*
		1.2	2.5	E	Notes 1 and 2
		1.6	3.6	DE	Note 1
5	change of state contact chatter > 2ms	1.3	2.7	DE	No malfunction
		1.5	2.8	DE	Starter chatter*

TABLE 3-1 (cont.)
Summary of Motor Control Center Test Results

Test Specimen No.	Electrical Functions Monitored	ZPA in "g"	ASA @ 2% in "g"	Electrical State	Test Results
6	change of state contact chatter > 20ms	3.3	4.6	DE-E	Starter chatter > 10ms* Timing relay either delayed in timing out or did not time out in energized tests
7	change of state contact chatter > 0.5ms	0.9	2.0	DE	No malfunction
		1.0	2.1	DE	Starter chatter*
		1.1	3.7	E	Starter chatter*
		2.2	4.6	E	Notes 1 and 2
8	change of state contact chatter > 5ms	2.1	5.6	E and DE	Some faulty devices were replaced (before this test); assembly weld cracked
9	change of state contact chatter > 1ms	1.5	3.3	E	No malfunction
		1.1	3.2	DE	Starter chatter 30ms*

TABLE 3-1 (cont.)
Summary of Motor Control Center Test Results

Test Specimen No.	Electrical Functions Monitored	ZPA in "g"	ASA @ 2% in "g"	Electrical State	Test Results
10	change of state contact chatter > 0.5ms	0.9	2.6	E	No malfunction
		0.9	2.6	E (voltage set at 85% then reduced to 60%)	Starter chatter* and relay chatter
		1.1	3.3	E	Starter chatter 100ms*
		1.3	3.4	DE	No malfunction
		2.3	5.6	DE	Starter chatter*; assembly bolts broke
11	change of state contact chatter	2.1	5.6	DE	No malfunction
		2.4	7.4	DE	Starter chatter 8ms*
12	change of state contact chatter > 0.5ms	1.0	2.1	DE	Starter chatter 40 ms*
		1.0	2.1	E	Starter chatter*
		1.6	4.0	E	Note 1
		2.4	5.0	DE	Note 2

TABLE 3-1 (cont.)
Summary of Motor Control Center Test Results

Test Specimen No.	Electrical Functions Monitored	ZPA in "g"	ASA @ 2% in "g"	Electrical State	Test Results
13	change of state contact chatter > 1ms	1.3	2.7	DE	No malfunction
		1.5	2.8	DE	Starter chatter*; base metal fractured
		2.0	3.4		Assembly bolt snapped
14	change of state contact chatter > 5ms	1.1	2.0	DE	No malfunction
		1.4	2.6	E	No malfunction
		1.4	2.7	DE	Chatter 10ms
		2.3	3.8		All four corners broke away from base; high g-values at high frequencies
15 (note 3)	output variations contact chatter	1.5	2.0	E	Starter chatter 8ms*
		3.0	3.2	DE	No malfunction

TABLE 3-1 (cont.)
Summary of Motor Control Center Test Results

Test Specimen No.	Electrical Functions Monitored	ZPA in "g"	ASA @ 2% in "g"	Electrical State	Test Results
16	change of state contact chatter > 2ms	0.6	1.2	E	No malfunction
		0.6	1.2	DE	No malfunction
		1.3	2.8	E-DE	Chatter
17	change of state contact chatter > 5ms	2.1	5.6	E and DE	Some faulty devices were replaced (before this test); assembly weld cracked
18	change of state contact chatter > 0.5ms	1.2	3.2	DE	No malfunction
		1.3	3.7	E-DE-E	Note 2
19a (note 4)	contact chatter change of state	1.0	2.9	DE	No malfunction
		1.3	4.1	DE	Starter chatter 9ms*, relay chatter 5ms
19b (note 4)	contact chatter change of state	1.6	4.1	DE	Starter chatter*
		1.9	6.5	-	Frame weld crack

TABLE 3-1 (cont.)
Summary of Motor Control Center Test Results

Test Specimen No.	Electrical Functions Monitored	ZPA in "g"	ASA @ 2% in "g"	Electrical State	Test Results
19c (note 4)	contact chatter change of state	1.5	4.8	DE	No malfunction
		1.5	4.8	DE	Starter chatter 3ms*, relay chatter 2ms
19d (note 4)	contact chatter change of state	1.7	3.7	DE	No malfunction (chatter < 2ms)
		2.1	7.7	DE	Starter chatter 19ms*; relay chatter 10ms; weld crack, plastic deformation
		2.2	8.1	-	Substantial damage of corners

NOTES:
1. Starter auxiliary contact changed state
2. Starter main contact load changed state
3. VDC MCC, top supported
4. a. 4 mounting bolts per bay, top supported
   b. 4 mounting bolts per bay, free standing
   c. 2 mounting bolts per bay, free standing
   d. 4 mounting bolts per bay, free standing, diagonal braces

LEGEND: E - Energized DE - De-energized ASA - Average Spectral Acceleration

* Auxiliary contact or main contact or both

metal panels, subpanels and the draw-out units, have their individual natural frequencies. The electrical devices are typically mounted on such sub-panels and are subject to the vibration level locally amplified corresponding to the natural frequencies of the supporting members. Moreover, the devices dynamically interact with these supports in producing the local frequencies and amplification values of the system. Thus, the time history that a device experiences depends to a great extent on the local structural layout and the associated dynamic phenomena. Since most devices are more sensitive to excitation in one frequency range than in other frequency ranges, the functional operability of a device depends on the local mounting conditions. This has been verified with the test data which indicate that a change in the frequency content of the input time history, changes the chattering behavior of a device. Test data also revealed that a change in location and/or orientation on the same panel affects the device functionally.

3.6.2 Failure Modes[1]

In general, as the vibration input level increased, the auxiliary contacts of motor starters were observed to malfunction first by exhibiting contact chatter. For most specimens, this occurred in the electrically de-energized state. However, for at least two specimens including the DC MCC, the chatter was first observed in the energized state, and for several other specimens chattering initiated at about the same vibration level for both the energized and the de-energized states. The normally closed (NC) contact was more vulnerable than the normally open (NO) contact in the de-energized state. The main contact of the motor starter was also observed to indicate chatter. Another malfunction exhibited by motor starters was a "change of state" of either the auxiliary contact or the main contact. For the latter case, the starter load either changed state inadvertently or did not change state on command during the test run. The change of state occurred in both the energized and the de-energized states. Dropping out of the starter load or its erratic behavior was also observed during some test runs.

Relay chatter was observed first for the NC and then for the NO contact, both in the de-energized state for the AC MCC's. Timing delay relays were found to fail in the energized state.

Structural problems of various types were also observed in the data base. Loosening of screws in contactor points was observed at a relatively low vibration level which was comparable to electrical malfunction levels discussed

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1 In this report, the term "failure" is used to indicate certain changes in the equipment performance that may be detrimental to the equipment functionality and/or structural integrity as described in Section 3.6.2. It is recognized that in certain applications some of these performances may be acceptable.

above. In one instance, such a loosening triggered an inadvertent change of state of the motor starter load. At a slightly higher level, self-tapping screws loosened up and, in one instance, broke. Loosening of mounting bolts was observed at about the same test level regardless of initial torque. With further increase of the vibration input, damage of the cabinet structure and the mounting means was observed. The structural damage initiated with deformation and cracking of the base metal, usually the corner members, and cracking of mounting welds where welding was used for mounting. Eventually, breaking of the frame members and connections at the base was observed. It should be noted that in most test programs a large number (e.g. 30) of test runs were performed on the same MCC enclosure. Some structural elements reached the inelastic strain state during these runs such that these elements quickly underwent plastic fatigue resulting in plastic deformation, cracks and eventual breaking. However, loosening of bolts, whenever this happened, was observed at an early stage of the tests.

In summary, the various failure modes discussed above can be enumerated as follows in the order they mostly appeared with increasing test levels:

- Motor starter: NC auxiliary contact chatter - mostly DE, sometimes E
- Motor starter: NO auxiliary contact chatter - mostly DE, sometimes E
- Relay chatter
- Motor starter: main contact chatter
- Motor starter: change of state of auxiliary contact - E, DE
- Loosening of screws and mounting bolts
- Snapping out of self-tap g screws
- Motor starter: change of state of main contact - E, DE (inadvertent change of state or no change of state on command)
- Motor starter load - dropping out and erratic behavior
- Structural damage, level 1 - plastic deformation, cracking and tearing of base metal especially in corner members.
- Structural damage, level 2 - breaking of panel bolts, mounting bolts and mounting welds; breaking and physical separation of cabinet structural members

For the DC MCC, the contact chatter initiated at the energized state.

It should be noted that the failure sequences described above are not necessarily the same for all MCC's. In addition, the extent of the structural damage depends on individual configurations, e.g. size, weight, pull box, cables.

3.6.2.1 Consistency of Failure Modes

The structural failure modes have been observed to be consistent for a given specimen in the sense that the same failure mechanism recurs in test runs with similar vibration inputs. However, the structural fragility level may vary from one specimen to the other, even for the same general MCC model series number, due to the individual configurations as mentioned above. Electrical failure modes for some specimens followed the expected trend that for a given specimen the failure occurs and the severity increases with an increase of the vibration level. However, there are other specimens for which an electrical malfunction occurred and then disappeared at similar or even higher vibration levels for different test runs in the same test program. For example, the following observations have been made regarding the consistency of contact chatter of a motor starter assembly containing auxiliary contacts:

1. Simply increasing the g-level the chatter may or may not occur. In one instance, after chatter had occurred at a certain vibration level, the chatter disappeared completely when the g-level was increased.

2. The duration of chattering is not uniformly dependent on the g-level. For example, in one test program the chatter duration of a particular contact increased four times although the corresponding TRS levels remained almost identical. In some other test runs, the chatter duration reduced to about a half in spite of more than a two-fold increase in the TRS level. Note that in all these test runs the ratios of the ASA to ZPA levels were comparable. Similar phenomena were observed in other test programs.

3. The relative chatter durations between two contacts in the same MCC specimen are not consistent for different test runs as evidenced from the following test results:

	Run No. 1	Run No. 2
Contact No. 1	25ms	7ms
Contact No. 2	16ms	60ms

For one contact, the chatter duration was reduced to less than a third; whereas, for the other contact it increased about four times. The vibration inputs in both runs were almost identical.

Based upon the above observations, one or more of the following scenarios can be hypothesized:

1. Contact chatter is sensitive not only to the frequency content but also to the acceleration level of the vibration input in that by increasing the g-level, a contact may be made to chatter; however, a further increase in g-level, all other conditions remaining unaltered, may lead to disappearance of the chatter.

2. A test response spectrum is not sufficient to measure the vibration input that causes a contact to chatter. For example, the precise occurrence of the peak g-level may control the chatter phenomenon, whereas this information is missing in the TRS data. In other words, there may be a variation in chattering depending on whether the peak acceleration occurs after 10 seconds or 20 seconds in the vibration input.

3. At or close to the fragility level, the parameters of the contact chatter phenomenon, in particular, its rate of occurence and duration, are quite variable. In other words, when the fragility level or a level close to it is reached, it is arbitrary whether or not chattering will occur and, if it does, to what duration.

4. There are additional factors involved, other than those discussed above, that are required for a complete understanding and quantification of the contact chatter phenomenon.

3.6.3 Fragility Estimates

For the purpose of statistical analyses, the failure modes discussed above have been divided into three broad categories.

1. Contact chatter, load (voltage) drop out.

2. Change of state:

   a) Starter auxiliary contact
   b) Starter main contact

3. Major structural damage, e.g. breaking away of frame members and connections at the base

The data associated with each of the above failure categories have been evaluated for determination of the respective fragility parameters. Sufficient test results have been found in the data base for performance of a separate statistical analysis corresponding to each of the first two failure categories. However, for the third failure category, the data have been considered inadequate for mathematical computation of the fragility parameters. Judgements in conjunction with the experience of the manufacturers have been used in estimating the fragility parameters for this category. For all three cases, the

respective fragility descriptors have been computed by use of the parametric values following the methods discussed in chapter 2. The fragility parameter and descriptor values corresponding to various failure categories for AC MCC's are shown in Table 3-2.

For uniformity of the statistical samples, only free-standing AC MCC's with four mounting bolts or with adequate mounting weld and with proper electrical monitoring during testing have been considered in the above analysis. Consequently, the data for specimen numbers 6, 15, 19a, 19c and 19d of Table 3-1 are not included. The test data used as inputs in the analysis are listed in Table 3-3. As discussed in Section 2.3.2, the entire data set has been used in the analysis. Table 3-4 describes the range of the MCC specimens covered in the analysis.

Since in the data base there is only one DC specimen which was subjected to fragility testing, no attempt has been made to provide fragility parameters or descriptors for DC MCC's. However, the test g-levels for this DC specimen corresponding to the first failure category (i.e. contact chatter) are available in Table 3-1.

3.7 MOTOR STARTER AUXILIARY CONTACT OR INTERLOCK

As it appears from the above discussion on failure modes, the auxiliary contacts of motor starters are the weak link of a typical MCC in an earthquake environment. Therefore, a special discussion on this device has been considered appropriate in the context of fragility analysis of the MCC. A description of the device, its function in a starter assembly and its seismic capacity are presented in this section.

3.7.1 Description

The device is a small flat modular kit containing electrical contacts screwed on a plate form (Figure 3-4). The contact buttons are usually butt welded to a copper plate. The kit may consist of one NO contact or one NC contact or both (i.e. one NO and one NC) contacts. Auxiliary contacts are furnished in the basic block design or as an adder block. An insulating shield is provided for use between each auxiliary contact unit and the starter. In a typical application each auxiliary contact is rated 10 amp and is suitable for either side or top mounting on the starter unit.

Depending on its application, an auxiliary contact can be referred to as a "standard holding interlock" or an "extra auxiliary contact." The term "electrical interlock" is also sometimes used in the industry. There is another kind of interlock known as a mechanical interlock used for reversing

TABLE 3-2
MCC Fragility Analysis Results[1]

Failure Mode	Indicator	Method[2]	Median in "g"	β_u	β_r	HCLPF in "g"
Contact chatter, voltage drop-out	ZPA	1	1.3	0.18	0.10	0.8
		2	1.3	0.24	0.09	0.8
		RECOMMENDED	1.3	0.20	0.10	0.8
	ASA @ 2%	1	2.9	0.25	0.06	1.8
		2	3.1	0.31	0.06	1.7
		RECOMMENDED	3.0	0.27	0.06	1.7
Change of state of starter auxiliary contact	ZPA	1	1.5	0.07	0.16	1.0
		2	1.9	0.26	0.14	1.0
		RECOMMENDED	1.7	0.17	0.15	1.0
	ASA @ 2%	1	3.5	0.04	0.19	2.4
		2	4.5	0.34	0.18	2.0
		RECOMMENDED	4.0	0.20	0.18	2.1
Change of state of starter main contact	ZPA	1	1.6	0.32	0.07*	0.9
		2	2.7	0.44	0.09*	1.1
		RECOMMENDED	2.1	0.33	0.07	1.1
	ASA @ 2%	1	3.7	0.27	0.05*	2.2
		2	7.0	0.53	0.11*	2.4
		RECOMMENDED	5.4	0.42	0.08	2.4
Structural damage, level2[3]						
a) without seismic stiffeners	ZPA		2.5*	0.20*	0.06*	1.6
	ASA @ 2%		5.0*	0.20*	0.06*	3.2
b) with seismic stiffeners	ZPA		2.9*	0.20*	0.06*	1.9
	ASA @ 2%		7.0*	0.20*	0.06*	4.6

1. These results are applicable only within the limitations described in section 3.8
2. Methods: 1. Method of Moments
   2. Method of Maximum Likelihood
3. For a description of the structural damage, level 2 refer to Section 3.6.2

* Based on judgement

TABLE 3-3
Input Data for Statistical Analysis - MCC

Failure Mode	ZPA in "g" Qualification	ZPA in "g" Fragility	ASA in "g" @ 2% Damping Qualification	ASA in "g" @ 2% Damping Fragility
Contact	0.9, 0.9, 1.1	0.9, 1.0, 1.0	2.0, 2.0, 2.6	2.1, 2.1, 2.1
Chatter	1.2, 1.3, 1.3	1.0, 1.0, 1.0	2.7, 2.7, 3.2	2.1, 2.1, 2.2
	2.1, 2.1, 2.1	1.0, 1.1, 1.1	5.6, 5.6, 5.6	2.2, 2.2, 2.2
	2.4	1.1, 1.1, 1.1	5.6,	2.2, 2.2, 2.2
		1.1, 1.1, 1.1		2.3, 2.3, 2.3
		1.1, 1.1, 1.1		2.3, 2.6, 2.7
		1.1, 1.1, 1.1		2.8, 2.8, 2.8
		1.1, 1.1, 1.1		2.8, 3.0, 3.0
		1.1, 1.1, 1.1		3.0, 3.0, 3.0
		1.2, 1.2, 1.2		3.1, 3.2, 3.2
		1.2, 1.3, 1.4		3.2, 3.2, 3.2
		1.5, 1.5, 1.5		3.2, 3.3, 3.3
		1.5, 1.5, 1.5		3.3, 3.3, 3.4
		1.5, 1.5, 1.5		3.5, 3.5, 3.6
		1.5, 1.6, 1.6		3.7, 3.7, 3.7
		1.6, 1.7, 1.7		3.7, 3.7, 3.7
		1.8, 1.8, 2.4		4.1, 4.9, 7.4
Auxiliary	1.1, 1.1, 1.2	1.0, 1.2, 1.3	2.3, 2.3, 3.0	2.0, 2.5, 3.2
Contact	1.2, 1.5, 1.5	1.4, 1.4, 1.5	3.0, 3.0, 3.1	3.4, 3.5, 3.6
Change	1.6, 1.8, 1.8	1.5, 1.5, 1.6	3.2, 3.7, 3.7	3.6, 3.6, 3.6
of	2.1, 2.1, 2.1	1.6, 1.6, 1.6	3.7, 5.6, 5.6	3.7, 3.7, 3.7
State	2.1, 2.2, 2.4	1.7, 1.7, 1.7	5.6, 5.8, 7.5	3.8, 4.0, 4.0
	2.5	1.8, 2.0	7.9	4.1, 4.6
Main	1.0, 1.1, 1.1	1.2, 1.3, 1.3	2.0, 2.3, 3.0	2.5, 3.4, 3.7
Contact	1.2, 1.5, 1.5	2.2, 2.4	3.0, 3.0, 3.1	4.6, 5.0
Change	1.6, 1.6, 1.8		3.2, 3.7, 3.7	
of	1.8, 2.1, 2.1		3.7, 4.0, 5.6	
State	2.1, 2.1, 2.2		5.6, 5.6, 5.8	
	2.4, 2.5		7.5, 7.9	

TABLE 3-4
Range of MCC Test Specimens included in the Statistical Analysis

No. of Bays	Size WxDxH (inches)	Approximate Weight (lbs)	Test Mounting
3	20 (D)	2000	12 bolts
3	64 x 20 X 92	1700	weld
2	50 x 26 x 92	1200	weld
2	40 x 20 x 92	1600	weld
2	40 x 20 x 92	1200	8 bolts
3	60 x 20 x 92	1700	12 bolts
3	60 x 20 x 9C	1700	weld
4	84 x 20 x 91	-	16 bolts
4	80 x 21 x 90	2000	16 bolts
2	40 x 21 x 90	800	8 bolts
2	48 x 21 x 90	1600	8 bolts
2	48 x 20 x 90	1600	weld
2	40 x 20 x 92	1000	weld
3	60 x 21 x 90	1100	12 bolts

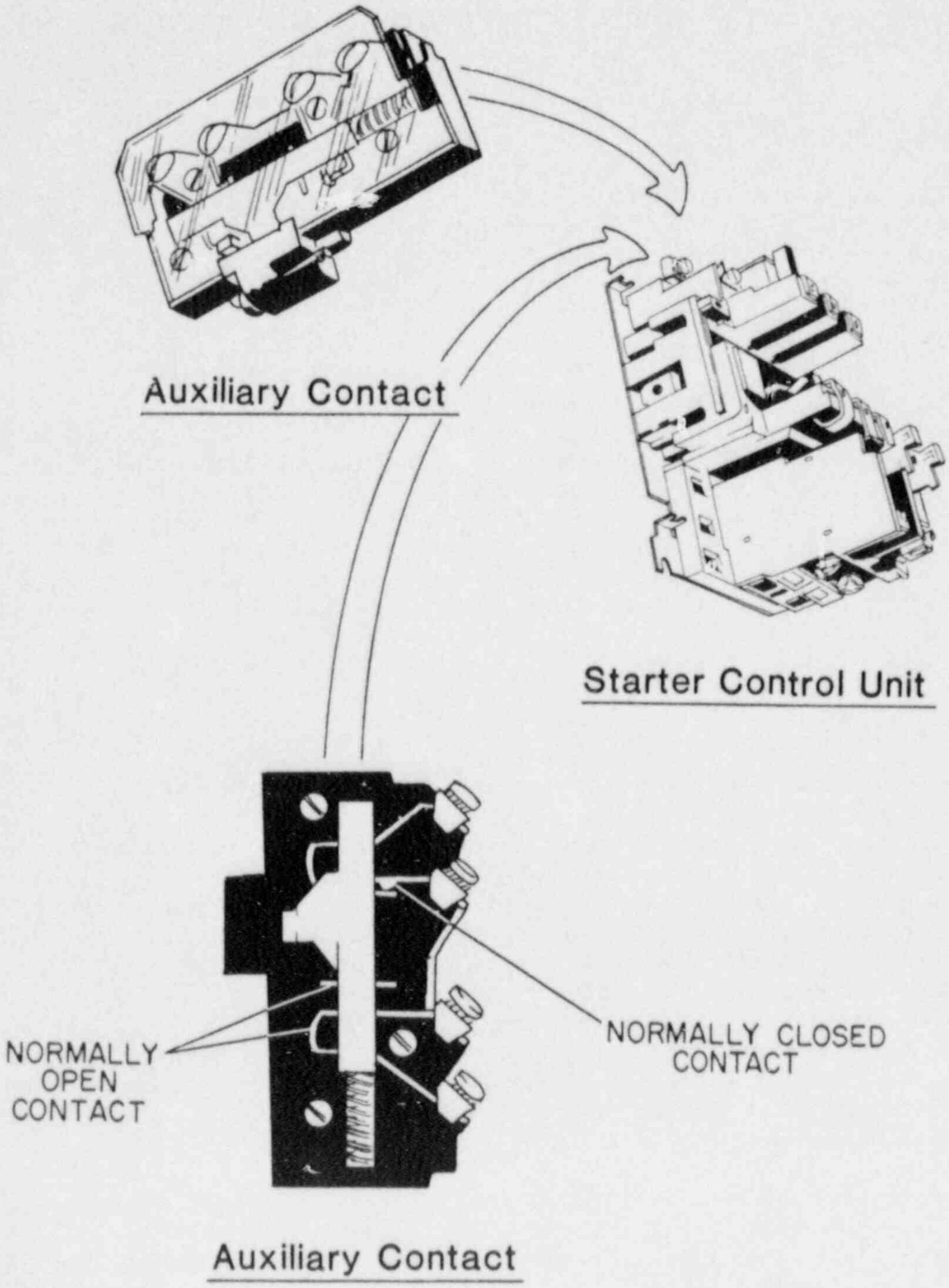

Figure 3-4 An Auxiliary Contact (Interlock) - Two Views

controllers. The kit contains the component necessary to mechanically interlock two magnetic contactors or starters so that one does not pick up until the other has dropped out. The mechanical interlocks are not a subject of discussion in this chapter and in the data base there is no indication of malfunction of a mechanical interlock.

