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SEISMIC FRAGILITY OF NUCLEAR POWER PLANT COMPONENTS (PHASE I)

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ABSTRACT

As part of the Component Fragility Research Program, sponsored by the U.S. Nuclear Regulatory Commission, BNL is involved in establishing seismic fragility levels for various nuclear power plant equipment by identifying, collecting and analyzing existing test data from various sources. In Phase I of this program, BNL has reviewed approximately seventy test reports to collect fragility or high level test data for switchgears, motor control centers and similar electrical cabinets, valve actuators and numerous electrical devices, (e.g., switches, transmitters, indicators, relays) of various manufacturers and models.

This report provides an assessment and evaluation of the data collected in Phase I. The fragility data for medium voltage and low voltage switchgears and motor control centers are analyzed using the test response spectra (TRS) as a measure of the fragility level. The analysis reveals that fragility levels can best be described by a group of TRS curves corresponding to various failure modes. The lower-bound curve indicates the initiation of malfunctioning or structural damage; whereas, the upper-bound curve corresponds to overall failure of the equipment based on known failure modes. High level test data for some components are included in the report. These data indicate that some components are inherently strong and do not exhibit any failure mode even when tested at the vibration limit of a shake table.

The common failure modes are identified in the report. It is observed that for most electrical equipment, the failure is initiated by malfunction of some weak devices, e.g., contactors, motor starters, relays, switches. A comprehensive and coordinated study of relays is recommended.

The fragility levels determined in this report have been compared with those used in the PRA and Seismic Margin Studies. It appears that the BNL data better correlate with the HCLPF (High Confidence of a Low Probability of Failure) level used in Seismic Margin Studies and can improve this level as high as 60% for certain applications. Specific recommendations are provided for proper application of BNL fragility data to other studies.

Table of Contents

Table of Contents (Cont'd)

Table of Contents (Cont'd)

List of Figures

List of Figures

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EXECUTIVE SUMMARY

S.1 INTRODUCTION

The seismic fragility of safety-related equipment used for nuclear power plants has been studied under the auspices of the NRC Component Fragility Program. The program is intended to determine fragility levels, that will primarily be used in the following studies:

- Reassessment of equipment in existing plants, especially in the eastern United States, for earthquakes whose intensity exceeds the design basis, if such earthquakes are considered possible.

- Overall safety analysis of existing and new plants, e.g., Probabilistic Risk Assessments (PRA's) and Margin Studies.

The first phase of the Component Fragility Program has been jointly conducted by Brookhaven National Laboratory (BNL) and Lawrence Livermore National Laboratories (LLNL). BNL's research scope in Phase I has comprised the following activities:

- Initiating cooperation with domestic and foreign institutions to: (a) establish lines of communication with vendors, owners and testing laboratories to determine availability of already existing component fragility data; (b) negotiate the transfer of existing component fragility data to BNL; and (c) host a workshop on component fragility.

- Assembling, analyzing and interpreting available fragility data for mechanical and electrical equipment important to safety.

- Comparing results with component fragilities used in current PRA and Seismic Margin Studies and recommending improvements where possible.

The objective of this report is to publish the component fragility study performed by BNL in Phase I following the above research scope. As part of this program, BNL published a separate report in August 1985, entitled "Proceedings of the Workshop on Seismic and Dynamic Fragility of Nuclear Power Plant Components" (NUREG/CP-0070), based upon the presentations in the Component Fragility Workshop hosted by BNL in June 1985.

LLNL's scope in Phase I has been to develop a scheme for prioritizing components for fragility testing and to demonstrate, by test, a procedure for performing component fragility tests. LLNL's study is being published as a separate NUREG.

S.2 DATA COLLECTION

In Phase I, BNL has collected existing fragility and high level test data for various electrical and control equipment including switchgears, motor control centers, small transformers, relays, switches, valve operators, etc. In obtaining the data, contact has been established with various source organizations. These contacts have yielded approximately seventy test reports which have been reviewed for extraction of test data. A summary of the collected data has been stored on an equipment basis in a computerized data bank at BNL. For switchgears and motor control centers, the collected data are considered adequate to generically represent a majority of the respective equipment families used in nuclear power plants in the United States.