3.7.2 Function

Auxiliary contacts improve the versatility of magnetic starters by producing additional control circuits to perform a variety of tasks without adding to the width of the starter. The kits make it easier to add contacts and to perform one or more of the following functions:

- To energize accessory equipment such as indicating lights
- To control sequencing of other motor starters
- To plug-stop motors, when the auxiliary contacts are used in conjunction with a standard reversing starter and a plugging switch

Note that chattering of an auxiliary contact in performing the first function above may not have any safety implication. However, if the contact performs any or both of the other two functions, chattering may have significant safety consequences.

3.7.3 Test Results

Fragility test results of seven auxiliary contact specimens manufactured by three major suppliers have been studied. In each case, the specimen was tested as part of a motor starter. Six of these motor starters were tested while installed in motor control center cabinets and one was tested separately being mounted on a rigid fixture. Each specimen had both NO and NC contacts. The NC contacts experienced chattering (2ms and greater) for all seven specimens; the NO contact exhibited chattering, almost simultaneously with the NC contacts, for three specimens. Multi-axis vibration inputs were applied to all specimens except that single-axis input was used for the separately tested specimen. Since the contact chatter phenomenon is judged to be dependent on theuniaxial input, no reduction factor was used on the results of the single-axis test while compared with the rest. Note that the single-axis test results werecomparable to the multi-axis results.

The controlling horizontal TRS levels at the device locations are shown in Figure 3-5. Curve 5A is the lower-bound of the passing levels. At about the same testing level, one auxiliary contact was observed to chatter and, as such, this curve can also be considered as the lower-bound fragility level. Note that a specimen in the data base was observed to pass a test level as high as that of curve 5B.

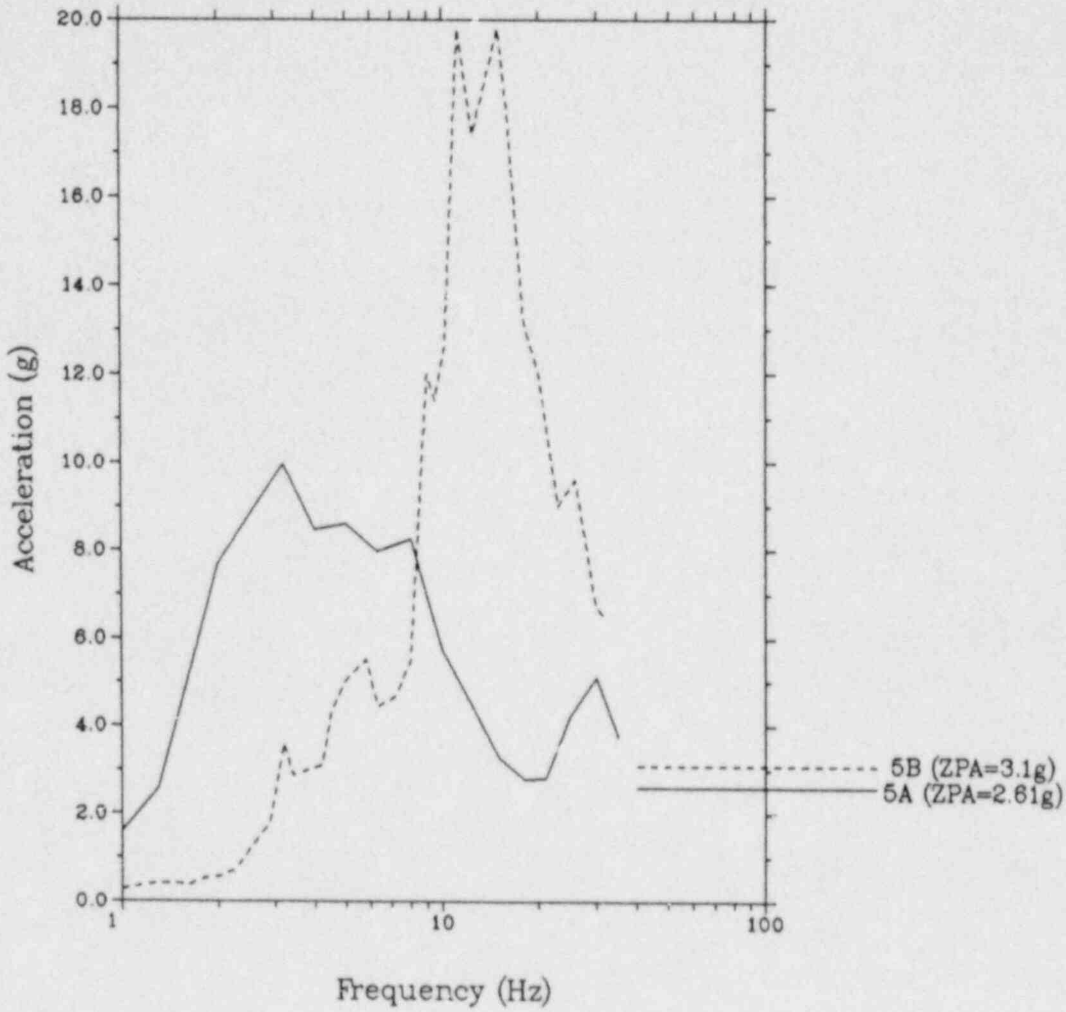

Fig. 3-5 Horizontal TRS @ 2% Damping - MCC Starter Auxiliary Contact

3.7.4 Data Analysis

A statistical fragility analysis of the test data has been performed for the auxiliary contact by employing the methodology discussed in Chapter 2. The results corresponding to the chatter failure mode are presented as follows:

	ZPA in "g"	ASA in "g" @ 2%	
Median	3.3	9.1	
β_u	0.14	0.28	
β_r	0.04*	0.07*	*Based on judgement
HCLPF	2.4	5.6	

Regarding the cause of chattering at a relatively low vibration level, one expert engineer associated with testing of several MCC's believes that the movement of the starter contact carriage causes the auxiliary contacts to chatter. With a relatively high mass and a low spring stiffness, in a seismic environment, the contact carriage experiences a larger movement which the auxiliary contact spring cannot accommodate. This results in chattering of the auxiliary contact.

In one instance, loosening of connecting screws of the auxiliary contacts initiated a chatter which disappeared once the screws were tightened. However, the chatter reappeared at a higher vibration level possibly due to the contact carriage movement phenomenon described above.

3.8 LIMITATIONS

The fragility results presented above are applicable provided the following limitations are satisfied:

- The MCC is manufactured after 1977
- The equipment is installed per test mounting described in paragraph 4.4 and Table 3-4
- The equipment types and electrical ratings are compatible to that described in paragraphs 3.2 and 3.3 and Table 3-4
- In the data base test programs, the relay chatter was preceded by the motor starter chatter. However, in order to ensure applicability of the above results in the presence of any type of relay, one should reconcile the relay qualification with the relay fragility data.

3.9 CONCLUSIONS

The fragility level of an MCC is, for most applications, controlled by chattering of motor starter auxiliary contacts or interlocks. However, an MCC typically contains several controlling relays which conceivably may chatter at a lower vibration level. Based on an on going study of relays, it appears that some of these relays may chatter at a lower vibration level. Therefore, screening of relays is recommended in using the fragility data presented above. There are sporadic instances of other relay problems in the data base. For example, in one test program, none of the timing delay relays performed its intended function even at the lowest vibration level. In another test program, the test report mentions that certain faulty devices were replaced during the tests. Such occasional problems are probably covered by the uncertainty band in the statistical analysis. However, for qualification purposes, one should carefully screen out weak or faulty devices.

The MCC data base is considered adequate for the generic fragility analysis presented in this chapter. However, if any improvement of the g-values is needed, a further study of the behavior of auxiliary contacts in a seismic environment should be undertaken. In addition, the data base covers MCC's manufactured and tested since 1977. It has been observed that the more recent MCC models were structurally improved by the addition of stiffeners. One notable improvement is the addition of structural members, e.g. plates and angles at the base, especially in bolted connections. Therefore, if the results discussed in this chapter need to be applied to earlier products, further research would be required.

CHAPTER 4
SWITCHBOARD

4.1 INTRODUCTION

The switchboard is a floor-mounted Class IE electrical distribution panel. The test data for switchboards are discussed and the fragility estimates are presented in this chapter. The data analysis follows the methods described in Chapter 2.

4.2 DATA BASE

The data base covers test results of six switchboard specimens from two major manufacturers. Test data for both 125 VDC and 480-600 VAC, circuit-breaker-type and fusible-disconnect-switch-type switchboards are included in the data base. All test programs in the data base were conducted between 1976 and 1983.

4.3 EQUIPMENT DESCRIPTION

The switchboard is a free-standing, vertical cabinet designed as a protective enclosure to house components and devices necessary for the interconnection, termination, identification, isolation and separation of controls and instrumentation associated with the safe operation of the reactor system (Figure 4-1). Circuit breakers and/or disconnect switches are the major devices contained in a switchboard. Relays and transducers are also sometimes included in a switchboard. A typical single-bay switchboard is 38 inches wide, 20 inches deep and 70-90 inches high, and weighs 1000 pounds. A list of the test specimens is provided in Table 4-1. The cabinet enclosure is typically constructed of die-formed, code gage steel members bolted together using formed steel panels and utilizing steel barriers to provide dead-front construction.

4.4 TEST DESCRIPTION

All test programs employed random multifrequency phase-incoherent biaxial vibration inputs, except one program during which triaxial inputs were used. All test samples were welded to the shake table with intermittent welds to simulate the field conditions recommended by the respective manufacturers. In all test programs and in each principal direction at least five OBE-level tests were performed prior to the final SSE and fragility-level tests. For the biaxial test runs, the vertical inputs were at least two-thirds of the corresponding horizontal inputs. However, in the highest level triaxial test run, the vertical input was about one half of the horizontal input. By

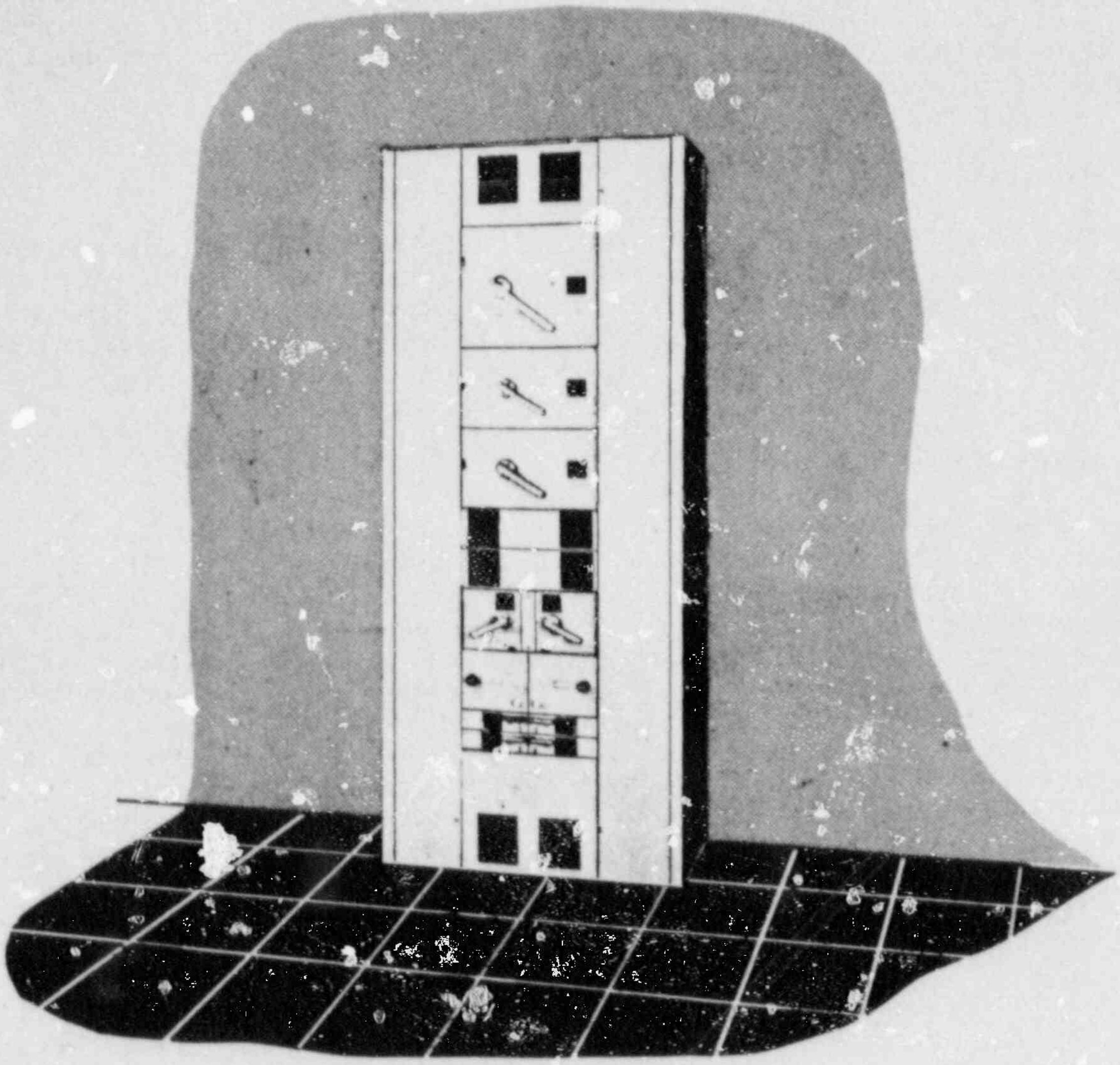

Figure 4-1 A Switchboard Cabinet

TABLE 4-1
Switchboard Test Specimens

Electrical Rating	Size WxDXH (inches)	Approximate Weight (lbs)	Test Mounting
DC	70x50x90	2700	welded
125VDC (application)	80x40x74	-	welded
125VDC (application)	38x17x92	1000	welded
480VAC (application)	38x17x72	1000	welded
600VAC	38x20x90	1000	welded
600VAC	38x20x90	1100	welded

considering the simultaneous second horizontal input, the severity of the triaxial test run has been judged comparable to that of the biaxial tests and the results of the triaxial test have been incorporated into the fragility analysis without application of any scaling factor.

Representative circuit breakers were electrically monitored during the test runs for detection of contact chatter and tripping. Although relays were monitored for operability and detection of contact chatter, most test reports do not address monitoring of relay chatters. Motor starters, wherever used, were monitored for chatter detection.

4.5 TEST RESULTS

The fundamental natural frequencies obtained from accelerometer readings at various locations were observed to vary as follows:

Horizontal	5-9 Hz
Vertical	15-20 Hz

With the increase of the vibration input, the malfunction observed was contact chatter of relays and motor starters whenever these were monitored. In Figure 4-2, curve 2A is a TRS plot which corresponds to chattering of several relays for a duration equal to or greater than 20 milliseconds. A mounting weld broke at the level of curve 2B. Chattering of a motor starter was observed at the level of curve 2C. The circuit breakers maintained electrical continuity during and after all these test runs. The corresponding vertical TRS plots are shown in Figure 4-3.

4.6 DATA ANALYSIS

The test results as discussed above and summarized in Table 4-2, indicate that in the fragility test of a switchboard, relay chatter is expected to be the initial electrical malfunction. Since many switchboards do not contain relays and since the relay chatter phenomenon is a generic issue, the switchboard fragility will be discussed here with reference to other malfunctions and the relay chatter will be generically addressed in a separate report.

Another electrical malfunction is the contact chatter of a motor starter. Motor starters are used with circuit breakers or fusible disconnects to provide a compact and convenient method of combining power distribution and control circuits in one location. Since the use of such modular-design switchboards containing motor starters are limited, the motor starter chattering problem does not apply to the majority of the switchboard population.