S.3 DATA EVALUATION

The test data collected for various models of switchgears and motor control centers manufactured by four major companies have been analyzed to determine their respective fragility levels. The test response spectrum (TRS) curves at 2% damping value have been used to compare and evaluate the performance of various types of equipment. From testing of a specimen subjected to a gradual increase in the test vibration, a number of response spectrum curves have been obtained corresponding to various failure modes. Instead of assigning one curve as the fragility level, a number of curves have been used and the associated anomalies observed for each response spectrum level have been identified, so that the user can select the appropriate fragility level of the component by considering its specific application. Thus, the fragility of an equipment is described by a group of response spectrum curves corresponding to various failure modes. The lower-bound curve indicates initiation of malfunctioning or structural damage; whereas the upper-bound curve corresponds to overall failure of the equipment occurring separately or interactively. Such fragility data for various equipment models from different manufacturers have been assembled to obtain the seismic fragility level for the generic equipment family. Thus, the fragility level used in this report may not necessarily be the ruggedness level, a term that has been used to indicate the highest available qualification level. It has been observed that some components were tested to high levels, often to the capacity level of the shake table, yet exhibited little or no structural damage. The response spectra of such tests might be high enough for some applications so that the real fragility levels of the equipment need not be established. Test data of some electrical components (e.g., EPA's, RTD's, terminal boards) have been included in this report.

S.4 OBSERVATIONS

In the process of collecting and evaluating test data, a number of important observations have been made regarding the amount and the quality of available fragility data, failure modes, device behavior, cautions to be exercised in defining a vibration input as the fragility level, etc. These observations are summarized as follows:

- A large amount of fragility data exists in the industry, residing especially with the manufacturers who conducted tests in the process of developing and improving their equipment. This information, if it can be made completely available, will greatly enhance the fragility data base and dramatically reduce the need and cost of any future fragility testing. This information is difficult to obtain due to proprietary constraints; however, some organizations are willing to release these data provided they are properly protected and utilized as part of a generic data base.

- In an equipment assembly (e.g., switchgear, motor control center) some devices are more vulnerable to seismic environment than others. Thus the overall fragility level of the equipment is limited by malfunction of such devices. These devices and their malfunctions are enumerated as follows:

  a) Contactors - chattering
  b) Motor Starter - chattering, dropping out load, changing state, erratic behavior
  c) Time Delay Relays - time setting
  d) Other Relays - chattering, non-operability
  e) Switches - chattering

  The presence of these devices and their effect on the fragility level should be carefully judged.

- Among the sensitive devices, certain types may withstand a substantially higher vibration level than that of another. Therefore, in evaluating the seismic margin or the risk of a specific plant, consideration should be given to the type of device used.

- Equipment design has evolved with time. Due to emphasis on stringent seismic qualification criteria since the mid-seventies, later products have been observed to withstand higher vibration inputs. Therefore, plants utilizing later products should not be unduly penalized by limiting the capacity level to that determined based on earlier products.

- Self-tapping screws have been observed to strip at a much lower vibration level than what the equipment frame can otherwise withstand. Proper consideration should be given if such screws are present.

- Sometimes in a fragility test the capacity level of a specimen in the horizontal direction is governed by the excitation level in the side-to-side direction. However, in application such equipment might be stiffened by the presence of a larger number of units or by some other means. Therefore, in such cases, the front-to-back vibration level, although higher, might be the governing fragility level in the horizontal direction in the actual installation.

- In multiaxis vibration tests, simultaneous test inputs in different directions should be considered while defining one input as the fragility level in that particular direction. For example, in a typical test program it has been observed that for the same input in one direction, the test specimen passed one test run but failed a subsequent run, due to the fact that the input in the second axis had been doubled. This is especially true for complex equipment for which a strong coupling effect is expected.

- Many electrical devices are frequency-sensitive. In a test program, the malfunction of a device was eliminated by reducing the low frequency content of the vibration input. In another test run, the vibration amplitude was very high at a high frequency band with a high ZPA level; while a low frequency-sensitive device withstood this level without any sign of malfunction. These facts indicate that frequency content of the vibration input must be incorporated in the definition of a fragility level. Obviously, defining the fragility by the ZPA level alone would not address this issue.

S.5 RECOMMENDATIONS FOR FUTURE RESEARCH

In Phase I of the Component Fragility Program, two simultaneous but distinct approaches were undertaken, namely, fragility determination by conducting new tests and by analyzing existing test results. The objective in pursuing different approaches was to establish a definite direction that would lead to a successful completion of the program. At the end of Phase I, it appears that the approach should be to exhaust all existing data sources prior to undertaking a new fragility test program. In this context, the following recommendations have been provided toward defining the seismic fragility levels of all important safety-related equipment families and presenting the fragility data in a fashion acceptable to current risk assessment and margin studies:

- The data collection task should continue until sufficient data are collected for all important equipment families. The amount and quality of these data are the pivotal factors for success and reliability of any subsequent fragility analysis.

- The analysis of all collected data should continue and be completed following the guidelines discussed and illustrated in this report.

- Special studies should be undertaken in the following areas concerning seismic fragility:

  - transformation of TRS from one damping value to another
  - effect of equipment mounting
  - seismically weak devices, e.g., contactors, motor starters, relays, switches
  - application of fragility data in PRA and Margin Studies (discussion follows).

S.5.1 Application of Fragility Data in PRA and Margin Studies

A special discussion on this item, recommended above as a future study, has been considered appropriate since the major and immediate application of the fragility levels determined by the Component Fragility Research Program will be in the overall safety analyses of the plants. The following two types of analysis are currently being performed or discussed:

1. Probabilistic Risk Assessment (PRA)
2. Seismic Margin Studies

Both of these analysis techniques in their current forms require the input of the equipment fragility level in terms of ZPA or PGA. ZPA, or the zero period acceleration, is the highest amplitude of a given time history and PGA is the peak acceleration of the ground motion[1]. Moreover, the ZPA or the PGA used in PRA and Margin Studies is a statistical number with a standard deviation. On the other hand, the fragility level data presented in this report based on test results, are in the form of test response spectra (TRS) including the ZPA of the test vibration time history. The reasons for selecting TRS as the indicator of a fragility level can be summarized as follows:

1. The test results are available in the form of TRS, and rarely in any other forms.
2. TRS, as opposed to ZPA alone, provide a better measure of the severity of the test vibration since it includes the effects of frequency content.
3. A TRS plot is a basic data source and the information needed for a specific application can be extracted from it. Thus, the fragility level defined by TRS is expected to serve the needs of various users.

Nevertheless, there is a gap between the fragility format being used for the PRA and Margin Studies and that presented in this report. Therefore, it is recommended that further study be pursued to determine how and in what format the fragility level data presented in this report can be best utilized in the PRA and Margin Studies. If needed, a conversion methodology should be developed. In this regard, a discussion is provided as follows, which identifies several aspects for consideration in future research.

First, current PRA and Margin Studies derive their basic inputs regarding component fragility from a table of fragility "g"-values based primarily on expert opinion and some test data. Many of these tests were "shock tests"; therefore, a g-value was used as the indicator of fragility level vibration input. The PRA and the Margin Studies were accordingly developed to accept <u>one number</u>, i.e., one g-value, as the fragility input for the overall safety analysis. The effect of frequency content in the test vibration was apparently not included in these studies. However, it has been observed that the operability of electrical devices is very sensitive to the frequency content of the vibration input. Therefore, a future study should explore

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[1]Therefore, ZPA of the ground motion in the PGA.

whether the fragility input in the form of TRS data can be accepted and incorporated in the PRA and Margin Studies thus reflecting a more developed picture of the fragility phenomenon by use of evolved seismic data.