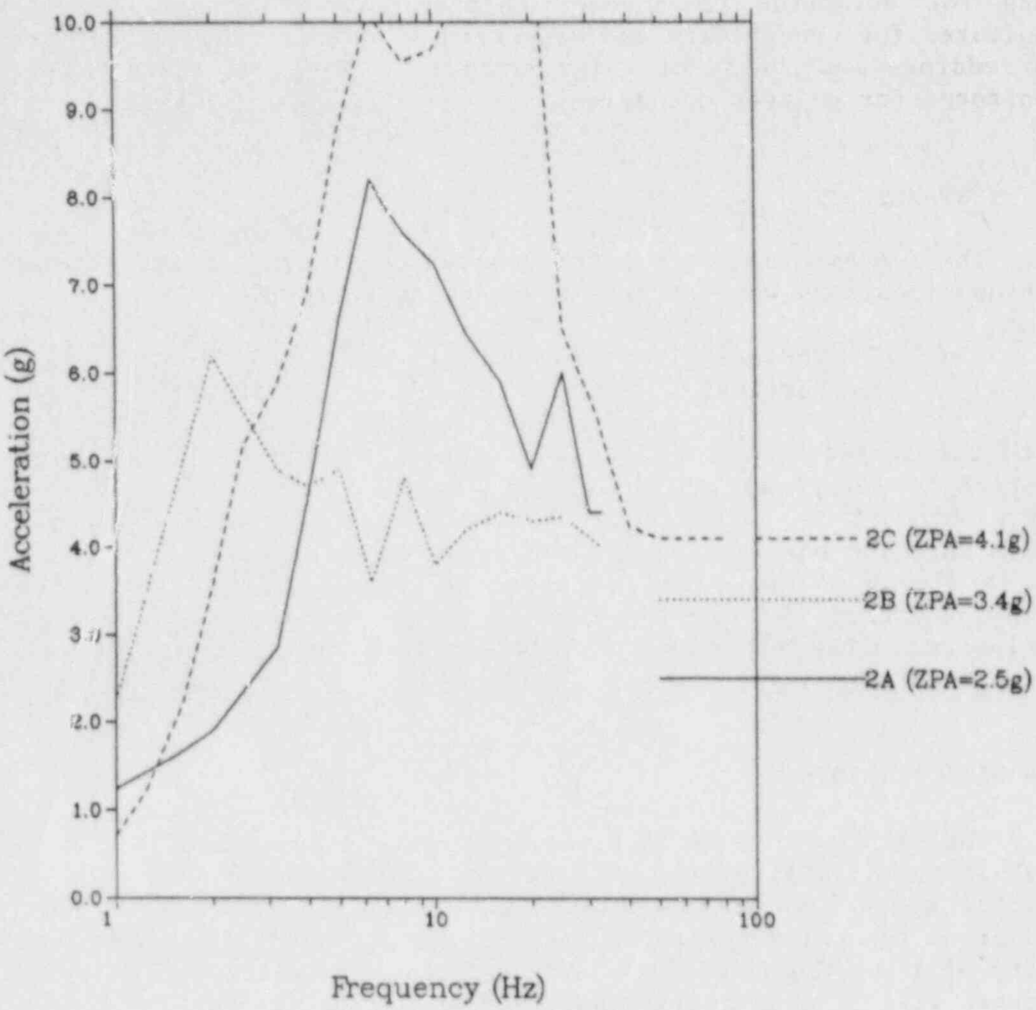

Fig. 4-2: Horizontal TRS @ 2% Damping - Switchboard

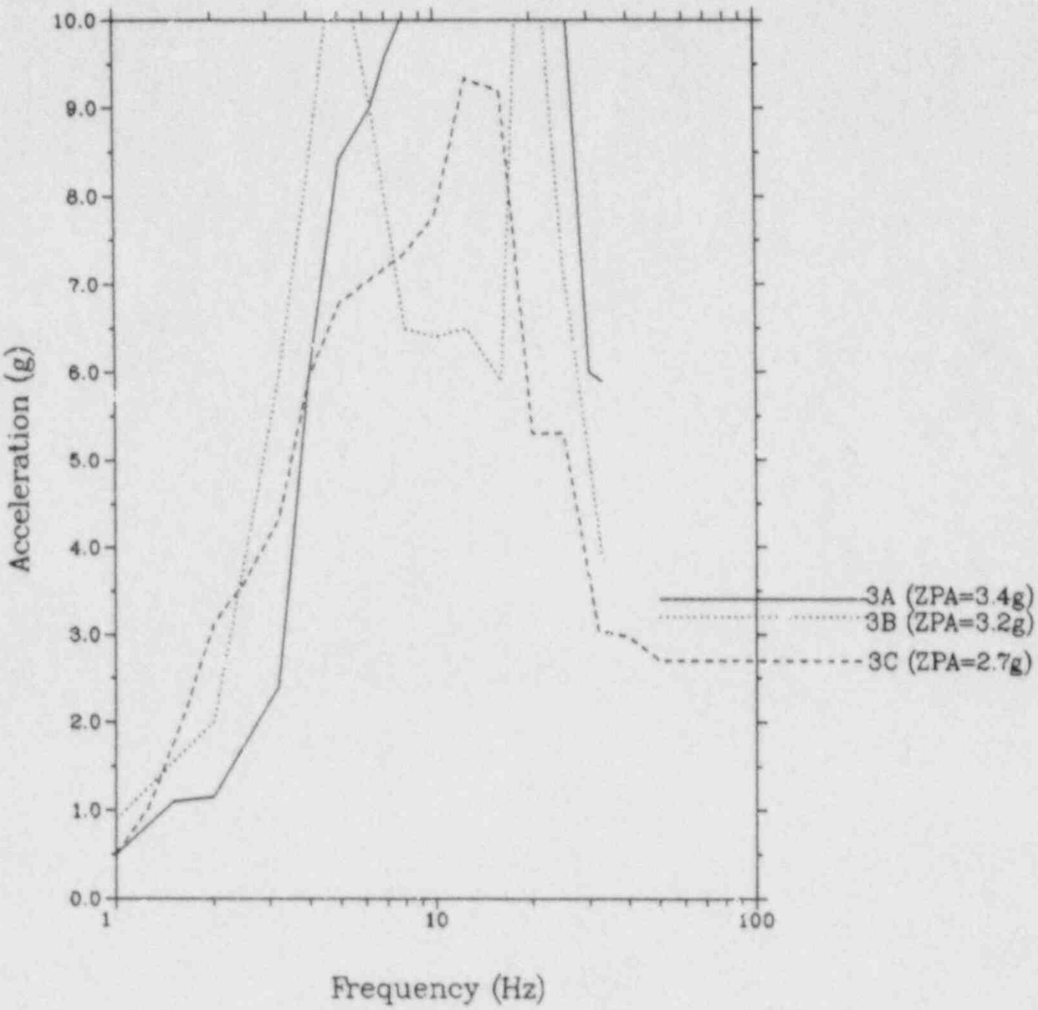

Fig. 4-3: Vertical TRS @ 2% Damping -- Switchboard

TABLE 4-2
Summary of Switchboard Test Results

Test Specimen No.	Contact Chatter Monitored	ZPA in "g"	ASA @ 2% in "g"	Remarks
1	Breaker and N/O relay > 2ms	1.0	2.0	No malfunction
2	Breaker > 1ms	1.0	-	No malfuction
		3.4	4.3	Mounting weld broke No electrical malfunction
3	Relay and CB aux contact > 20ms Power circuit > 2ms	1.4	-	No malfunctuion
		2.5	6.9	Several relays chattered; no other malfunction
4	Breaker	4.1	10.3	No malfuction
5	Breaker > 1ms	3.4	4.3	No malfuction
6	Switch and motor starter (inadequate monitoring of starter)	2.6	7.5	No malfunction
		4.1	10.4	Motor starter chattered

Cracking and breaking of the mounting welds were observed in one test program. The specimen was welded to the test fixture in accordance with the manufacturer's specifications. An examination of the mounting means revealed that due to irregularities of the test fixture surface, there were gaps between the base of the equipment and the fixture in the region between consecutive weldments. The loss of the base contact probably caused the weld failure. Since, in the field, an equipment is mounted on steel elements embedded in concrete, similar mounting problems in achieving a level surface have been observed to occur. Therefore, the weld break as witnessed in the test could also happen in the field.

In the data base test programs, there was no evidence of breaker malfunction, nor was there any indication of structural damage to the switchboard cabinet. Therefore, the fragility levels of the circuit breakers and the cabinet structures are higher than the respective levels achieved during testing.

Based upon the above information and discussion with several engineers from the manufacturing companies, who were actively involved in developing and testing the product, and by use of judgement, a conservative estimate of the fragility parameters is made as follows provided the switchboard does not contain any relays:

	ZPA	ASA @ 2%
Median	3.5g	7.5g
β_u	0.3	0.3
β_r	0.1	0.1

By use of these parameters, the fragility descriptor is calculated as follows:

	ZPA	ASA @ 2%
HCLPF	1.8g	3.9g

4.7 LIMITATIONS

The fragility estimates discussed above are applicable provided the following limitations are satisfied:

- The switchboard is manufactured after 1976.
- The equipment is installed in the field such that the base is in continuous contact with the supporting structural element.
- The switchboard does not contain any relays. Note that in actual operations many switchboards do not contain relays anyway.

4.8 CONCLUSIONS

The fragility parameters presented above are considered to be conservative. Although these results are applicable to switchboards produced since the mid-seventies, one manufacturer indicated that they supplied basically similar switchboards all through the seventies and that there were no modifications made to the latter products due to any seismic concerns. However, more research is recommended before the results presented here are applied to the earlier products, especially in the area of mounting and its effects on the malfunction and failure of the equipment.

CHAPTER 5
PANELBOARD

5.1 INTRODUCTION

The panelboard is a wall-mounted Class 1E electrical distribution panel. The test data for panelboards are discussed and the fragility estimates are presented in this chapter. The data reduction and analysis techniques follow the methods discussed in Chapter 2.

5.2 DATA BASE

The data base covers test results of sixteen panelboard specimens manufactured by four major companies. Test data for both 125 volt DC and 120-600 volt AC panelboards are included in the data base. The data base panelboards contain circuit breakers and/or fusible disconnects, but not any motor starters. The current ratings of the main breakers in the data base vary from 225 amps to 800 amps. The data base test programs were conducted in the time period 1975-85.

5.3 EQUIPMENT DESCRIPTION

The panelboards are wall-mounted box-type cabinets, manufactured in an assortment of sizes, and essentially used as protective enclosures for circuit breakers, switches and relays. These devices of various types, styles and electrical ratings are required for the termination, identification and separation of circuits to provide control and safety in power distribution. The number and ratings of branch circuits that can be installed in a panelboard depend upon the size of the enclosure and the service required.

The box, front, shield and internal frames of a panelboard are usually constructed of code gage steel, while the current-carrying parts, such as bus bars and the breaker straps are copper alloys (Figure 5-1). The rear panel is usually fitted with four ear-type lugs, one at each corner, through which bolts (one bolt per lug) are anchored to the adjoining structure. Six-bolt and eight-bolt mountings directly penetrating the rear panel wall have also been observed in the data base. It has been observed that in some field installations welding was used instead of bolting due to construction constraints. A typical panelboard is 20-40 inches wide, 6-12 inches deep and 40-80 inches high, and weighs 200-400 lbs. Some panels in the data base are as deep as 17 inches, as high as 90 inches and as heavy as 600 lbs. On the other hand, some panel sizes are smaller than the typical dimensions given above.

5.4 TEST DESCRIPTION

Ten of the total of sixteen specimens were tested with biaxial multifrequency vibration inputs; the remaining specimens were tested on triaxial shake

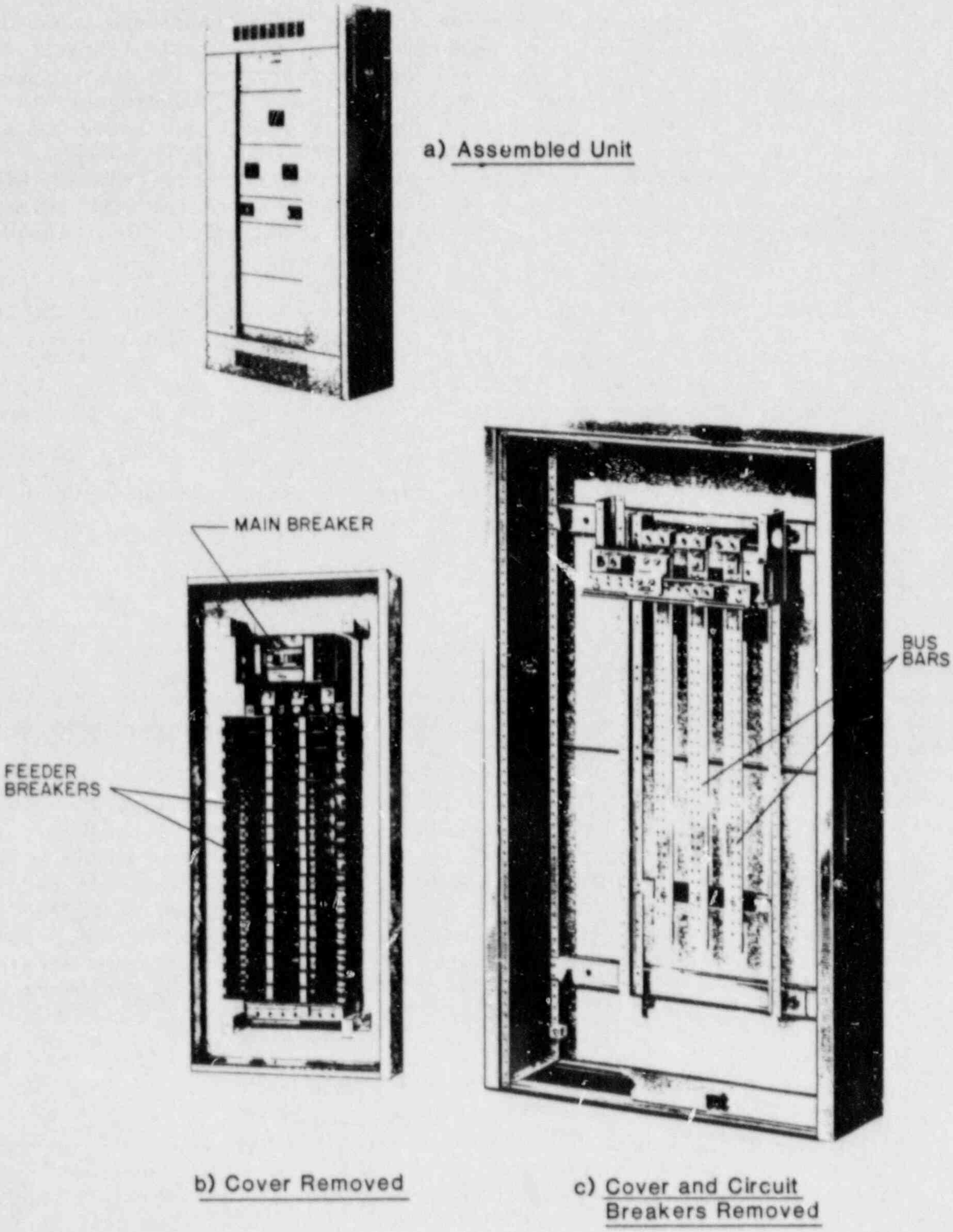

Figure 5-1 A Panelboard Illustrating Current-Carrying Parts

tables. In order to simulate wall mounting, the test specimens were mounted on vertical fixtures which were, in turn, anchored to the shake table. Bolts of 1/2-inch diameter were used for a four-bolt mounting system; 3/8 inch diameter bolts were used for six-bolt and eight-bolt connections. In all programs in the data base, at least five low level (e.g. OBE) tests were performed in each principal direction prior to the high level (e.g. SSE) or fragility tests. The vertical inputs were at least two thirds of the corresponding horizontal inputs except for two specimens. Since these two specimens were tested with triaxial waveforms, the test data are considered valid and used with the rest in the data base.

Representative circuit breakers were electrically monitored during the test runs for detection of false operation, chattering, current discontinuity and malfunction in the contacts.

5.5 TEST RESULTS

Almost all test specimens exhibited fundamental natural frequencies in the following ranges at a sine sweep level of approximately 0.2g:

Front-to-Back	12-18 Hz
Side-to-Side	12-20 Hz
Vertical	20-30 Hz

Only one 80-inch high cabinet indicated a front-to-back frequency of 8 Hz which is outside the above range.

A summary of the test results including the highest qualification levels and/or the fragility information is shown in Table 5-1. The lower-bound TRS plots are shown in Figure 5-2. Curve 2A represents the lower-bound of the highest qualification level in the horizontal direction. Curve 2B corresponds to the initiation of spurious breaker tripping. At the level of Curve 2C, the attachment structural elements and screws for circuit breakers vibrated loose and this resulted in breaker tripping. Also at this level, a breaker terminal became loose causing the breaker trip. The corresponding vertical TRS plots are shown in Figure 5-3.

5.6 DATA ANALYSIS

Test results discussed in the previous section indicate that spurious breaker tripping is the first failure mode that a generic panelboard will exhibit with gradual increase of the vibration input. If the breakers can be reset such that this failure mode is considered "recoverable," the next failure mode appears to be loosening of a terminal or misalignment of a shunt trip,

TABLE 5-1
Summary of Panelboard Test Results

Test Specimen No.	Contact Chatter Monitored	ZPA in "g"	ASA @ 2% in "g"	Remarks
1	Breakers > 2ms	1.6	4.1	No malfunction
		2.0	5.5	Breaker trip
2	Breakers > 2ms	2.2	5.1	No malfunction
3	Main Breakers > 2ms Aux contact > 20ms	2.3	7.8	No malfunction
4	Breakers > 5ms	2.5	7.0	No malfunction
5	Breakers > 2ms	2.0	5.5	No malfunction
6	Breakers > 2ms	1.0	2.8	No malfunction
		1.2	3.9	Breaker trip
		2.2	5.0	Breaker trip-loose terminal
		2.2	5.0	Breaker trip-loose attachment screws
7	Breakers > 5ms	2.7	7.9	No malfunction
8	Main Breaker > 2ms Aux contact > 20ms	2.5	6.9	No malfunction

TABLE 5-1 (cont.)
Summary of Panelboard Test Results

Test Specimen No.	Contact Chatter Monitored	ZPA in "g"	ASA @ 2% in "g"	Remarks
9	Breaker > 2ms	1.3	3.3	No malfunction
		2.3	5.1	Breaker trip
		2.3	5.1	Linkage adjustment eliminated breaker trip
10	-	2.5	7.8	No malfunction
11	Breakers > 1ms	-	4.3	No malfunction
12	Breakers > 5ms	2.5	7.4	No malfunction
13	Main Breaker > 2ms Aux contact > 20ms	1.3	4.7	No malfunction
		2.5	6.9	Relay armature disengaged, contact burned away
14	Switch > 2ms	2.4	5.2	No malfunction
15	-	3.0	10.6	Overcurrent breaker opened at 180% load, Undervoltage breakers tripped below 50% load
16	Breakers > 5ms	2.4	4.9	Breaker Trip