Second, if incorporation of the entire TRS in the PRA and Margin Studies, as discussed above, is found to be prohibitive for practical reasons, the next attempt should be to explore the possibility of inclusion of several key parameters of the TRS rather than only one parameter (i.e., ZPA or PGA) in the safety analysis. As a minimum the following parameters are recommended to be considered in such simplification of the TRS:

1. Peak response
2. Frequency at peak response
3. ZPA
4. Fundamental frequency of the equipment
5. Response at the fundamental frequency
6. Consideration of possible presence of frequency-sensitive devices

Third, if neither of the above two options proves to be feasible and future studies indicate that the PRA and Margin Studies cannot be modifed to accept more than one fragility indicator (i.e., a g-value), the following course of study is recommended. In order to retain the information regarding frequency content in the fragility level TRS, a standard time history should be used as the reference time history and a comparative number should be assigned to the testing time history (analyzed as the TRS) with respect to the reference time history. This number should basically indicate the severity of the test vibration compared to the reference time history. The ZPA, the peak response of the TRS, an equivalent ZPA, or any other comparative parameter can be selected for this purpose. An analysis technique or the judgment of an experienced engineer will probably be the tool to arrive at this number.

Fourth, the fragility level by TRS describes the vibration level at the location of the equipment. In other words, if the equipment is installed on a floor in a plant, the floor response spectra should be compared with the fragility TRS to evaluate the component's ability to withstand a specific earthquake event. However, if the PRA and Margin Studies can only accept the vibration parameter at the ground level and not the amplified response at the floor level of a particular plant, a further evaluation should be made to transform the fragility level of the equipment from its location to the ground level.

As further clarification of the above discussions, the PRA and the Margin Studies performed for the Zion Nuclear Plant have been considered as an example. Low and medium voltage switchgears and motor control centers have been used for comparison of the results obtained from various studies. The PRA used the fragility level as a median value (A_m) expressed in terms of "the effective-peak ground acceleration" (i.e., peak ground acceleration/1.23). The Seismic Margin Group defined the fragility level in terms of a "high-confidence-of-a-low-probability-of-failure" (HCLPF) level and measured this level in terms of the peak ground acceleration. In the Seismic Safety Margin Research Program (SSMRP), the component fragilities were expressed as "median values for local accelerations." The results of all these three previous studies have been compared with the BNL TRS fragility format and the corresponding ZPA levels. In conclusion, it appears that the BNL fragility data correlate better with the HCLPF levels, and that these levels can be further improved and enhanced by use of the BNL fragility analyses. As an illustration, the HCLPF level of Motor Control Centers determined for the Zion Plant has been compared with an equivalent PGA value based upon the fragility level presented in this report. It appears that the BNL Study can improve the HCLPF number by at least 60%. For switchgears, the improvement appears to be even greater. However, a proper application technique is to be developed as recommended above.

CHAPTER 1.

INTRODUCTION

1.1 BACKGROUND

Safety related electrical and mechanical equipment for nuclear power plants is seismically qualified by proof testing or analysis whereby the equipment function is demonstrated for a plant specific earthquake excitation level or for an excitation level which envelops the requirements of multiple plants. Although this qualification approach meets the requirements of a plant or a group of plants, it has an inherent limitation in that the qualification data may not reveal the equipment capacity level and failure modes. In the United States, this limitation has never been felt so acutely as in recent years primarily due to two reasons.

First, the possibility of earthquakes greater than the design basis is being considered for many nuclear plants, especially for eastern U.S. plants. This would require reassessment of the existing qualification in the light of a higher excitation level. However, extrapolation of proof or generic qualification data to new requirements often raises additional concerns rather than resolving the original problems.