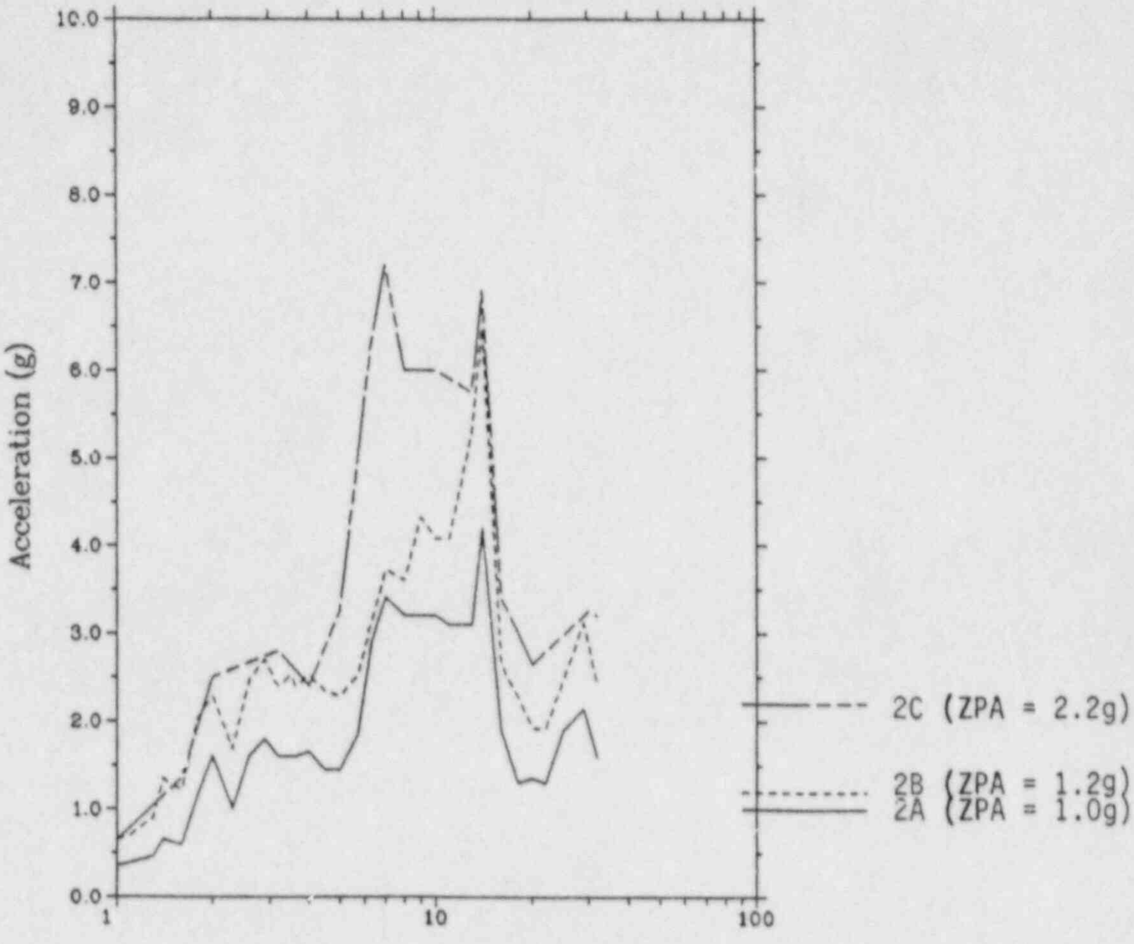

Fig. 5-2 Horizontal TRS @ 2% damping - Panelboard

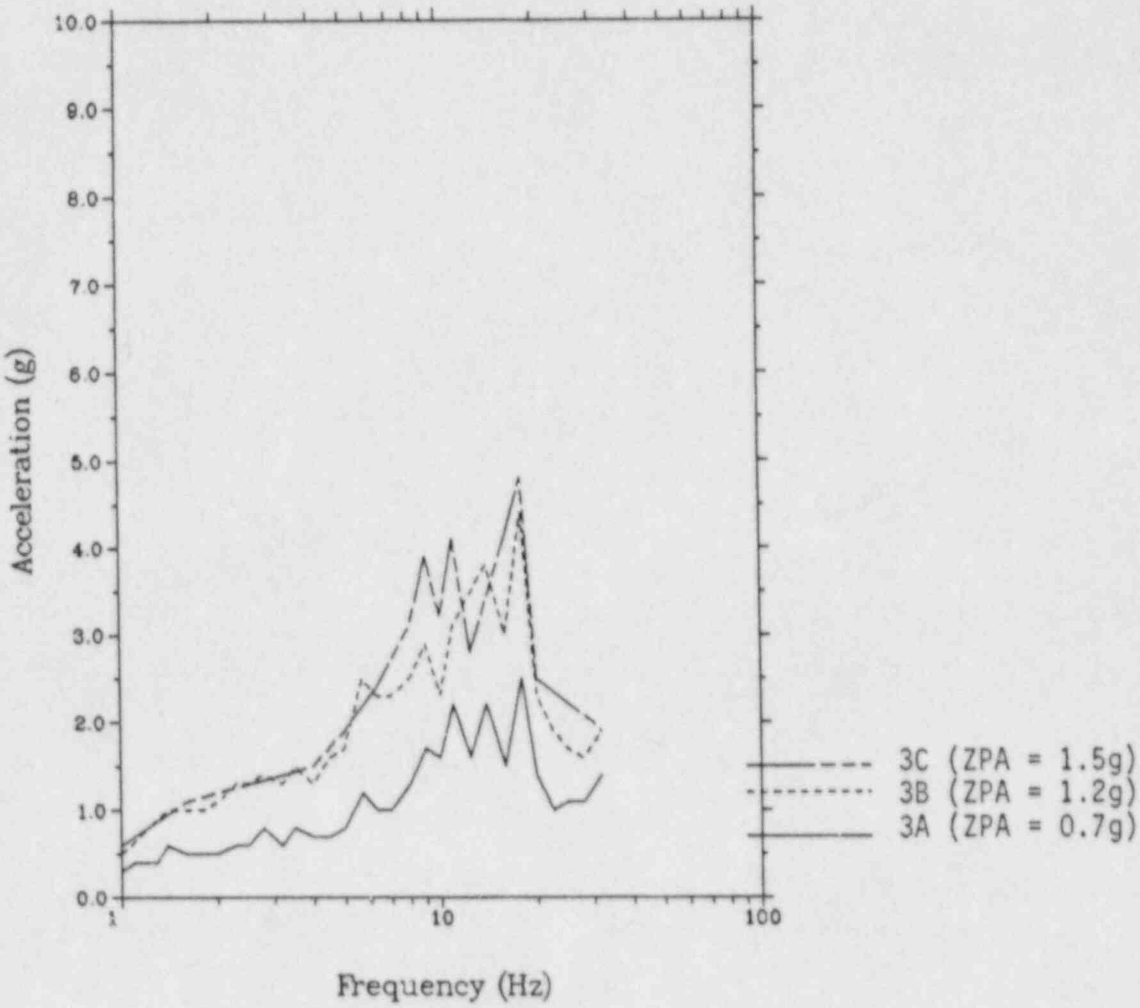

Fig. 5–3 Vertical TRS @ 2% Damping – Panelboard

either of which causes breaker tripping again. However in this event, breaker tripping cannot be easily recovered since it requires certain adjustments in order to reset the breaker. Therefore, in this report breaker tripping as a consequence of loosening or misalignment is considered unrecoverable. Similarly, burning away of relay contacts as observed in the data base is considered an unrecoverable failure mode.

Based upon the above discussion, the entire data base can be divided into the following three categories:

1. Highest qualification level data.

2. Data corresponding to breaker tripping that can be possibly recovered.

3. Data associated with unrecoverable failure modes.

By employing the methods discussed in Chapter 2, the fragility analysis has been performed for both the (possibly) recoverable breaker tripping and the unrecoverable failure modes. The respective fragility parameters and descriptors are presented in Table 5-2. The results indicate that both the median and the HCLPF values are considerably higher when the qualification data are included in the analyses in the maximum likelihood method. This is due to the fact that in some test programs the qualification levels are higher than the fragility levels observed in other programs. Therefore, by using judgement on results from both methods, a set of median and HCLPF values are recommended also in Table 5-2.

Due to structural dissimilarities and unspecified test monitoring, specimen numbers 10 and 15 of Table 5-1 have not been considered in the statistical analysis. The test data used as input for the analysis are listed in Table 5-3. A brief description of each specimen covered in the analysis is provided in Table 5-4.

It is interesting to note that the data base indicates that the initial setting of an overcurrent or an undervoltage breaker could cause a trip during a seismic environment. In one instance, the overcurrent breakers opened at 180% of the rated current; whereas, the undervoltage breakers tripped at voltages as low as 50% of the rated voltage. For the latter case, the manufacturer recommends a setting of 80% of the rated voltage to avoid tripping during a strong earthquake.

5.7 LIMITATIONS

The fragility results presented above are applicable provided the following limitations are satisfied:

- The panelboard is manufactured after 1975.

TABLE 5-2
Panelboard Fragility Analysis Results[1]

Failure Mode	Indicator	Method*	Median in "g"	β_u	β_r**	HCLPF in "g"
Breaker Tripping (possibly recoverable)	ZPA	1	1.7	0.49	0.10	0.6
		2	3.2	0.54	0.11	1.1
		Recommended	2.5	0.45	0.10	1.0
	ASA @ 2%	1	4.5	0.16	0.03	3.3
		2	8.7	0.51	0.10	3.2
		Recommended	6.6	0.37	0.07	3.2
Unrecoverable	ZPA	1	2.3	0.05	0.03	2.1
		2	2.6	0.10	0.02	2.1
		Recommended	2.6	0.10	0.02	2.1
	ASA @ 2%	1	5.5	0.15	0.03	4.1
		2	8.2	0.33	0.07	4.3
		Recommended	6.9	0.25	0.05	4.2

1 These results are applicable only within the limitations described in section 5.7

* Method: 1. Method of Moments
2. Method of Maximum Likelihood

** based on judgement

TABLE 5-3
Input Data for Statistical Analysis - Panelboard

Failure Mode	ZPA in "g" Qualification	Fragility	ASA in "g" @ 2% Damping Qualification	Fragility
Breaker Tripping (possibly recoverable)	1.0, 1.3, 1.3 1.6, 2.0, 2.2 2.3, 2.4, 2.5 2.5, 2.5, 2.5 2.7	1.2, 1.3, 2.0, 2.4	2.8, 3.3, 4.1 4.7, 5.1, 5.2 5.5, 6.9, 7.0 7.4, 7.5, 7.8 7.9	3.9, 4.0, 4.9, 5.5
Un-recoverable	1.2, 1.3, 1.3 2.0, 2.0, 2.2 2.3, 2.4, 2.5 2.5, 2.5, 2.5 2.7	2.2, 2.3, 2.3 2.5	3.3, 3.9, 4.7 5.1, 5.2, 5.5 5.5, 6.9, 7.0 7.4, 7.8, 7.8 7.9	5.0, 5.2, 5.2 6.9

TABLE 5-4
Panelboard Test Specimens included in the Statistical Analysis

Electrical Rating	Size WxDxH (inch.)	Approximate Weight (lbs)	Test Mounting
600 VAC	40 x 12 x 62	400	4 bolts
600 VAC	35 x 12 x 70	400	4 bolts
120 VAC (application)	22W X 67H	-	4 bolts
120 VAC (application)	35W x 82H	-	4 bolts
125 VDC (application)	35W x 70H	-	4 bolts
600 VAC	20 x 7 x 53	260	weld
600 VAC	20 x 7 x 83	350	bolts
600 VAC	38 x 17 x 90	480	weld
600 VAC	32 x 17 x 70	425	weld
-	20 x 6 x 44	200	6 bolts
-	20 x 6 x 53	200	6 bolts
-	26 x 6 x 54	350	6 bolts
-	41 x 9 x 80	600	8 bolts
120 VAC (application)	30 x 7 x 30	120	4 bolts

- The equipment is installed in the field in accordance with the test mounting as discussed in paragraphs 5.3 and 5.4 and Table 5-4.

- The equipment size and electrical rating are limited to that stated in paragraphs 5.2 and 5.3 and Table 5-4.

- The panelboard does not contain any motor starters.

- Chattering duration up to a maximum of 5 milliseconds for main breaker and that of 20 milliseconds for auxiliary contacts can be tolerated by the system.

5.8 PANELBOARD VS. SWITCHBOARD

A comparison between the test data and the results of the fragility analysis for panelboards as discussed in this chapter and that for switchboards presented in Chapter 4 indicates that the panelboard tends to malfunction at a lower vibration level than the switchboard. However, being wall-mounted, panelboards are expected to have a lower dynamic response and supposedly a better electrical performance. A discussion is presented as follows to address this apparent paradox.

Both the panelboards and the switchboards are part of the power distribution system and perform similar functions in that they receive a high current from the source and distribute it to the branch circuits. In both equipment categories, electrical separation from the source is maintained by main breakers, main lugs or main switches and separation from the branch circuits is regulated by circuit breakers, fusible switches or motor starters. However, there are significant differences in their electrical ratings, structural configurations, masses and mounting mechanisms. As a result, the dynamic and electrical responses of these two equipment families in an earthquake environment are different. Interestingly, some of these controlling parameters reduce the dynamic response and improve the electrical performance, whereas the other parameters tend to act in the opposite direction. Therefore, a straight-forward comparison between the two equipment categories is not possible. Instead, the impact of each of the above parameters on the equipment response is studied in this section.

In general, the bus amperage rating and the feeder size are higher for a switchboard. Typically a panelboard may have main breakers with current ratings of 400 amps and less, with the branch feeders of 100 amps or less. Whereas, switchboards typically have main breakers or fused switches rated at 1200 amps or less, with branch feeders rated 300 amps or less. This means that switchboards contain heavier breakers which result in heavier overall weight.

Structurally, both panelboards and switchboards are constructed of similar materials. However, a switchboard is usually deeper than a panelboard. All data base switchboards were welded on the shake table in order to simulate the floor-mounted free-standing field installations; whereas, the panelboards were bolted to a vertical test fixture to represent the wall-mounted field condition.

From the above discussion, it is expected that a switchboard structure will exhibit a higher dynamic response than a panelboard. This has also been substantiated by the test data in that the fundamental frequency of a switchboard is in the range of 5-9 Hz, whereas that of a panelboard is 12-20 Hz. In spite of the high dynamic response in the low frequency range, switchboards appear to perform better electrically. None of the switchboards in the data base experienced breaker tripping, in spite of mounting weld damage; whereas, about one-third of the panelboards exhibited breaker trip or a similar malfunction, even at a lower level. This apparent inconsistency was discussed with experts from manufacturing companies who were actively involved in developing and testing their products. The gist of their explanations is as follows:

> In both cabinets, the branch circuit breakers are mounted on the electrical bus bars. In a switchboard, the bus bars have shorter spans, larger cross sections and more tie bars, and usually run horizontally. In a panelboard, the vertical busses are supported only at the top and bottom (Figure 5-1). Thus, although the wall-mounted panelboards are structurally stiffer than the free-standing switchboards, the circuit breakers are subjected to a higher dynamic response of the internal bussing system. In addition, most breakers are more sensitive to high frequencies. Therefore, a switchboard usually acts as a vibration isolator by filtering the critical higher frequency content of the input, whereas, a panelboard amplifies the vibration input which critically affects the performance of the circuit breakers.

5.9 CONCLUSIONS

Based upon the test information collected and the discussion held with various manufacturers, the following observations are highlighted:

- The capacity level of a panelboard varies over a wide range.
- Compared to switchboards, panelboards have a lower fragility level.
- Circuit breakers are sensitive to high frequencies.
- Circuit breakers use strong springs and a pivoting mechanism to achieve rapid contact opening and closing. Trip mechanisms of circuit breakers require very little movement to cause a breaker trip. Therefore, the spring adjustment could cause a significant shift in the fragility level associated with the breaker tripping failure mode.

CHAPTER 6
DC POWER SUPPLY

6.1 INTRODUCTION

The DC power supply is a panel mounted class IE electrical device. The device is commercially known as a "regulated DC power supply." The test data for power supplies are discussed and the fragility estimates are presented in this chapter. The data analysis method follows the approach discussed in chapter 2.

6.2 DATA BASE

The data base covers test results of eleven DC power supply specimens manufactured by four major companies. These test programs were conducted in the time period 1976-83.

6.3 EQUIPMENT DESCRIPTION

A typical power supply consists of a step-down AC transformer, capacitors and rectifiers required to convert AC input to DC output, all mounted on a sheet metal base. For a typical unit, the overall dimensions are 19 inches long, 5-10 inches wide and 6-12 inches high, and the weight is 25-100 lbs. In its field installation, a power supply unit is mounted on a vertical surface in the panel. Sometimes several units are installed in the same panel to form a power supply assembly which supplies power to various plant devices and monitoring instruments (Figure 6-1).

The device functions to convert a nominal 120 VAC input into a desired DC output (e.g. 24 VDC) while providing isolation between the input power source and the output circuit. Since, in its application, a power supply provides power to instruments that are highly sensitive to input signals, it should maintain a precise output voltage within an acceptable tolerance, e.g. $\pm 2\%$, despite incoming line-voltage fluctuations. For functional operation of some circuitry, e.g. a computer, a dropout of the power supply output may not be acceptable even for a very short duration (e.g. on the order of milliseconds).

6.4 TEST DESCRIPTION

Biaxial vibration inputs were employed for all test specimens in the data base except for two specimens which were subjected to single-axis sinusoidal inputs. In order to simulate the in-service mounting condition, all test specimens were attached to the vertical surface of a test fixture with machine screws, typically four #10-32. The test fixture, in turn, was mounted on the shake table.

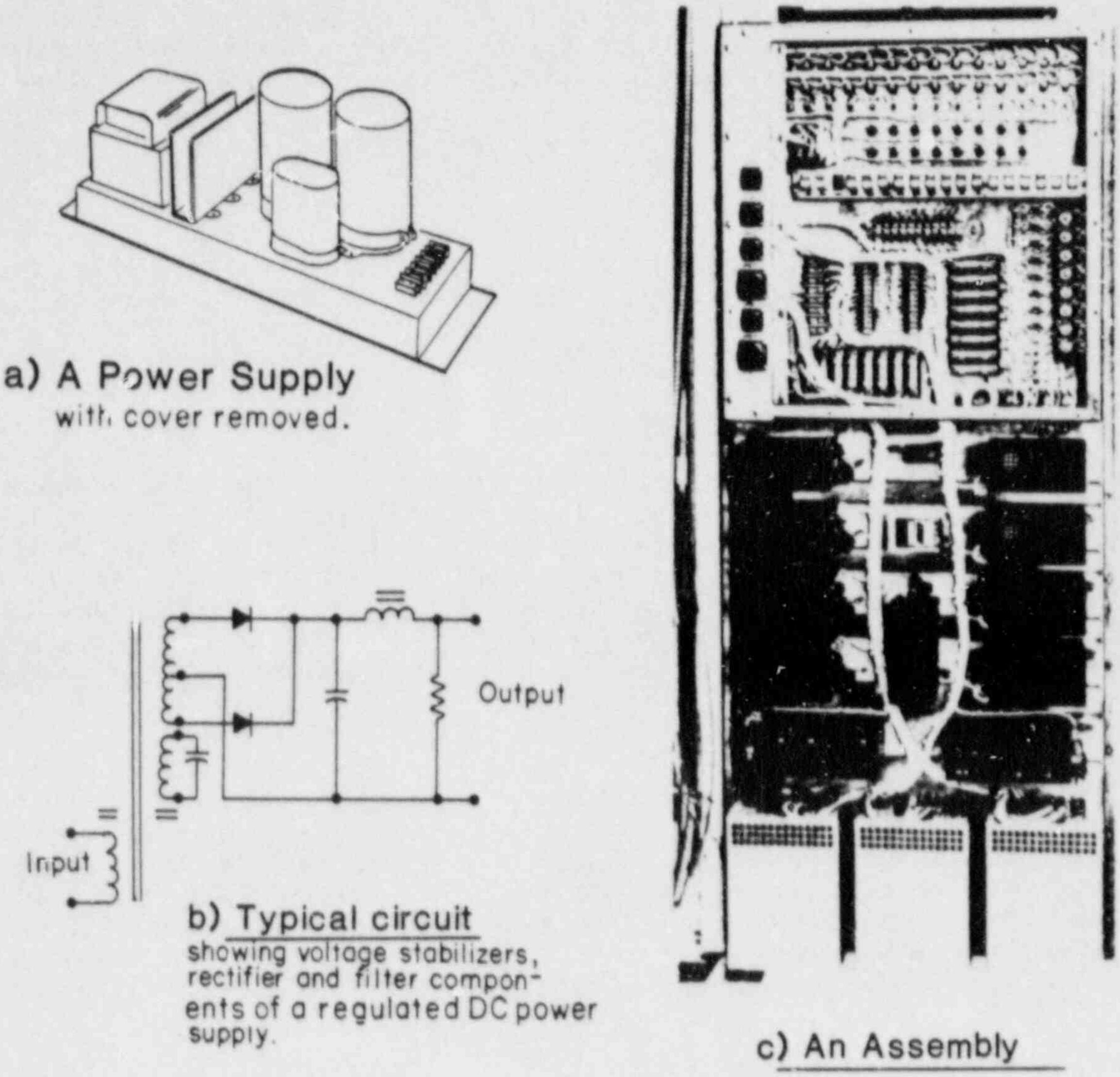

Figure 6-1 A Power Supply Unit and Assembly

In all test programs, the output voltage and current were monitored and any fluctuation beyond a specified tolerance limit was considered a malfunction. Although in most test programs, a tolerance limit of 1-2% was used, at least for two test specimens, output variations up to 10% were considered acceptable. Electrical continuity was monitored during the strong motion for all test items. However, the maximum duration to which the output was monitored for possible interruptions was not specified in most test reports. For at least one specimen, an interruption for a duration of less than 0.5 millisecond was monitored.

6.5 TEST RESULTS

For most specimens, there was no indication of structural resonance in the testing frequency range (1-33Hz) during the low level resonance search tests. However, three specimens were reported to exhibit resonant conditions in all three principal directions in the frequency range 27-30 Hz. Additionally, one specimen showed a natural frequency of 5-6 Hz when shaken with a sine dwell input in the direction normal to its own plane. The structural configuration of this specimen was similar to most other test specimens, and was very similar to or even structurally stronger than another specimen manufactured by the same company. From examination of the accelerometer locations shown in the test reports, it appears that the accelerometers for previous specimens were not mounted in the critical locations. Comments on the frequency data are provided in the following analysis section.

The critical vibration levels and the associated device response are summarized in Table 6-1. Some bounding levels are pictorially exhibited in Figure 6-2. Curve 2A of this figure represents a lower-bound envelop of the qualification level TRS for the data base results. Output variations of less than 2% were satisfied by this TRS level. A qualification level as high as curve 2B exists in the data base. However, a short duration output voltage dropout was observed at the g-level of curve 2C and this resulted in system failure. Note that for curves 2A and 2B, the test reports did not specify whether the device output was monitored for continuity on the order of milliseconds. Further discussion regarding the acceptance criteria follows.

6.6 DATA ANALYSIS

The test data discussed above and summarized in Table 6-1 have been evaluated and the results are presented in the following subsections.

6.6.1 Natural Frequency

As mentioned above, only one test specimen showed a natural frequency of 5-6Hz at a high level test, whereas no other specimen indicated a resonance below 27 Hz during low level tests. Moreover, this specimen was structurally very similar to many other specimens. From examination of the test conditions,

TABLE 6-1
Summary of Power Supply Test Results

Test Specimen No.	Electrical Continuity and Output Level Monitored?	ZPA in "g"	ASA at 2% in "g"	Remarks
1	Yes	5.7	12.6	No malfunction
2	Yes	4.3	11.7	No malfunction
3*	Yes	3.0	-	Structural loosening
		3.0	-	No malfunction when connections were modified
		3.8	-	Structural failure
4	Yes	5.0	-	No malfunction
5	Yes	4.0	7.0	No malfunction
		7.0	17.0	Basic model did not function
		7.0	17.0	Modified model no malfunction
6	Yes	4.2	11.5	No malfunction
7	Yes	6.1	13.2	No malfunction Criteria 10% variation
8	Yes	3.1	-	Temporary power loss
		4.3	-	Temporary power loss; Structual loosening

TABLE 6-1 (cont.)
Summary of Power Supply Test Results

Test Specimen No.	Electrical Continuity and Output Level Monitored?	ZPA	ASA at 2%	Remarks
9	Yes	4.0	9.0	Voltage dropout for less then 0.5ms, system failure
10	Yes	4.4	11.9	No malfunction
11	Yes	6.0	13.0	No malfunction Criteria 10% variation

* specimen of older design

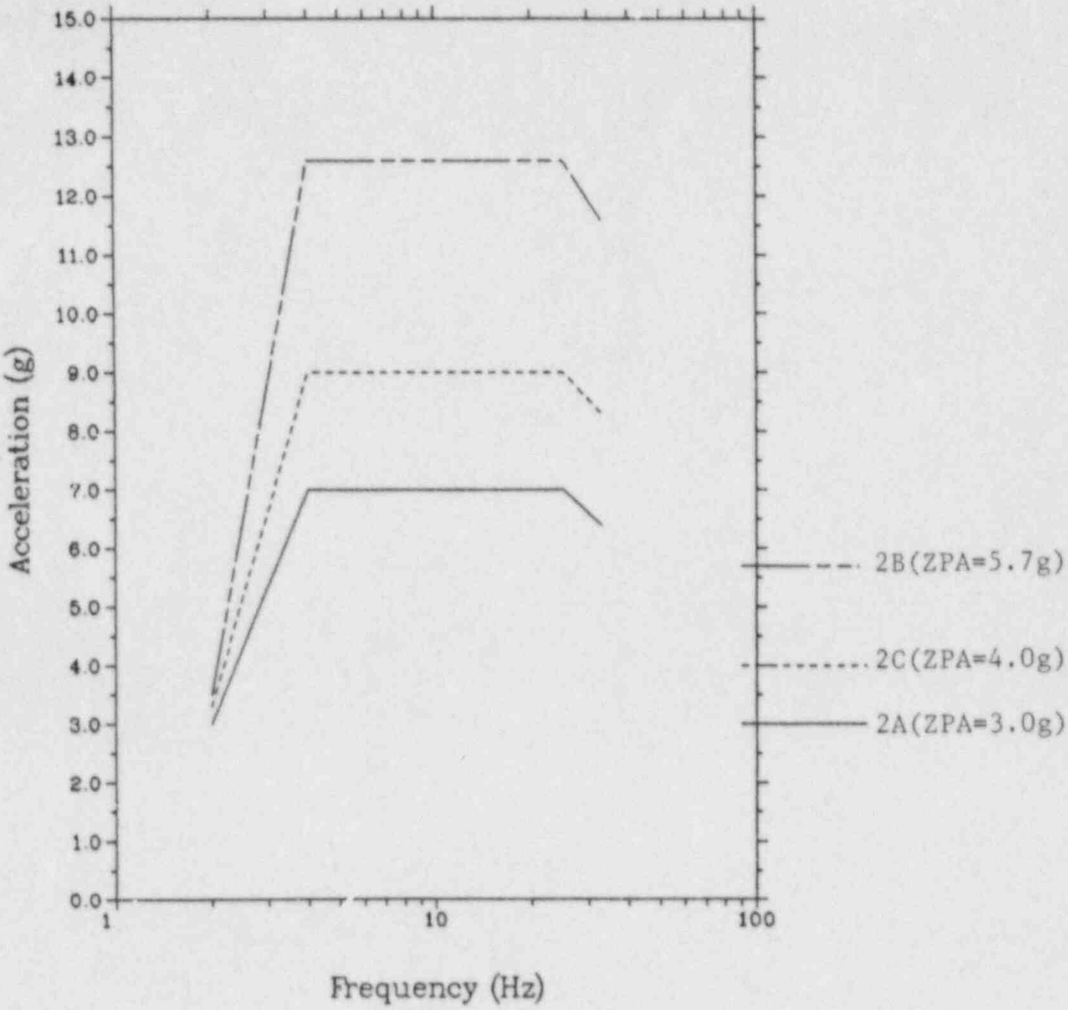

Fig. 6-2 TRS @ 2% Damping - DC Power Supply

it appears that natural frequencies for other specimens were not properly established. One or both of the following reasons could have contributed to these results:

- Response accelerometers were not mounted at the critical locations.
- Low level tests did not adequately excite the structure.

6.6.2 Failure Modes

The performance of the regulated DC power supply depends upon how well it maintains the continuity of the output voltage and current levels. Therefore, the following are the basic acceptance criteria:

1. Variation of the output level should not exceed a specified range. Most manufacturers used a tolerance limit of $\pm 2\%$, although a deviation up to 10% has been used for two test specimens.

2. Interruption of the output voltage or the temporary power loss, if it happens during an earthquake, should not exceed a specified duration.

Regarding the second criterion, most test reports document the satisfaction of this requirement in general terms by simply stating that the continuity of the output current was maintained. But, it is not clear to what duration limit the continuity was monitored. On the other hand, for two specimens which are very similar to other test specimens, the electrical output continuity was monitored by means of oscillograph recorders for possible short interruptions as small as 1/10 to 1/2000 second. Both these specimens suffered temporary power losses for such time intervals. The testing laboratory commented on this finding that if the output of the specimens had been monitored with a meter instead of the oscillograph recorder, the short duration interruption would not have been detected. This explains why most specimens survived a strong vibration input without exhibiting any malfunction while a similar unit experienced a temporary power loss at a lower vibration level.

Based on the above discussion, the various failure modes observed in the data base can be summarized as follows:

1. Temporary loss of output power.

2. Variation of the output level in excess of the acceptable limit.

3. Structural loosening.

4. Structural failure.

Structural loosening was observed to initiate with loosening of panel screws. This, in one instance, resulted in formation of cracks in a structural element and damage of the electrical terminal.

A workmanship error for solder joints was identified as a common cause of electrical malfunctioning. In one test program, each time the unsoldered connection was broken, the coil produced an inductive voltage spike which in turn caused disturbance of the output.

6.6.3 Fragility Estimate

Although a large number of specimens were tested at very high levels and up to the malfunction levels, the acceptance criteria and the failure modes are not necessarily the same in all test programs, as discussed above. Therefore, the fragility estimates are made for different acceptance criteria and failure modes. When subdivided into various groups, the data base is considered inadequate for a statistical analysis for each failure mode. Therefore, judgements are used in processing the test results and arriving at the fragility parameters. The fragility descriptors are calculated by use of the parametric values. The results are presented in Table 6-2.

6.7 LIMITATIONS

The fragility results presented above are applicable provided the following limitations are satisfied:

- The power supply is manufactured after 1976.

- The device is installed with #10-32 machine screws by using all the screw holes provided on the chassis. A minimum of four screws should be used. Several test programs indicated loosening of panel screws, and the device performance was improved by modification of this connection with welding.

- All solder joints are verified for compliance.

- The device size and electrical rating are limited to that stated in paragraphs 6.3 and 6.4.

6.8 CONCLUSIONS

The data base indicates a wide range of capacity levels for the regulated power supply. Basically, the device looses accuracy of the output voltage and current as the vibration level increases. A short duration interruption, i.e., temporary power loss, was observed to be a critical failure mode. The fragility results are presented for various failure modes. The nature and acceptability

TABLE 6-2
Power Supply Fragility Analysis Results[1]

Acceptance Criteria/ Failure Mode	Indicator	Median in "g"	β_u	β_r	HCLPF in "g"
Output level variation less than ±2% and output continuity satisfied when monitored by meter.	ZPA	4.6	0.13	0.03	3.5
	ASA @ 2%	10.7	0.13	0.03	8.2
Output level variation less than +10% and output continuity satisfied when monitored by meter.	ZPA	6.0	0.15	0.05	4.3
	ASA @ 2%	13.1	0.15	0.05	9.4
Output continuity monitored by oscillograph recorder and duration of power loss not greater than 0.5ms.	ZPA	3.6	0.15	0.05	2.6
	ASA @ 2%	9.0	0.15	0.05	6.5

1 These results are based on judgement and are applicable only within the limitations discussed in Section 6.7

of these failure modes in terms of recoverability are left to the user. However, one comment appears appropriate in that, an output power loss for a very short duration, e.g., on the order of milliseconds, may cause a system problem, for example, in a computer circuit.

CHAPTER 7
SUMMARY AND CONCLUSIONS

7.1 INTRODUCTION

The BNL Component Fragility Program involves the use of existing test data and was initiated in FY 1985. The results of Phase I of this program were published in 1986 [1]. This is the second report by BNL in presenting the results of the continuing fragility study. This chapter provides a summary of the data evaluation performed in Phase II under the scope of the program. An assessment is made of the fragility levels and the important observations are listed. The tasks in establishing fragility levels of the remaining equipment categories are also discussed in this chapter. Recommendations for future research are provided as concluding remarks.

7.2 PROGRAM STATUS

The methods for data evaluation and determination of fragility levels by use of existing test results were established in Phase I. The use of these methods was demonstrated by performing a preliminary analysis of limited data for motor control centers and switchgears. In Phase II, the analysis procedure has been refined. An important addition is the statistical analysis of the fragility data and providing a single fragility descriptor for each equipment category. A lognormal distribution has been assumed for the test data in the statistical analysis and both the median and the HCLPF values are presented in this report. By employing these techniques, four equipment pieces, namely, motor control centers, switchboards, panelboards and power supplies have been analyzed. For the motor control center, additional data have been collected in Phase II and assembled with that obtained in Phase I.

7.3 SUMMARY AND OBSERVATIONS

The following generic observations have been made in analyzing the data presented in this report:

a) The seismic test programs from which the data have been collected were conducted in the period 1975-1985.

b) Electrical malfunctions and instrument accuracy problems occur at lower excitation levels than required for a structural damage.

c) Although minor structural problems, e.g. loosening of screws, did not pose a problem to the overall structural integrity of an equipment, in some instances, they triggered electrical malfunctions.

d) Self-tapping screw connections and bolted connections at the base are structural weak links. Therefore, the structural capacity of an electrical panel, especially an MCC, can be raised by avoiding the use of self-tapping screw connections and by strengthening the bolted connections at the base.

e) In some instances, the workmanship of solder joints for electrical devices and connections of panel structural members, especially for early products, controlled the fragility limit where apparently proper inspection had not been performed.

f) Some products in an equipment category are capable of withstanding a seismic event significantly greater than that depicted by the lower-bound fragility limit presented in the report.

g) At or close to the fragility level, the equipment performance varies and appears unpredictable.

h) Since some relays apparently have very low fragility levels, relays should be carefully screened.

i) The natural frequency of a cabinet structure decreases with an increase of the vibration level.

A summary of the data evaluation results for each equipment category is provided in Table 7-1 and is also briefly described in the following sub-sections.

7.3.1 Motor Control Center

The fundamental frequency of most MCC's in the BNL data base is 5-7 Hz at a sine sweep amplitude of 0.2g. The lower envelope of the fragility level is 0.9g ZPA and 2.0g ASA at 2% damping. The respective HCLPF values are 0.8g and 1.7g. This fragility level corresponds to the chatter failure mode which occurs first. The auxiliary contact is typically the weak link. The HCLPF values for the auxiliary contact are 2.4g ZPA and 5.6g ASA at 2% damping. The various failure modes which usually occur with increasing vibration inputs are as follows:

a) Contact chatter - motor starter (including auxiliary contact), relay.

b) Change of state - motor starter (including auxiliary contact).

c) Loosening of screws and bolts.

d) Snapping out of self-tapping screws.

e) Breaking of mounting and panel bolts, weld and structural members.

Table 7-1
Recommended Probabilistic Fragility Levels[1]

Equipment	Failure Mode	HCLPF Values in "g"[2] ZPA	HCLPF Values in "g"[2] ASA @ 2% Damping
Motor Control Center	Contact chatter	0.8	1.7
	Change of state of starter		
	a) auxiliary contact	1.0	2.1
	b) main contact	1.1	2.4
	Major structural damage:		
	a) without seismic stiffeners	1.6	3.2
	b) with seismic stiffeners	1.9	4.6
Switchboard	Breaker tripping	1.8	3.9
Panelboard	Breaker tripping (possibly recoverable)	1.0	3.2
	Unrecoverable	2.1	4.2
DC Power Supply	Power loss for 0.5ms	2.6	6.5
	Output level variation:		
	a) 2%	3.5	8.2
	b) 10%	4.3	9.4

1 Caution: These results are applicable only within the limitations separately listed for each equipment (Reference chapters 3-6)

2 The g-values are measured at the base of the equipment

An EPRI study has indicated a ruggedness "function during" ZPA value of 1.0g with a possible reduction factor for inclusion of auxiliary contacts and a "function after" ZPA value of 2.8g[1][5]. Although the EPRI results and that contained in this report cannot be directly correlated, it appears that the BNL results agree with the EPRI results better for the "function during" mode than for the "function after" mode for which the BNL results may indicate a lower fragility level.

A complete list of HCLPF values for various failure modes is provided in Chapter 3, Table 3-2.

7.3.2 Switchboard

The fundamental frequency is in the range of 5-9 Hz at the 0.2g sine sweep level. Relay chattered and mounting welds broke at a lower envelope of 2.5g ZPA and 4.3g ASA at 2% damping. However, no breaker tripping has been observed in the data base. A conservative value of the HCLPF is estimated as 1.8g ZPA and 3.9g ASA at 2% damping. A comparison with EPRI's results is discussed in the following sub-section.

7.3.3 Panelboard

The fundamental frequency is 12-18 Hz at the 0.2g sine sweep level. The lower-bound fragility level for breaker tripping is 1.2g ZPA and 3.9g ASA at 2% damping. The corresponding HCLPF values are 1.0g and 3.2g. Instances of burning away of an electrical contact and breaker tripping due to loosening of an electrical terminal exist in the data base. Table 5-1 in Chapter 5 provides a complete list of the probabilistic parameters and the HCLPF values for various failure modes.

In the EPRI study [5], the panelboard and the switchboard have been evaluated together as distribution panels and a combined ruggedness ZPA value of 3.0g[1] has been reported for the breaker tripping failure mode compared to the 1.2g ZPA value stated above.

7.3.4 DC Power Supply

The basic failure modes of DC power supplies are the temporary loss of output power and variation of output level. The power loss for a duration on the order of 0.5ms may be detrimental for some electrical circuits, e.g.

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1 At the time of preparation of this report, according to the information available to the authors, EPRI is further evaluating certain results contained in Reference 5.

computer circuitry. The corresponding estimated HCLPF value is 2.6g ZPA and 6.5g ASA at 2% damping. A complete list of the fragility analysis results is provided in Chapter 6, Table 6-1. The aforementioned EPRI study did not address the ruggedness of this device and therefore no comparison is made in this report.

7.4 CURRENT PROGRAM

The Component Fragility Program at BNL is continuing. Test data for the following equipment are being collected and analyzed and the results will be published in the next report:

1. Switchgear
2. Instrumentation and Control Panels and Racks
    a) Nuclear Instrumentation System
    b) Process Control Equipment
3. Local Instruments
    a) Transmitter
    b) Switch
    c) Indicator
4. Relay

The other equipment items which are in the priority list for study in FY 1988 are as follows:

1. Transducer
2. Transformer
3. Auxiliary Relay Panel
4. ESF Sequencer
5. Circuit Breaker
6. Inverter
7. Bistable
8. Ion Chamber Electrical Connector
9. Batteries and Battery Racks
10. Fire Protection and Deluge Equipment
11. Small Valves
    a) Spring Operated PRV
    b) PORV
    c) Pilot Operated Valves
12. Bearing Cooling Equipment
13. CRD Equipment
14. Air Handling Units and Fans

As part of the Fragility Program, BNL is also involved in testing relays and computing dynamic amplification factors for electrical cabinets. Both these tasks are briefly discussed in the following sub-sections.

7.4.1 Relay Test Program

The data collection for relays and the complexity of relay issues were discussed in the Phase I report.[1] Additional data have been collected in Phase II. The existing test data indicate that for most relays the chatter fragility level varies with the frequency. In addition, adjustments of certain variables, e.g. spring tension for hinged-armature relays, end-play for rotary relays, contact gap, appear to influence the seismic fragility of relays. A design change without change of the basic model number has also been found to affect the fragility level.[1] In order to better understand the sensitivity of relay chatter due to various parameters and to demonstrate construction of frequency-dependent fragility TRS curves, BNL is planning to conduct a test program on some popular relay models extensively used in nuclear plants. The test results are expected to be published in FY 1988.

7.4.2 Dynamic Amplification of Electrical Panels

The seismic fragility of electrical panels is typically controlled by malfunction of devices, e.g., relays. These devices are mounted at various locations on the panel and experience amplified vibration inputs compared to the excitation level applied at the base of the panel due to the overall and local flexibility of the panel structure. BNL is computing the dynamic amplification factors at various locations of the panel by use of existing test data. A total of eighteen electrical panels including MCC's and switchgears will be studied as part of this task.

An initial study at BNL expectedly indicated that the amplification is typically higher at a low vibration level, e.g. sine sweep at an amplitude of 0.2g. Therefore, the current study concentrates on test data obtained from high level tests, i.e. qualification or fragility tests. The ratio of the spectral accelerations corresponding to the response and the control accelerometer readings is used as a measure of the dynamic amplification value and the result is plotted against the frequency. On a limited basis, the amplification factors at some device locations will be computed for an excitation level which causes the device to malfunction.

Amplification factors for two electrical panels are presented in Appendix C. Test data will be evaluated for additional sixteen panels and the complete results will be published in FY 1988.

7.5 RECOMMENDATIONS FOR FUTURE RESEARCH

The Component Fragility Program is continuing and more in-depth knowledge regarding fragility of equipment will be gained. However, based on the study

1 The serial number added to the relay model makes the test specimen unique.

performed to-date, some generic issues of great practical value are emerging and are therefore recommended for future research. A definition and description of some of these issues and some thoughts regarding how to address them are presented in the following sub-sections.

7.5.1 Vintage

Among all the concerns in applying the fragility results, the vintage of the equipment is probably the most outstanding issue. For obvious reasons products of two manufacturers are not necessarily the same; similarly products of one manufacturer at different times are not necessarily the same. This is more so in the realm of seismic capacity of electrical equipment. The seismic requirements have evolved through the seventies; as did the outlook of engineers and the capacity of equipment. Acceptable equipment qualification methods and the seismic criteria were specified for the first time in 1971 through IEEE Std 344 which was subsequently revised in 1975, which in general made the requirements more stringent.

As a result, the equipment design was modified to meet these new criteria. In the overall structural area, braces were added at critical locations and connections were strengthened. More structural changes were made at device locations either to reduce a local amplification or to stop a mechanical movement or both. Bolts were preferred to self-tapping screws. Lock nuts were used to stop loosening. The design of devices also evolved and improved, e.g., stronger springs, more efficient magnetic material, greater ampere turns in the coil. Certain devices were replaced in equipment assemblies. In summary, the modifications were not extensive, but were skillfully and economically performed at critical locations that had been identified in earlier tests. The "basic design" remained the same, but the seismic capacity improved significantly.[1]

Based upon the above discussion, the entire range of nuclear plant electrical equipment, and probably other equipment, can be broadly categorized in the following groups by correlating the vintage with the seismic capacity:

1. Pre-1971 Products
2. 1971-75 Products
3. 1975-77 Products
4. Post-1977 Products

Most of the seismic test programs were conducted after 1975.

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[1] It is strongly emphasized that the authors recogni that the earlier products must have met the requirements of the time and even that of later standards. The purpose of the discussion is to bring out how the technology developed and the equipment was improved to satisfy, often too conservatively, the increasingly stringent criteria.

For the four equipment categories analyzed in this report, most of the data base products belong to group 4 and the rest belong to group 3. Therefore, the use of the results presented in this report and those that will be presented in future BNL reports will be limited to recent plants unless further research is conducted to determine applicability of these results to earlier products. To this end, it is recommended that some or all of the following approaches be pursued to address the vintage issue:

1. Search for early test data.
2. Test some specimens from early vintage.
3. Test new specimens by duplicating the old test procedure if the search for early test data becomes successful. Note that due to the absence of proper seismic test criteria and test equipment, earlier test data are not expected to exist in a form that can be readily used for qualification and fragility analysis purposes. Such data can only be used for comparison. Therefore, if a later version of the same product is tested by duplicating the old method, the relative capacity of the older version can be assessed from comparison of the two sets of data.
4. Study the structural and electrical details of the products from early vintage. Follow the design changes made through the years of evolution. Concentrate on the seismically weak links.
5. No matter which approach is used, it will be extremely difficult, if not impossible, to obtain information for an adequate number of specimens to draw a generic conclusion regarding the capacity of earlier products of a specific equipment category. Therefore, instead of searching in vain for sufficient data points of many products, select a small group of products, follow the trail of their design changes and estimate a variation of the capacity in that time domain. This time-bound variation due to vintage should then be combined with other variations obtained for products of the same vintage. The combined variation will be used for an overall estimate of the capacity.

7.5.2 Inconsistency of Results

At or close to the fragility level, the performance of an electrical component appears to be inconsistent. One such example has been provided in the discussion of MCC's regarding contact chatter of a motor starter assembly (Reference Section 3.6.2.1). It is recommended that an in-depth study be performed to better understand the parameters, both the internal (i.e. component design) and the external (i.e. test input), that control the fragility and are the cause of such apparent inconsistencies of equipment performance. The study should concentrate on critical devices. Limited testing may be required.