The second reason stems from the Probabilistic Risk Assessments (PRAs) and Margin Studies being performed on new and existing plants to evaluate their overall safety. Both studies have indicated that seismic events are a non-trivial contributor to overall plant-induced risk or safety to the public and that the seismic behavior of safety related equipment plays an important role in the risk assessment. In order to include in a realistic manner the behavior of equipment in the PRA and the Margin Studies, the seismic fragility levels of such equipment are needed. To this end, usually a qualitative estimate of fragility levels is made based primarily upon engineering judgment and extrapolation of qualification data. Nevertheless, the existing proof or generic qualification results fail to satisfactorily meet this need.

Although the emphasis in the past has been on proof or generic qualification, numerous tests have been performed at very high seismic levels which approach the capacity of the tested equipment. Some fragility testing has also been conducted in the process of development and evolution of the product. Such testing has been performed by a wide variety of organizations utilizing various methods and vibration inputs; however, little has been done to present the results in a systematic fashion to meet current needs as mentioned above.

To meet these needs, the United States Nuclear Regulatory Commission (USNRC) has embarked on a research program to define the seismic fragility levels of safety related electrical and mechanical equipment. Obviously, testing all equipment under this program is not practical from a financial point of view. However, as indicated earlier, it has also been recognized that a certain amount of high level test results exists in various names and forms, that can clearly be utilized to establish seismic fragility of such equipment. Therefore, it has been judged that prior to undertaking an expensive fragility test program, the availability of existing fragility data will be explored. This approach will either outright eliminate the necessity of testing some equipment for which adequate fragility test data exist already, or minimize the testing expense by reducing the gap between the real fragility level and the starting vibration input for a new fragility test.

As part of this component fragility research program sponsored by the USNRC, Brookhaven National Laboratory (BNL) is involved in establishing seismic fragility levels for various equipment by identifying, collecting and subsequently analyzing capacity and fragility test data from various sources.

1.2 BNL's RESEARCH SCOPE

The scope of BNL's research program includes the following activities:

- Initiating cooperation with domestic and foreign institutions to: (a) establish lines of communication with vendors, owners and testing laboratories to determine availability of already existing component fragility data; (b) negotiate the transfer of existing component fragility data to BNL and (c) host a workshop on component fragility.

- Assembling, analyzing and interpreting available fragility data for mechanical and electrical equipment important to safety.

- Comparing results with component fragilities used in current PRA and Seismic Margin Studies and recommend the improvements where possible.

This program is being coordinated with Lawrence Livermore National Laboratory (LLNL) which is developing a scheme for prioritizing components for fragility testing and demonstrating by test a procedure for performing component fragility tests.

The combined efforts of BNL and LLNL represent Phase I of the NRC Component Fragility Program. Phase II of the program may be devoted to significantly greater data collection activities and comprehensive user-oriented component fragility analyses. Obviously, the more useable data that is uncovered during Phase I will minimize the need for a future testing program.

1.3 SUMMARY

As part of the research program, BNL has contacted various equipment manufacturers, testing laboratories, utilities, reactor suppliers and Architect-Engineer (A/E) firms to obtain information on existing component capacity data to establish fragility levels for generic classes of equipment. In the process of developing and/or qualifying their product, these organizations sometimes have capacity level test results of some equipment. Many of these organizations have responded favorably to support BNL's program and provided fragility level or related test data of some equipment. BNL'S Phase I effort has concentrated primarily on electrical equipment since according to present views these are the dominant risk contributors. Through a cooperative agreement and contract, BNL is also acquiring data from an industry-based seismic qualification and data collection program sponsored by the Electric Power Research Institute and conducted by ANCO Engineers, Inc.

Chapter 2 discusses the data collection procedure and provides a summary of data collected from various sources. The methodology used in interpreting and evaluating the data from individual sources and in obtaining the fragility or capacity level of the generic equipment is also described in this chapter.