7.5.3 Frequency-Dependent Fragility Level

It has been observed in the existing data base that the frequency content of the random excitation influences the functionality of an equipment. In other words, an increase of g-level in a TRS at one particular frequency, or over a narrow band, may trigger an equipment malfunction. This is more so if the equipment fragility is controlled by malfunction of a single device, e.g. the auxiliary contact in an MCC. Representation of the fragility level by such a TRS curve has a strong limitation in that the equipment capacity at other frequencies may well be significantly higher than the g-levels depicted by the TRS. This short-coming becomes more pronounced if the so-called fragility TRS curve is used to predict the resistance of the equipment in an earthquake environment for which the time history contains sharp peaks at a narrow band frequency zone, e.g. Perry Earthquake 1986 (peak at 20 Hz), Mexico City Earthquake 1985. In order to overcome such limitations of the so-called fragility TRS, it is recommended that a study be performed in deriving frequency-dependent fragility TRS for equipment assemblies such that at any frequency the g-level depicted by the TRS is the true fragility g-level at the particular frequency.

7.6 CONCLUSIONS

The approach to assess seismic fragility by use of existing data has emerged out of the initial demonstration stage. The probabilistic method has complemented and added strength to the deterministic approach. The outcome is a fragility TRS for deterministic use and a single fragility descriptor along with other statistical parameters for use in margin studies and PRA's. The results are finding applications in different programs.

Regarding the use of the results, it is emphasized that the purpose of this report is to provide a generic evaluation of each equipment category. However, a brief discussion is included for each test specimen of an equipment category only to highlight certain characteristics and identify generic weak links. The fragility analysis and the final results, both deterministic and probabilistic, are based on a large amount of test and equipment information which for practical reasons is not included in the report. Moreover, the disguised, scrambled and sketchy information about individual test specimens provided in this report is intentional in order to preclude the possibility of inference about the particular product or the manufacturer. The data source organizations cooperated in the BNL Component Fragility Program and furnished the test data on an assurance that their identification could not be inferred from any published report. The cooperation from these organizations was essential to include data for all major products and to produce a true generic evaluation regarding publication of which no compromise has been made. In summary, this report should be used only for generic understanding of an equipment category. Due to inadequate information provided for individual test specimens, any attempt to qualify such products or to obtain their fragility levels by use of this report could produce erroneous results and is therefore strongly discouraged.

The Component Fragility Program by use of existing test data is continuing and the fragility results for additional equipment categories will be published in the coming reports. The future research items recommended in section 7.5, if implemented, are expected to shed more light regarding the roles of various parameters in controlling the complex fragility phenomenon and extend the use of the results to equipment in earlier nuclear plants.

Chapter 8
REFERENCES

1. Bandyopadhyay, K.K. and Hofmayer, C.H., "Seismic Fragility of Nuclear Power Plant Components (Phase I)," NUREG/CR-4659, June 1986

2. Holman, G.S., et al., "Component Fragility Research Program: Phase I Demonstration Tests," NUREG/CR-4900, Vols. 1 and 2

3. Holman, G.S. and Chou, C.K., "Component Fragility Research Program: Phase I Component Prioritization," NUREG/CR-4899, June 1987

4. Budnitz, R.J., et al., "An Approach to the Quantification of Seismic Margins in Nuclear Power Plants," NUREG/CR-4334, August 1985

5. Smith, C.B. and Merz, K.L., "Generic Seismic Ruggedness of Power Plant Equipment," EPRI NP-5223, May 1987

APPENDIX A
STATISTICAL ANALYSIS METHODS

APPENDIX A
STATISTICAL ANALYSIS METHODS

A.1 INTRODUCTION

The aim of the statistical analysis is to compute a median fragility value associated with the coefficients of variation and ultimately to obtain a fragility descriptor, expressed as an acceleration level, to predict the probability of failure of each equipment category. The fragility descriptor selected for this study is the HCLPF (High Confidence of a Low Probability of Failure) which gives the seismic acceleration for which there is a 95% confidence level for not exceeding 5% probability of failure. It is computed from the formula

$$\text{HCLPF} = \text{Median} * \text{Exp}[-1.645\ (\beta_r + \beta_u)]$$

where the "median" represents the median acceleration of the input data set and β_r and β_u are the coefficients of variation due to randomness and modeling uncertainties in the median capacity, respectively. The coefficient, β_u, is determined from the relation

$$\beta_u^2 = \beta_c^2 - \beta_r^2$$

in which β_c represents the total coefficient of variation or standard deviation of the data base for the particular equipment.

In this appendix, the statistical methods used to compute the coefficients β_c and β_r and the median required to reach the fragility descriptor are presented in detail. Since the data set for each equipment includes two TRS indicators, namely, the ZPA and ASA (average spectral acceleration), the HCLPF as well as the coefficients β_c, β_r, and β_u are computed and reported separately for each of the aforementioned indicators. The data set for each indicator is treated as a separate entity.

The median fragility level and the total coefficient of variation (β_c) for a particular equipment are computed from the entire data set assembled for the equipment category. The coefficient of variation due to randomness (β_r), on the other hand, is computed in two steps. First, the coefficient of variation is calculated for each specimen of the equipment category separately. Each specimen is a product of one manufacturer and is subjected to a number of relevant seismic tests. The test data for a specimen form a subset in the data base. Then, a weighted average of all of the specimens is considered as the coefficient (β_r) for the equipment. Once β_c and β_r are computed then the coefficient of variation due to uncertainties (β_u) and the HCLPF are found from the previously mentioned relations.

Two methods are described to compute the fragility parameters β_c and β_r along with the median value. These methods are the method of moments and the method of maximum likelihood. In the former method, only the fragility data are used as the input data, whereas in the latter method, both the fragility and the highest qualification data are included in the data set. In a typical test programs, with gradual increase in the level of vibration input, the highest qualification level is the highest possible TRS level at which the equipment performs its intended function without any malfunction. The fragility level is defined as the TRS level at which the equipment begins to malfunction.

A.2 METHOD OF MOMENTS

In this method, the data base consists of the fragility data for either of the TRS indicators, namely, ZPA or ASA. Let the random variable f_{ij}, $i = 1, 2, \ldots, k$; $j = 1, 2, \ldots, n_i$, represent the fragility level of the jth test from the ith manufacturer for a particular equipment category. It is assumed that there exist a constant μ and two independent random variables R_i and U_{ij} such that

$$f_{ij} = \exp\left(\mu + R_i + U_{ij}\right)$$

The constant, μ, is the mean of the logarithmic values of the data set. The random variables R_i and U_{ij} have a normal distribution with zero mean and variances b_r^2 and b_u^2, respectively. Note that the variable R_i represents the variability under a controlled test environment while U_{ij} represents all other uncertainties. It follows that

$$X_{ij} = \mathrm{Ln}\, f_{ij} = \mu + R_i + U_{ij}$$

An estimate of μ, denoted by X, is given by

$$\bar{X} = \frac{1}{N} \sum_{i=1}^{k} \sum_{j=1}^{n_i} X_{ij}$$

$$N = \sum_{i=1}^{k} n_i$$

while the coefficient of total variance (β_c) is computed from

$$\beta_c^2 = \sum_{i=1}^{k} \sum_{j=i}^{n_i} \frac{(X_{ij} - \bar{X})^2}{N - 1}$$

In order to compute the coefficient (β_r) which is an estimated value of b_r, the data from the ith manufacturer can be used. For this specimen, the sample mean and the sample of variance are expressed as

$$\bar{X}_i = \frac{1}{n_i} \sum_{j=1}^{n_i} X_{ij}$$

$$S_i^2 = \sum_{j=1}^{n_i} (X_{ij} - \bar{X}_i)^2/(n_i - 1)$$

where S_i^2 is an unbiased estimate of b_r^2 for the specimen. Computing the S_i^2, $i = 1,\ldots,k$, for all manufacturers, β_r^2 is estimated for the equipment category by taking a weighted average of all the S_i^2 values as follows

$$\beta_r^2 = \sum_{i=1}^{k} (n_i - 1)\, S_i^2/(N - 1)$$

$$= \sum_{i=1}^{k} \sum_{j=1}^{n_i} (X_{ij} - \bar{X}_i)^2/(N - 1)$$

A.3 METHOD OF MAXIMUM LIKELIHOOD

This method is used to compute the statistical parameters when the data base includes the highest qualification and the fragility data of the equipment. Let f_{ij} ($i=1,\ldots,k$; $j=1,2,\ldots,n_i$) represent the fragility data and q_{ij} ($i=1, 2,\ldots,l$; $j=1, 2,\ldots,m_i$) represent the highest qualification data of the equipment. It is also assumed that the random variables f_{ij} and q_{ij} follow the same model behavior as described in Section A.2. Let

$$X_{ij} = \text{Ln}\, f_{ij}, \quad Y_{ij} = \text{Ln}\, q_{ij}$$

Then, the likelihood of an event in the data base is expressed as

$$L(\mu, b_c) = \prod_{i=1}^{k} \prod_{j=1}^{n_i} \phi\left(\frac{X_{ij} - \mu}{b_c}\right) \prod_{i=1}^{\ell} \prod_{j=1}^{m_i} \left[1 - \Phi\left(\frac{Y_{ij} - \mu}{b_c}\right)\right]$$

in which $\phi(z) = (2\pi)^{-1/2} \exp(-z^2/2)$ and

$$\Phi(z) = \int_{-\infty}^{z} \phi(x)dx$$

The values $\bar{\mu}$ and β_c which maximize the likelihood function $L(\mu, b_c)$ are the maximum likelihood estimates of μ and b_c, respectively. A computer algorithm to compute $\bar{\mu}$ and β_c follows.

In order to estimate the coefficient, β_r, first the maximum likelihood formula is applied to the data from the ith manufacturer to obtain $\bar{\mu}_i$ and β_{ri} which are the estimated values of μ_i and b_{ri} that maximize the likelihood function

$$L_i(\mu_i, b_{ri}) = \prod_{j=1}^{n_i} \phi\left(\frac{X_{ij} - \mu_i}{b_{ri}}\right) \prod_{j=1}^{m_i} \left[1 - \Phi\left(\frac{Y_{ij} - \mu_i}{b_{ri}}\right)\right]$$

Then, the estimate of b_r, denoted by β_r, is obtained from a weighted mean of the values $\beta_{r_i}^2$ for all subsets, i.e.

$$\beta^2_r = \sum_{i=1}^{k} (n_i - 1)\, \beta_{r_i}^2/(N - k)$$

A.3.1 Algorithm to find $\bar{\mu}$ and β_c

The algorithm employed is the standard expectation and maximization (EM) algorithm. First, initial values of $\bar{\mu}$ and β_c are given as follows

$$\bar{\mu}(0) = \bar{X}$$

$$\beta^2_c(0) = \sum_{i=1}^{k} \sum_{j=1}^{n_i} (X_{ij} - \bar{X}_i)^2/(N - 1)$$

Then, the calculations are executed in two steps. In the first step, the following computations are performed

$$Y^{*}_{ij} = \frac{\beta^{(0)}_c * \exp(-Y^2_{ij}/2)}{(2\pi)^{1/2}\,[1 - \Phi(Y_{ij})]} + \bar{\mu}(0) \qquad i=1,\ldots,\ell;\ j=1,\ldots,m_i$$

$$Y^{**}_{ij} = [\beta^{(0)}_c]^2 \left[\frac{Y_{ij} \exp(-Y^2_{ij}/2)}{(2\pi)^{1/2}\,[1 - \Phi(Y_{ij})]} + 1\right]$$

$$+ \frac{2\beta^{(0)}_c\, \bar{\mu}(0) * \exp(-Y^2_{ij}/2)}{(2\pi)^{1/2}\,[1 - \Phi(Y_{ij})]} + \bar{\mu}(0) \qquad i=1, 2,\ldots,\ell;\ j=1,\ldots,m_i$$

The second step in the analysis computes the following

$$\bar{\mu}(1) = \frac{1}{N + M} \left[\sum_{i=1}^{k} \sum_{j=1}^{n_i} X_{ij} + \sum_{i=1} \sum_{j=1}^{m_i} Y^{*}_{ij} \right]$$

$$\beta_c^2(1) = \frac{1}{N + M} \left[\sum_{i=1}^{k} \sum_{j=1}^{n_i} X_{ij}^2 + \sum_{i=1}^{\ell} \sum_{j=1}^{m_i} Y^{**}_{ij} - (N + M)(\bar{\mu}(0))^2 \right]$$

where N and M stand for

$$N = \sum_{i=j}^{k} n_i$$

$$M = \sum_{j=1}^{\ell} m_j$$

If $|\mu(1) - \mu(0)| < \varepsilon$ and $|\beta_c(1) - \beta_c(0)| < \varepsilon$, then let $\bar{\mu} = \bar{\mu}(1)$ and $\beta_c = \beta_c(1)$ where ε is a small number, e.g. 0.0001. Otherwise, let $\bar{\mu}(0) = \bar{\mu}(1)$ and $\beta_c(0) = \beta_c(1)$ and continue the previous calculations in the two steps until it converges.

NOMENCLATURE:

b_c = Total coefficient of variance of the population
b_r = Coefficient of variation due to randomness of population
b_u = Coefficient of variation due to uncertainty of population
f_{ij} = Fragility data
$L(.,.)$ = Likelihood function of the data
M = Total sample size of qualification data for all specimens
m_i = Sample size of qualification data of ith specimen
N = Total sample size of fragility data for all specimens
n_i = Sample size of fragility data of ith specimen
q_{ij} = Qualification data
R_i = Random variable
U_{ij} = Random variable
X = Sample mean of X_{ij}, moment estimate of μ
X_{ij} = Ln f_{ij}
Y_{ij} = Ln q_{ij}
β_c = An estimate of b_c
β_r = An estimate of b_r
β_u = An estimate of b_u
$\phi(.)$ = Standard normal density function
$\Phi(.)$ = Standard normal distribution function
μ = Mean of logarithmic values of population
$\bar{\mu}$ = Maximum likelihood estimate of μ

APPENDIX B
TRS AT 5% DAMPING VALUE

APPENDIX B

B.1 INTRODUCTION

This appendix is added to the report to provide fragility TRS curves at a damping value of 5% for ease of comparison with the ruggedness curves obtained by EPRI/ANCO at the same damping value [5]. All the TRS curves included in Chapters 3 - 6 to exhibit the equipment performance levels are presented in this section at a damping value of 5%.

Since, as mentioned above, the anticipated use of these curves is to compare with the EPRI/ANCO curves, the TRS data are converted to 5% damping, wherever necessary, by employing the same conversion factors as used by EPRI/ANCO, which are the square roots of the inverse ratio of the damping values. For example, in conversion from 2% to 5%, the responses are divided by a factor of $(5/2)^{1/2}$, e.g., 1.58, with no high-frequency response values lower then the ZPA. Obviously, the curves which were originally presented in the test report at 5% damping are simply redrawn in this section. It is emphasized that the above conversion factors (e.g., 1.58) are used only for direct comparison with the EPRI/ANCO curves similarly obtained, although the authors do not necessarily endorse these numbers for any other use (Reference Section 2.1).

For convenient reference, a suffix has been added to the figure numbers at 2% damping to present the figures at 5% damping. The curve numbers in any figure are identical. For description and use of these curves, one should refer to the appropriate texts provided in Chapters 3 - 6 of this report.

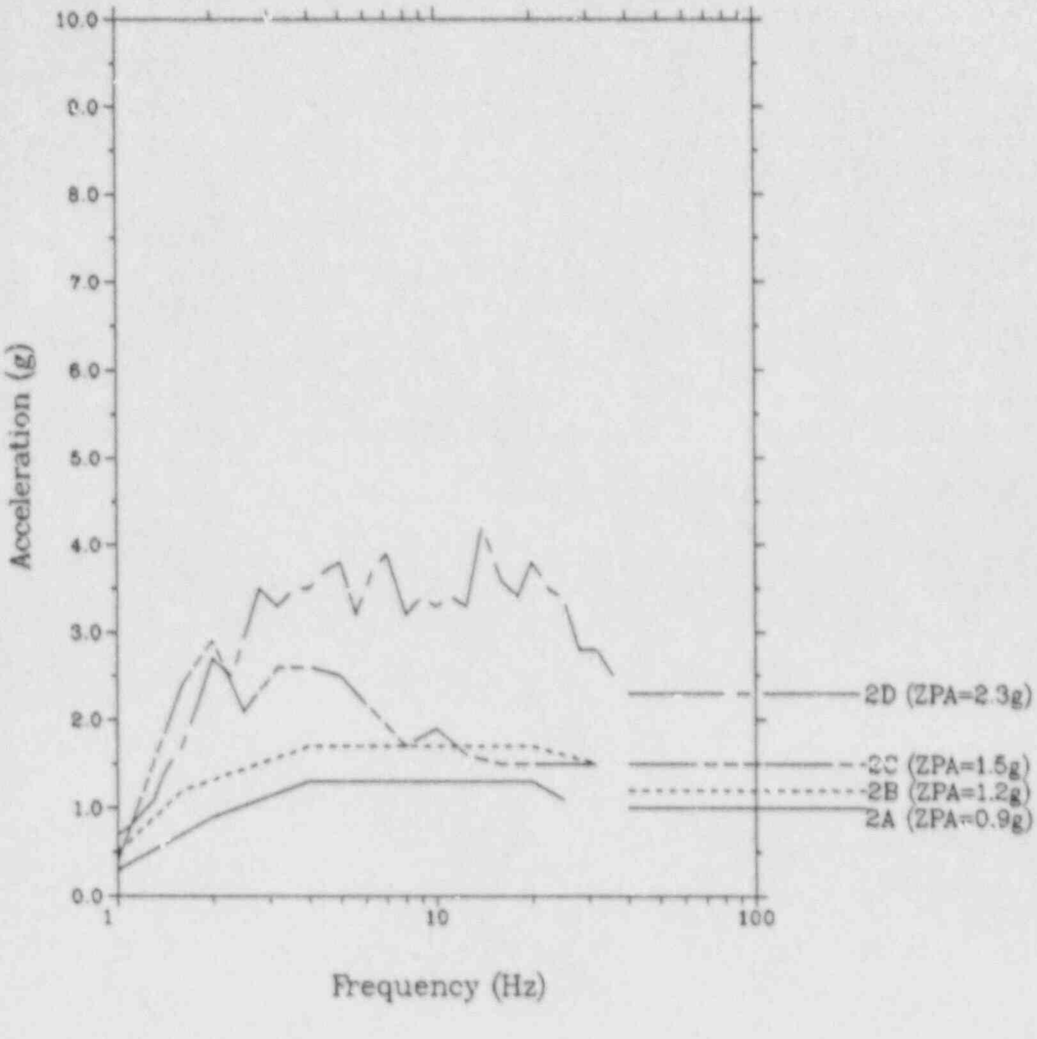

Fig. 3-2a Horizontal TRS @ 5% Damping - Motor Control Center

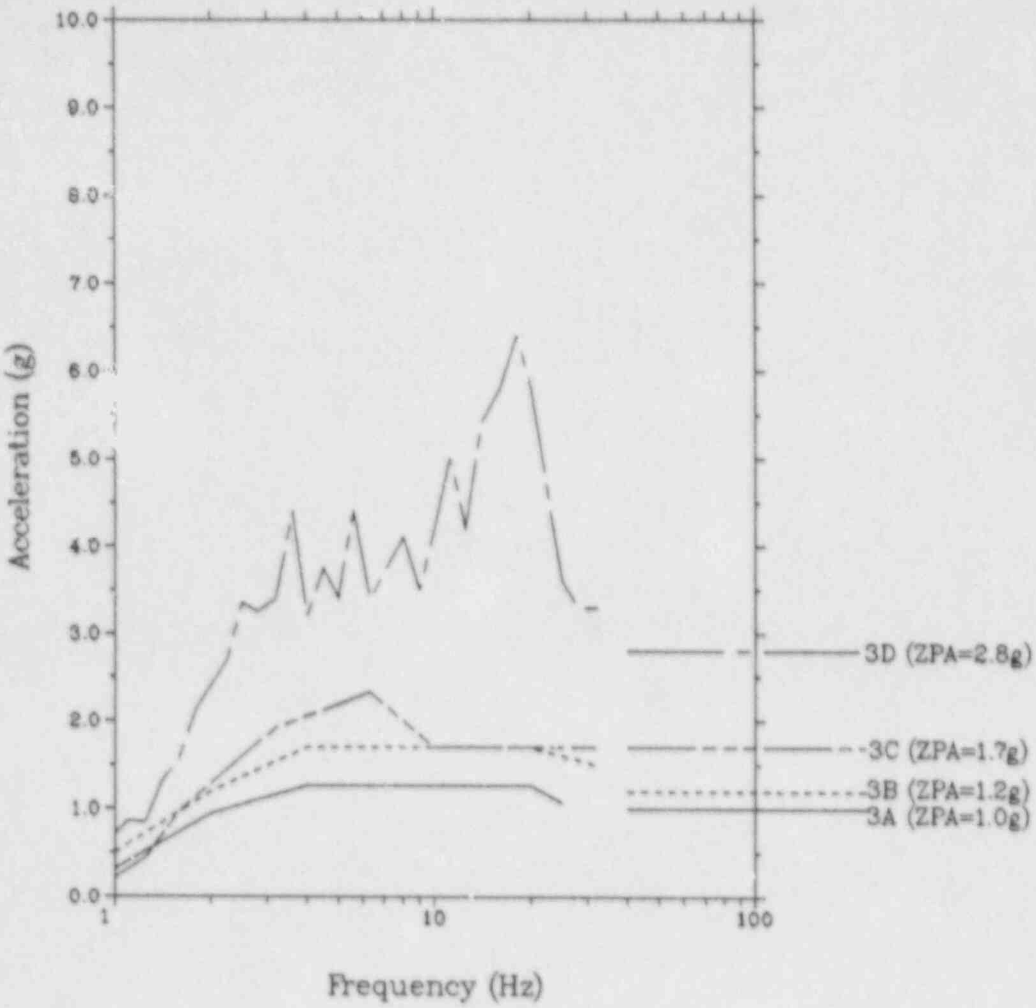

Fig. 3-3a Vertical TRS @ 5% Damping – Motor Control Center

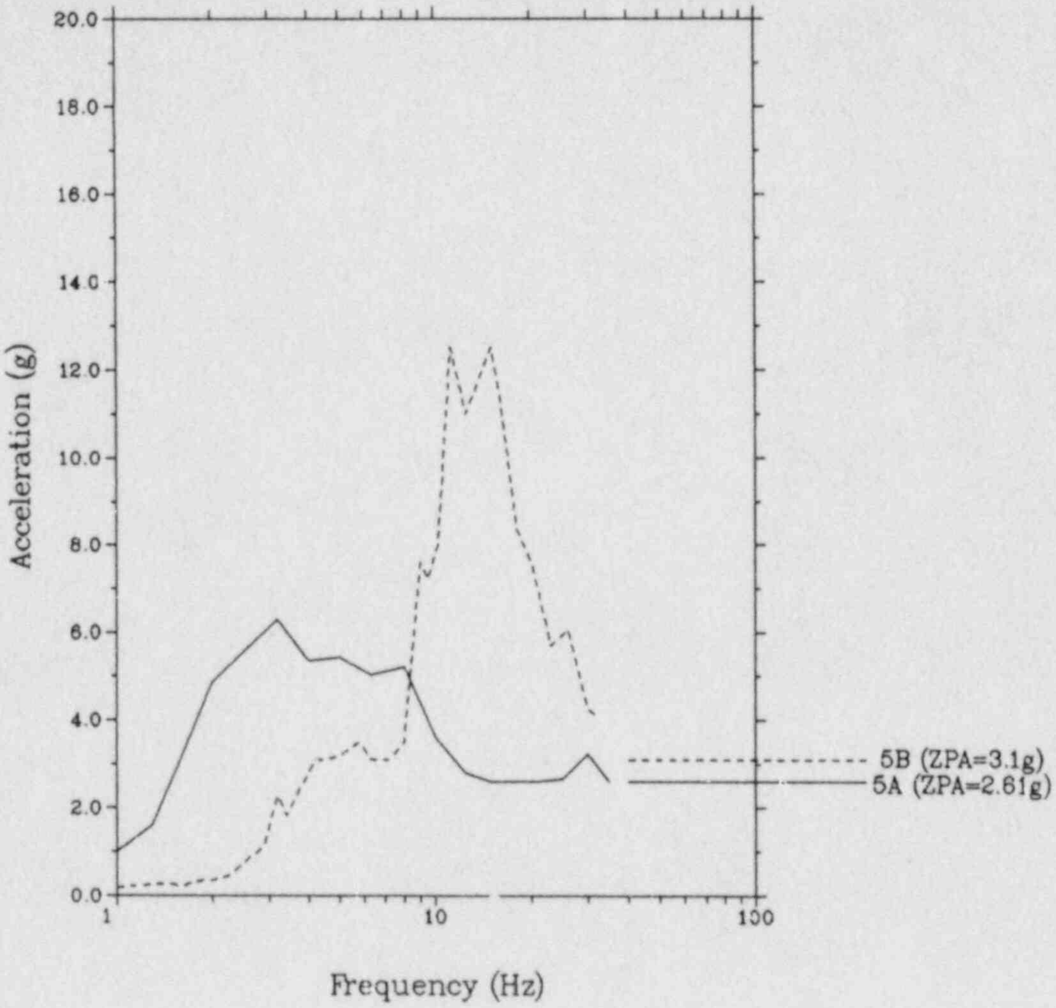

Fig. 3-5a Horizontal TRS @ 5% Damping - MCC Starter Auxiliary Contact

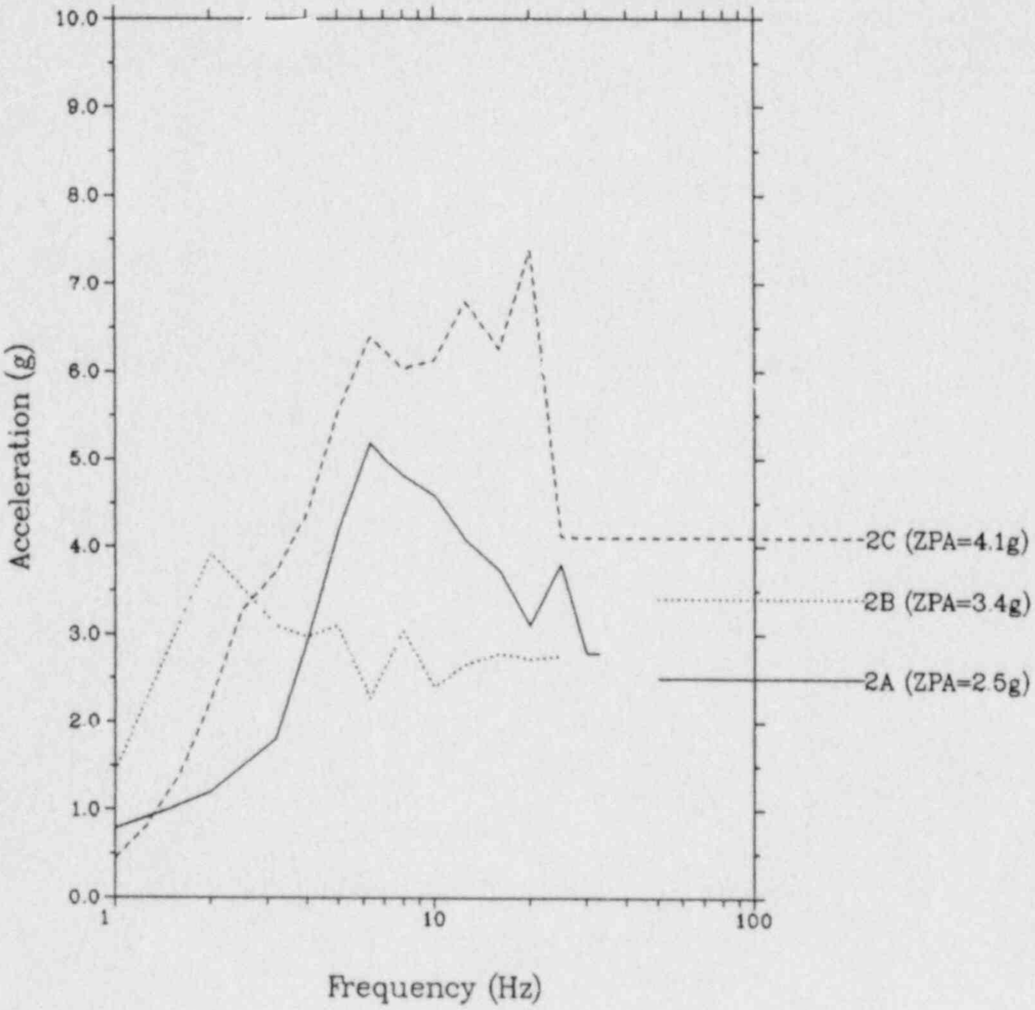

Fig. 4-2a: Horizontal TRS @ 5% Damping - Switchboard

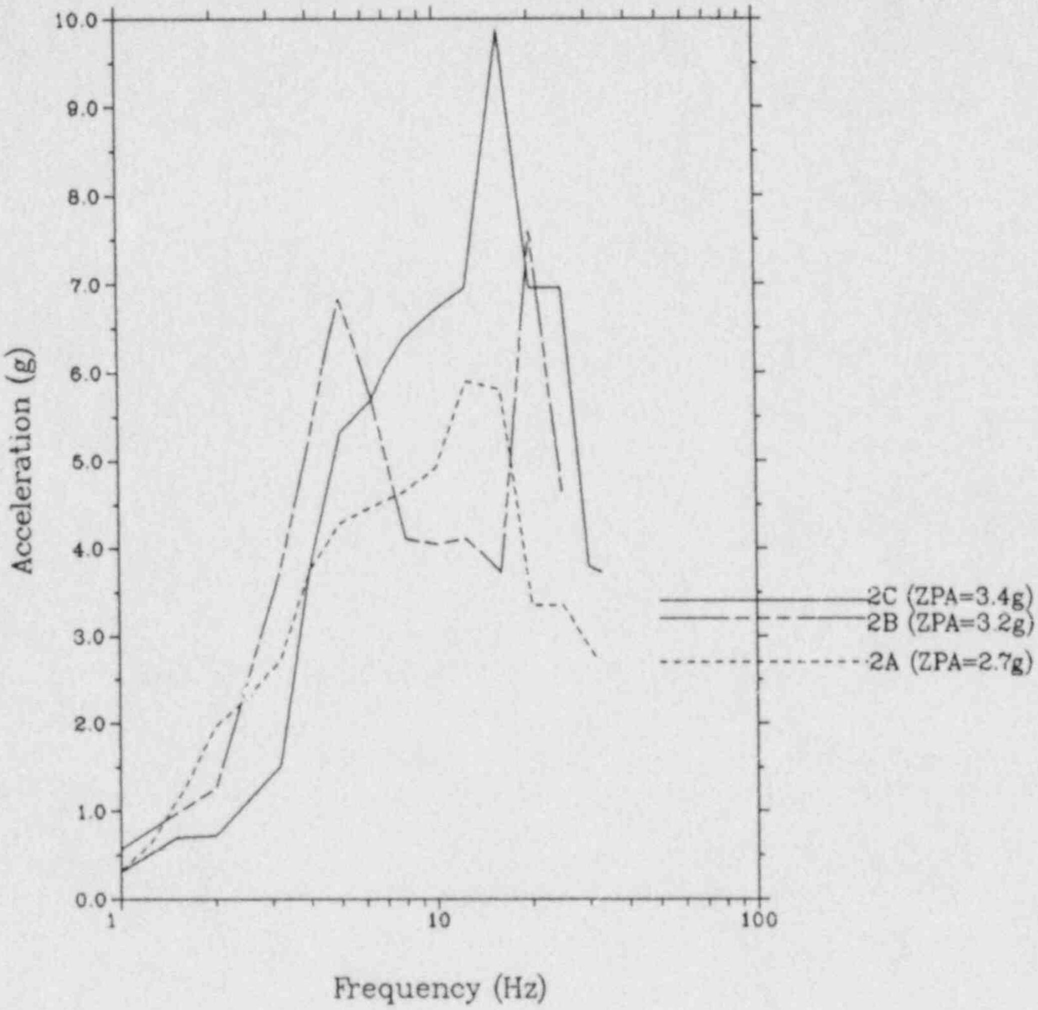

Fig. 4-3a: Vertical TRS @ 5% Damping – Switchboard

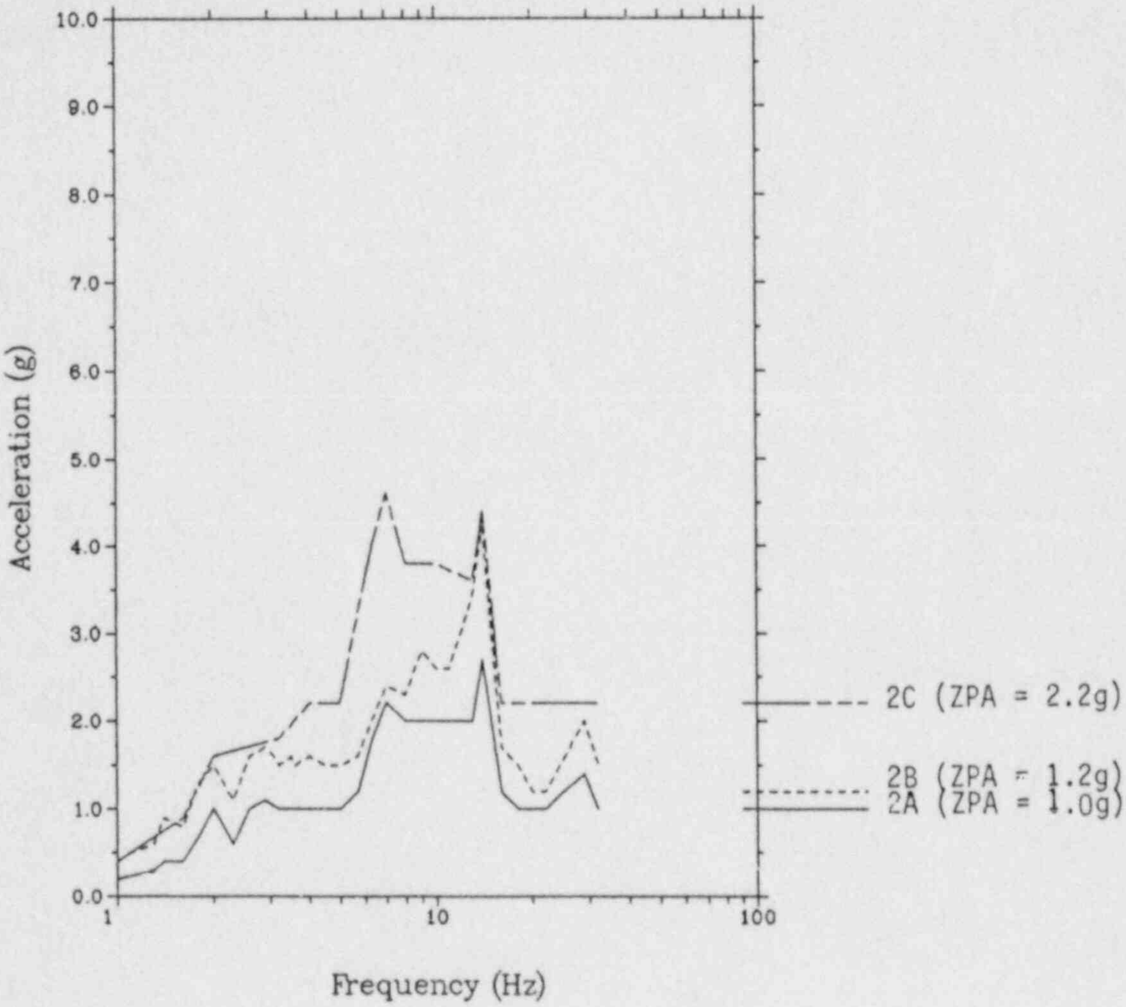

Fig. 5-2a: Horizontal TRS @ 5% Damping - Panelboard

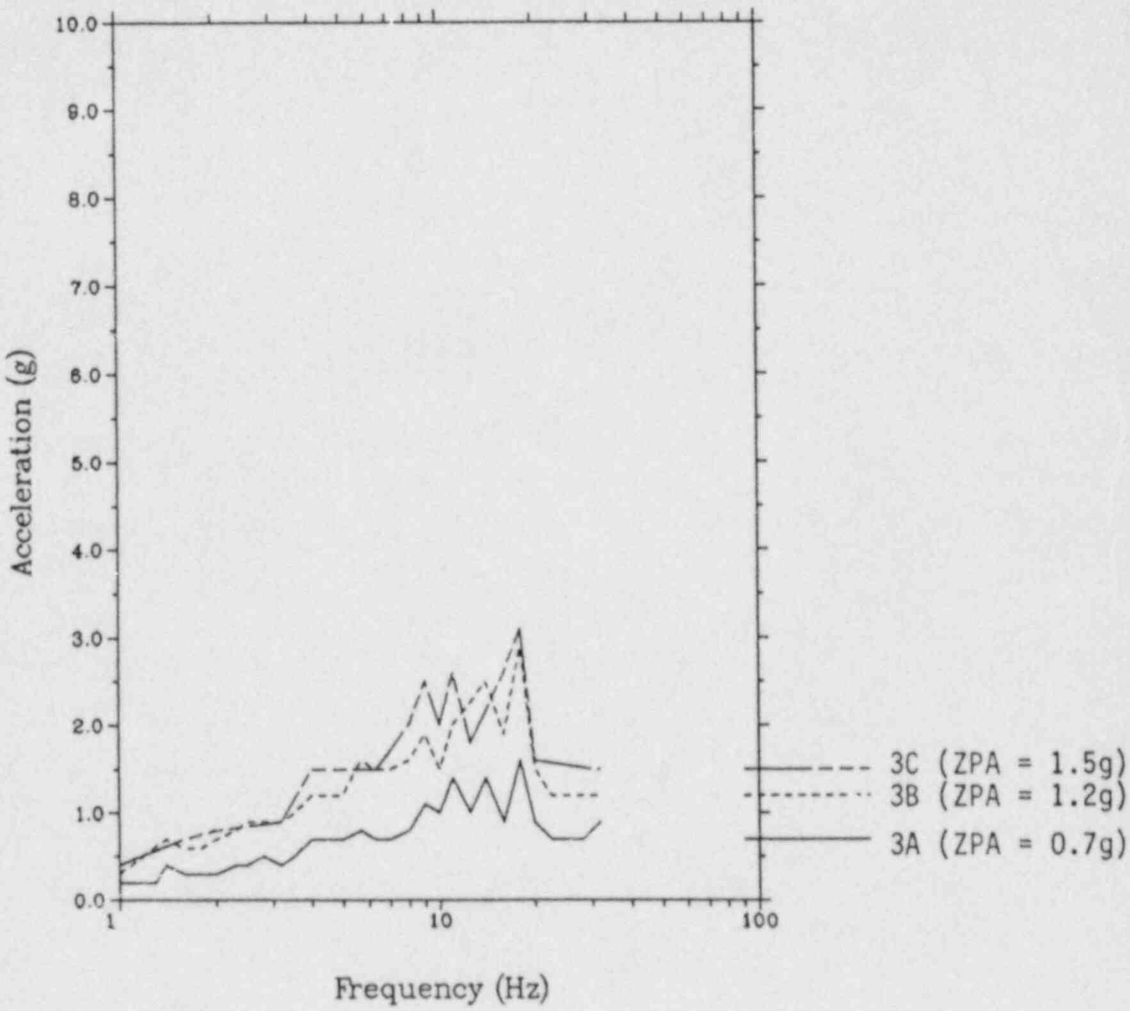

Fig. 5-3a: Vertical TRS @ 5% Damping - Panelboard

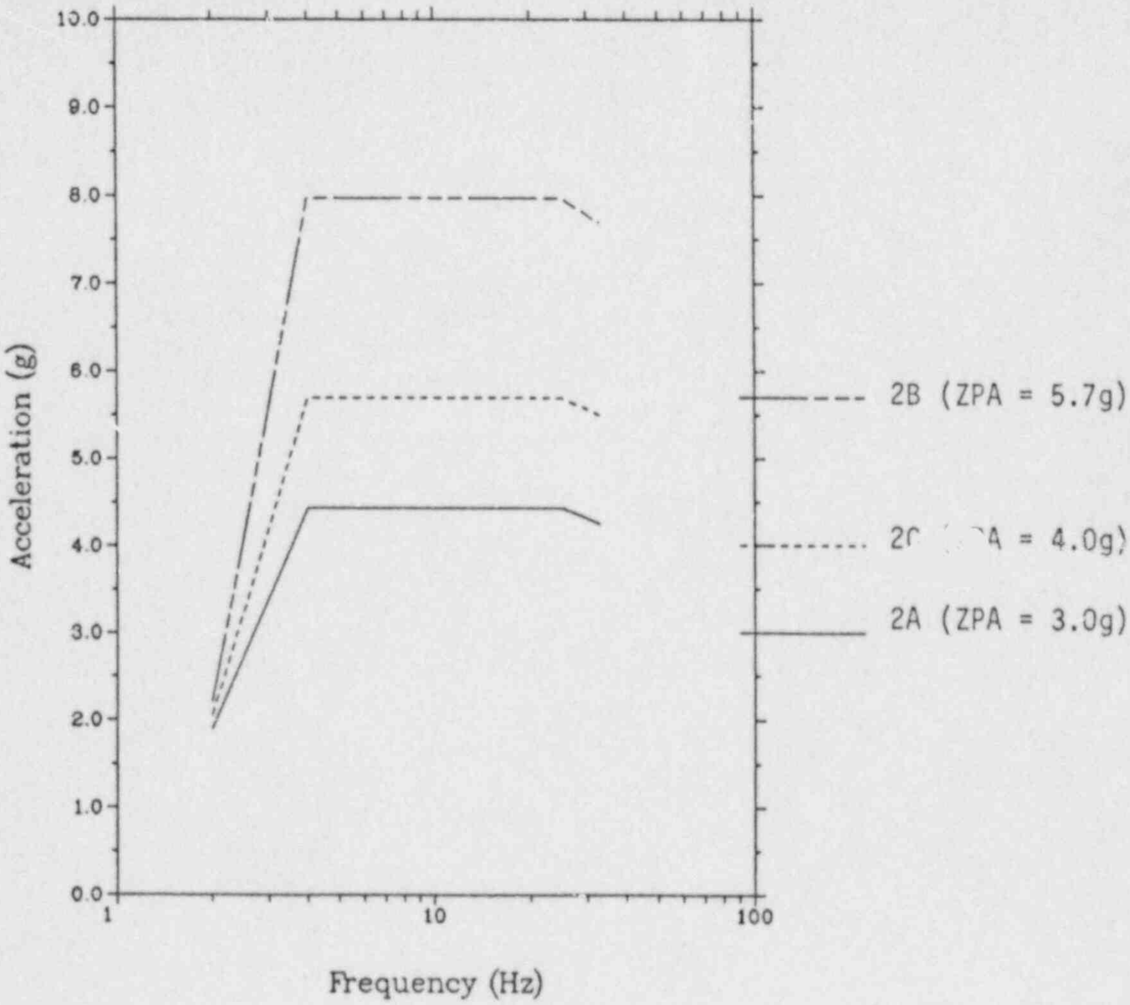

Fig. 6-2a TRS @ 5% Damping - DC Power Supply

APPENDIX C
DYNAMIC AMPLIFICATION OF ELECTRICAL PANELS

APPENDIX C
DYNAMIC AMPLIFICATION OF ELECTRICAL PANELS

C.1 INTRODUCTION

As part of the Component Fragility Program, BNL is involved in computation of dynamic amplification factors for approximately eighteen electrical panels by use of existing test data. The amplification exhibited by the panel at the qualification or fragility level vibration input is being studied. In these test programs, the input is typically multi-frequency excitation and is measured in terms of a test response spectrum (TRS). In this study, the amplification factor at any frequency is defined as the ratio of the respective spectral acceleration values corresponding to the response and the control accelerometer readings. The results are presented in the form of amplification spectra i.e. plots exhibiting the amplification value at each frequency.