Evaluation of the fragility data is illustrated by considering two important Class 1E equipment assemblies. Chapter 3 presents the fragility test data of switchgears. Both medium voltage and low voltage switchgears are included in the study. Test data covers various models of switchgears supplied by four major manufacturers. A description of the test specimen, test mounting, resonant frequencies, test levels and the corresponding failure modes, if any, for each test specimen, is included in this chapter. A generic study including an enveloping fragility level is also included in this chapter for both the medium and the low voltage switchgears.

Chapter 4 presents the fragility study of motor control centers. The various models from four major manufacturers are considered in this study.

Some components were tested to a high seismic level and sometimes to the shake table capacity level; still, no malfunctions were detected. Examples of such high level test data are presented in Chapter 5 by considering terminal boards, electrical penetration assemblies, electrical conductor seal assemblies, resistance temperature devices and thermocouple temperature sensors.

Chapter 6 covers the various type of relays, discusses the complexities of their analysis and presents some test data. A detailed study of relays is recommended as part of the Phase II program.

Chapter 7 provides a summary of the Phase I program and recommends specific items for a future research program (e.g., Phase II) needed to supplement the results of the Phase I program to address all important seismic issues associated with the equipment used in nuclear power plants. A comparative study of the BNL fragility levels and formats with respect to those used in the PRA and Margin Studies is also included in this chapter. Specific recommendations are provided for proper application of the BNL data in the above studies and for the future improvement and enhancement of the fragility data used in the PRA and Margin Studies.

Chapter 8 provides a list of publications used for reference in this report.

Appendix A presents a number of selected TRS curves at the 5% damping value for ease of comparison with "ruggedness" curves being generated by EPRI/ANCO.

In June 1985, BNL hosted a Workshop on Seismic and Dynamic Fragility of Nuclear Power Plant Components. The workshop participants included representatives of nuclear power plant utilities, major reactor suppliers, USNRC, A/E firms, testing laboratories, equipment manufacturers and suppliers, and seismic consultants. The workshop provided a forum for exchanging concepts, information and experiences on the fragility of electrical, control and mechanical equipment used in nuclear power plants when subjected to seismic and other dynamic environments. The exchange was partly in the form of contributed papers and partly through discussions by the participants. The importance of establishing seismic fragility levels of safety related equipment was upheld in the workshop and the participants expressed their willingness to support the fragility research program by sharing their experience and information. The workshop identified many past and present fragility testing programs and methods to compile, analyze and use fragility data. It highlighted the fact that there are considerable existing data within the industry which if compiled and evaluated could yield better estimates as to how well nuclear power plant components will operate in the event of an earthquake. Twenty-two oral presentations were made during the six workshop sessions. The written contributions that correspond to each presentation were published in August 1985 in NUREG-CP-0700, "Proceedings of the Workshop on Seismic and Dynamic Fragility of Nuclear Power Plant Components."

CHAPTER 2.

DATA COLLECTION AND EVALUATION METHODOLOGY

2.1 INTRODUCTION

One of the goals of Phase I of the Component Fragility Program was to determine whether adequate test data exist in the industry, which when collected and properly analyzed could reveal the seismic fragility level of most equipment. In order to explore the existing data sources, BNL has contacted various equipment manufacturers, testing laboratories, utilities, reactor suppliers and Architect-Engineer (A/E) firms. Many of these organizations have responded favorably and provided fragility level or related test data of various equipment. The test data collected from various sources have been subsequently evaluated and assembled on an equipment basis. The extent of the data collected in Phase I for various equipment and the methodology used in analyzing such data are discussed in this chapter. Illustrations by equipment class are included in the following chapters.

2.2 DATA COLLECTION

The data collection effort has concentrated primarily on electrical and control equipment since according to present views they are the dominant risk contributors. It has been observed that in the process of developing and/or qualifying their products, manufacturers and users have fragility level test data of some equipment. Sometimes, although the equipment was tested to a very high level, or even to the capacity level of the shake table, no structural damage or malfunction was reported. Such high level test data have also been collected. In Phase I, more than seventy test reports have been reviewed for collection of fragility or high level test data. Some of these reports contain test data for more than one piece of equipment. A wide spectrum of electrical components were covered including switchgears, motor control centers, switches, transmitters, relays, etc. For some equipment, test data were collected for various models from different manufacturers. On an equipment basis, the extent of the data collected in Phase I is discussed in the following subsections, and is summarized in Table 2-1. For each equipment, a summary of the collected data is stored in a computer data base at BNL, a sample copy of which is shown in Table 2-2.

The data have been collected for equipment models, including devices, that are typically used in nuclear plants in the United States. Therefore, it is believed that the fragility and the high level data presented in this report are applicable to U.S. nuclear plant equipment.

2.2.1 Switchgear

A total of fourteen independent test reports have been reviewed for switchgears. Some test reports include results on more than one specimen. Both medium voltage and low voltage switchgears from four major manufacturers are included in the data base. The collected data are believed to contain the fragility information of a major percentage of switchgears being used in nuclear power plants in this country. It is expected that during Phase II, more test results will be incorporated in the data base. A detailed discussion on switchgears is provided in Chapter 3.

TABLE 2-1
Summary of Collected Test Data

Equipment	Number of Manufacturers	Number of Reports
Switchgear	4	14
Motor Control Center	4	6
Other Electrical and Control Panels	4	14
Transformer (small)	6	12
Relay	4	10
Switch and Contactor	4	10
Electrical Penetration and Conductor Seal Assemblies	1	5
Other Electrical and Control Devices, e.g., Transmitter, Potentiometer, Indicators, etc.	3	15
Mechanical Equipment and Accessories, e.g., Operator	3	4

TABLE 2-2

NRC/BNL - EPRI/ANCO Equipment Data Base

Equipment Descriptor File

FORM ID:	BNL.SWGR001
GENERIC CLASS:	Switchgear
SPECIFIC EQUIP TYPE:	Medium voltage metal-clad 3-frame cabinet
MANUFACT STANDARDS:	Not available
MANUFACTURER/MODEL:	*
SIZE LxWxH (INCHES):	108x98(D)x90
WEIGHT (LBS):	11,500
CG (INCHES):	Not available
SOURCE OF INFO:	BNL
TEST ORGANIZATION:	*
TEST PLAN:	*
TEST REPORT:	*
ENVIRON QUAL:	Not available
TEST DATE:	8-25-77
INPUT DIRECTION:	Independent bi-axial
EQUIP TEST ORIEN:	FB,SS
TEST TYPE:	Random multi-frequency, 45 sec duration, more than 5-OBE and 3-SSE
FUNCTION MONITORED:	Electrical continuity, current/voltage levels, spurious operation, contact chatter timing of relay operation, etc. before, during and after tests in three electrical conditions: a) static operation - breaker closed, b) static operation - breaker open and c) dynamic operation.
ACCEPT CRITERIA:	No electrical malfunction, no gross structural failure. Record relay chatter.
EXCEPTIONS:	Fuse blocks came out, position indicator lights broke, shutter arm roller came off, breaker did not trip and under voltage relay did not reset until fuse blocks were reinstalled, lockout relays were in tripped condition during 2 SSE tests
RESONANT SEARCH:	FB 7.5 hz, SS 12 hz, V 60 hz
TEST MOUNTING.	Cabinet on shake table
BOLT DESCRIP:	Not applicable
WELD DESCRIP:	1/2 inch long fillet weld - 10 places
BASE/FRAME DAMAGE	3 base welds broke, base frame buckled
APPEND SIMULATED:	Not available
NO. OF SUBCOMP:	55
NO. OF TRS:	3
COMMENTS:	Breaker-retaining brackets 3-inch long 2x2x3/16 angle were added to alleviate inadequate racking roller engagement. This design change was implemented in 1977.

* Concealed information.