In this appendix, the amplification factors of one motor control center and one switchgear are presented for illustration purposes only. The results for all the eighteen pieces of panels including these two panels will be discussed in detail and published in a separate report in FY 1988.

C.2 MOTOR CONTROL CENTER (MCC)

The MCC specimen was a four-bay cabinet each bay measuring 90 inches (high) X 20 inches X 20 inches and weighing approximately 600 lbs. The cabinet structure was strengthened with seismic stiffeners especially at the base. The MCC was mounted with sixteen (16) 1/2 inch diameter grade 5 bolts torqued to 60ft-lbs.

The results of a fragility level test run have been studied. The specimen exhibited the fundamental frequency of 7-9Hz in the FB direction at this vibration level. The dynamic amplification factors have been computed at six locations on the MCC (Figure C-1). The locations have been visually estimated from photographs of the test set-up. Accelerometer number 1 was mounted on the MCC panel. All other accelerometers were placed inside the plug-in units containing devices such as motor starters and circuit breakers, and were installed at or very close to the mounting locations of these devices.

The dynamic amplification values corresponding to each accelerometer reading at this test run are presented in Figures C-2 and C-3.

C.3 SWITCHGEAR

The switchgear was a three-bay cabinet containing medium voltage breakers. It measured 90 inches high, 36 inches wide and 90 inches deep, and weighed approximately 2700 lbs. The specimen was welded to the shake table. The accelerometers were mounted on the panel next to devices and their approximate locations are shown in Figure C-4. The corresponding dynamic amplification spectra are shown in Figure C-5.

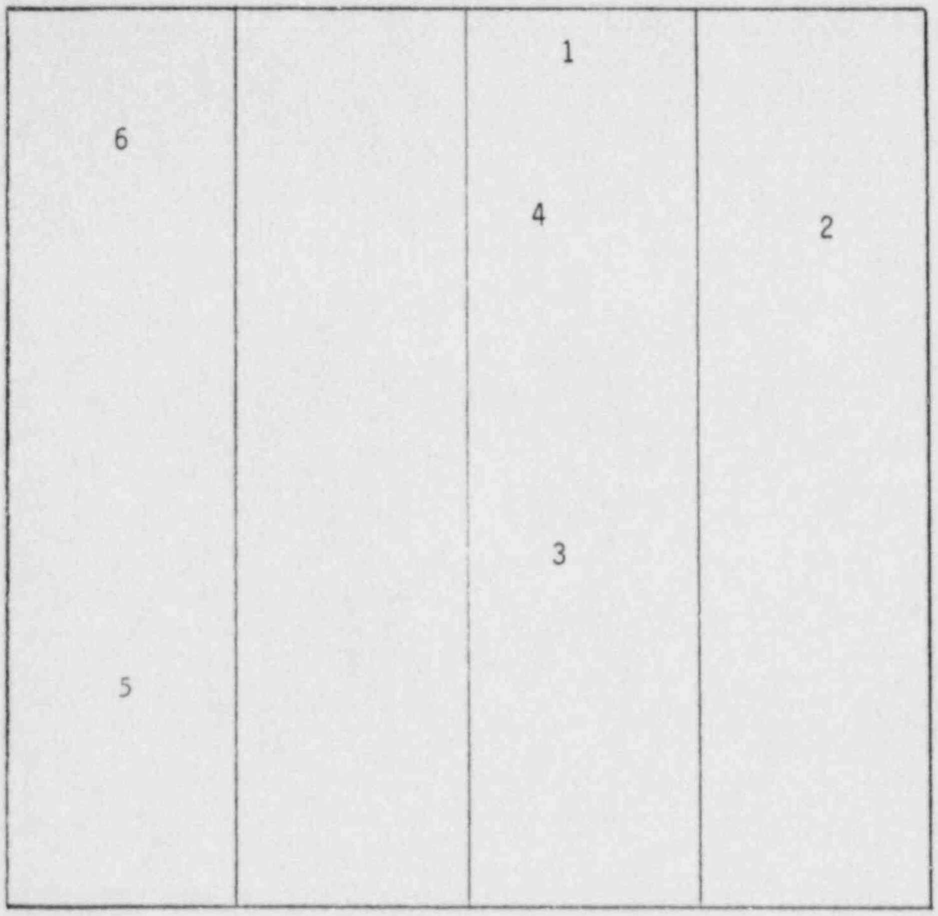

Fig. C-1 Acclerometer Locations on a Four-Bay Motor Control Center (Front View)

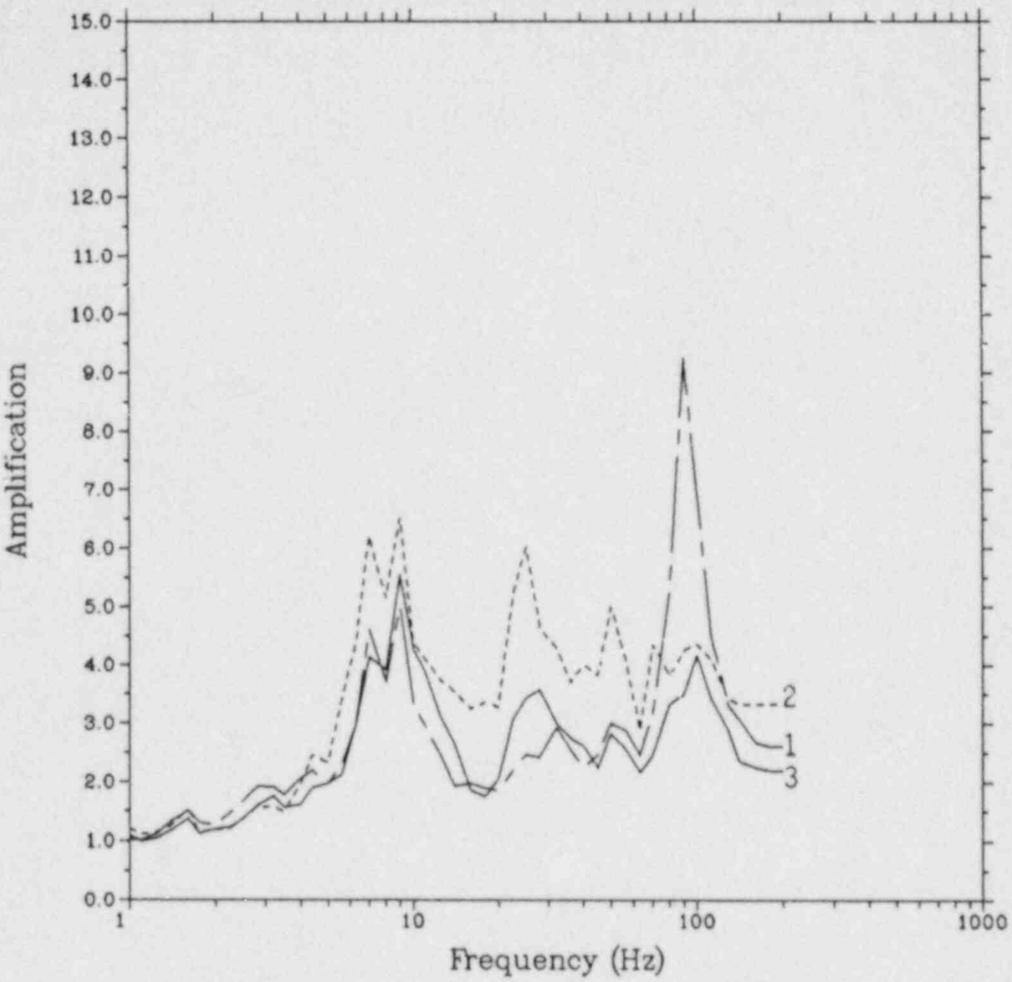

Fig. C–2 Amplification Spectra for Motor Control Center Accelerometers 1, 2, and 3

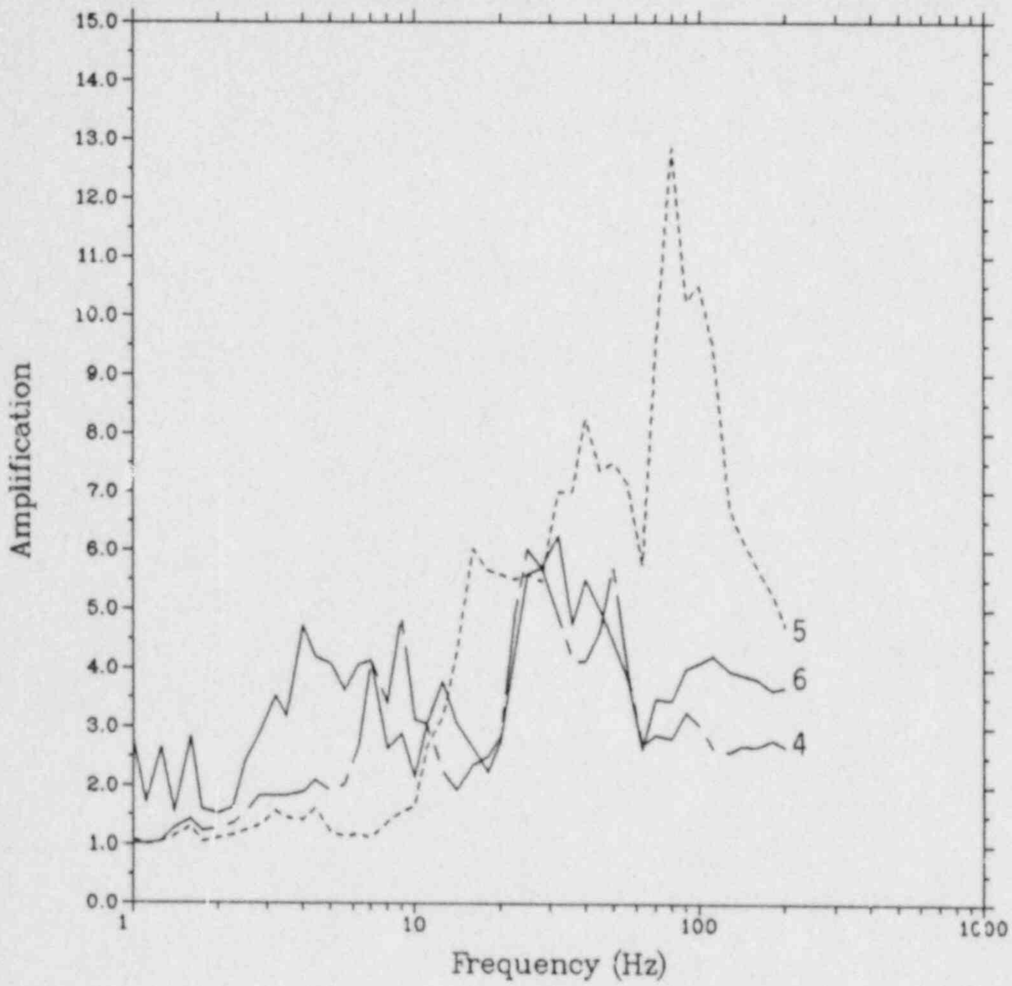

Fig. C-3 Amplification Spectra for Motor Control Center Accelerometers 4, 5, and 6

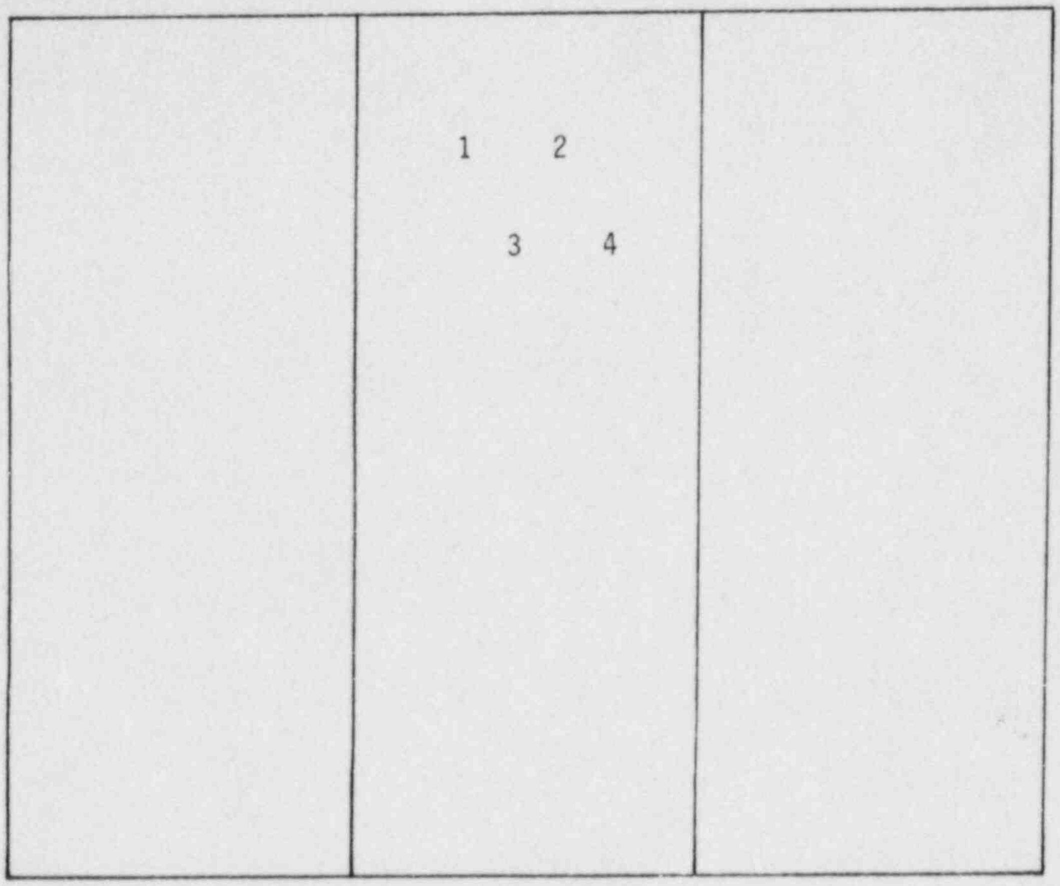

Fig. C-4 Accelerometer Locations on a Three-Bay Medium Voltage Switchgear (Front View)

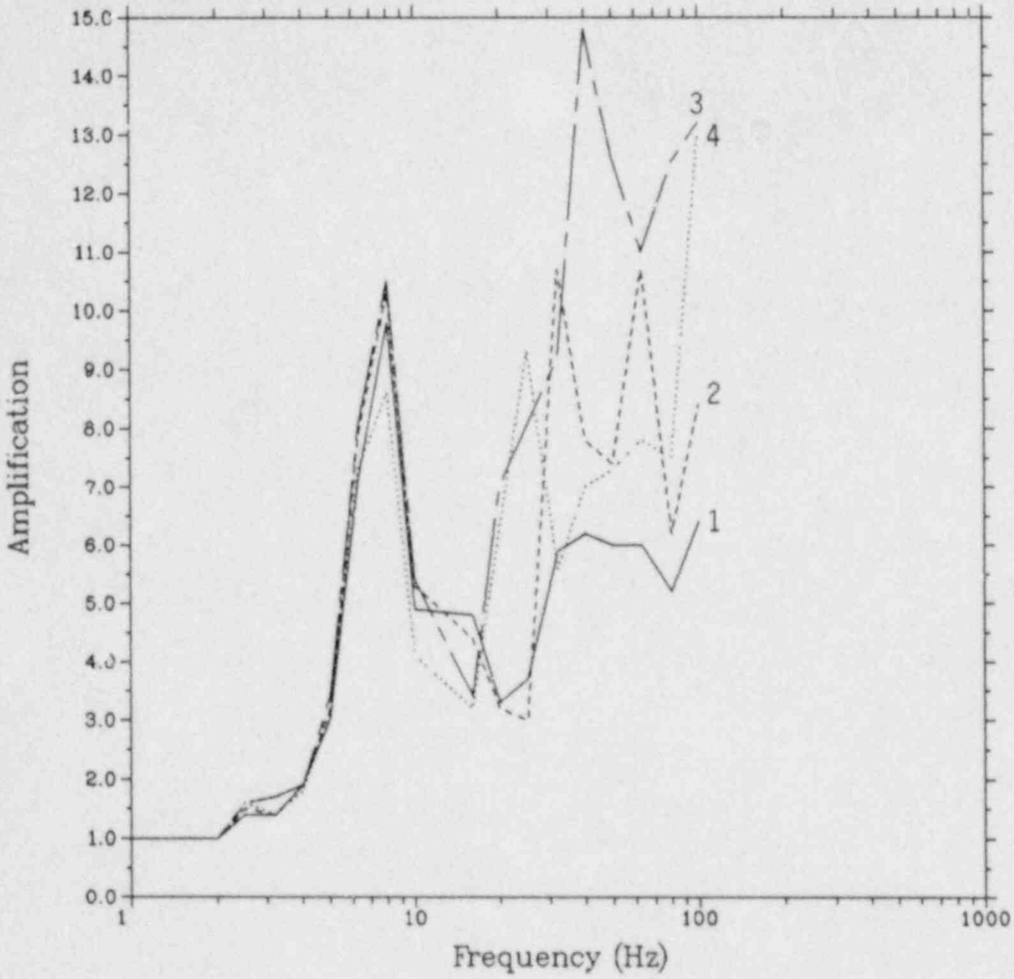

Fig. C-5 Amplification Spectra for Switchgear

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13. ABSTRACT (200 words or less)

In Phase I of the Component Fragility Program, Brookhaven National Laboratory (BNL) has developed a procedure to establish the seismic fragility of nuclear power plant equipment by use of existing test data and demonstrated its application by considering two equipment pieces. In Phase II of the program, BNL has collected additional test data, and has further advanced and is applying the methodology to determine the fragility levels of selected essential equipment categories. The data evaluation of four equipment families, namely, motor control center, switchboard, panelboard and power supply has been completed. Fragility levels have been determined for various failure modes of each equipment class and the deterministic results are presented in terms of test response spectra. In addition, the test data have been analyzed for determination of the respective probabilistic fragility levels. The zero period acceleration and the average spectral acceleration over a frequency range of interest are used as inputs in the statistical analysis. The resulting fragility parameters are presented in terms of a median value, an uncertainty coefficient and a randomness coefficient. Ultimately, each fragility level is expressed in terms of a single descriptor called an HCLPF value corresponding to a high (95%) confidence of a low (5%) probability of failure. The important observations and recommendations for future research work in the fragility area are included in this report. One of the important needs is to study the applicability of the fragility results to the earlier vintage equipment for which little or no test data exist.

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