TABLE 2-2 (Cont'd)

NRC/BNL - EPRI/ANCO Equipment Data Base

Subcomponent Descriptor File

FORM ID:	BNL.SWGR001
NO. SUBCOMPONENTS:	55
GENERAL SUBCOMP TYPE:	Electrical devices
SPECIF SUBCOMP TYPE:	Relay, Power Breaker, Switch, Transducer
MANUFACT STANDARDS:	Not available
MANUFACTURER/MODEL:	*
SIZE LxWxH (INCHES):	Not available
WEIGHT (LBS):	Not available
LOCATION (ELEV-INCHES):	Various
MOUNTING TYPE:	Screws, details not available

TRS File

FORM ID: BNL.SWGR001

TRS TYPE:	SSE	SSE	SSE
TRS DIRECTION:	FB	SS	V
TRS LOCATION:	Base	Base	Base
TRS DAMPING:	2%	2%	2%
1.0 HZ:	0.7g	0.7g	0.5g
2.0 HZ:	2.4g	2.3g	1.9g
3.2 HZ:	4.2g	4.2g	4.0g
4.0 HZ:	6.0g	5.9g	5.5g
5.0 HZ:	6.8g	5.6g	6.9g
6.3 HZ:	6.4g	5.6g	6.4g
8.0 HZ:	6.0g	5.6g	6.8g
10.0 HZ:	6.2g	6.0g	5.8g
12.5 HZ:	7.0g	6.5g	6.0g
16.0 HZ:	6.5g	8.0g	6.4g
20.0 HZ:	7.5g	9.5g	7.5g
31.5 HZ:	4.0g	4.0g	6.0g
PK1/HZ:	7.5g @ 20.0	9.5g @ 20.0	8.5g @ 25.0
PK2/HZ:	7.0g @ 12.5	5.9g @ 4.0	6.9g @ 5.0
ZPA:	2.3g	2.6g	2.8g

* Concealed information.

2.2.2 Motor Control Center (MCC)

The BNL data base covers test results of motor control centers from four major manufacturers. A total of six test reports have been reviewed for data collection. Most reports present test data on more than one MCC configuration or specimen, in order to envelop the characteristics of numerous electrical devices located at various elevations in an MCC. Although the current BNL data base covers a fair percentage of typical MCC's being used, more data are expected to be included in Phase II, especially the results of an MCC test currently being conducted by LLNL as part of Phase I. A complete discussion on MCC data is furnished in Chapter 4.

2.2.3 Miscellaneous Electrical and Control Panels

In addition to the switchgears and motor controls centers, many other types of panels and cabinets are typically used in a nuclear plant in order to house numerous electrical and control devices. Fourteen test reports have been reviewed in Phase I for extraction of data for various electrical and control panels manufactured by four companies. Due to diverse nature, size and function of these panels, the present data base is not enough for a generic analysis. More test data are needed and will be collected in Phase II.

2.2.4 Transformer

Twelve test reports have been reviewed to extract data for ten different models of small transformers manufactured by six companies. More test data are needed for a generic analysis.

2.2.5 Relay

Relay test data have been extracted from ten reports. The data base covers auxiliary, protective, general purpose and time-delay relays manufactured by four companies. Due to the large family size, varied design patterns, inherent behavioral complexities and interaction with the system where the relay is located, additional test data from both individual and assembly (e.g., panel) testing are required for generic and/or specific analyses. This task is expected to be accomplished in Phase II. A detailed discussion on relays is provided in Chapter 6.

2.2.6 Switch and Contactor

Nine test reports and a study report have been reviewed to prepare the data base for switches and contactors. The present data base covers products from four manufacturers and is expected to be augmented in Phase II with additional test results.

2.2.7 Electrical Penetration and Conductor Seal Assemblies (EPA and ECSA)

Five separate reports from a leading manufacturer of EPA's and ECSA's have been reviewed. The test specimens were tested at a very high vibration level. The test results are discussed in Chapter 5 as part of high level test data. Test data from other manufacturers need to be collected in Phase II for a generic analysis of the EPA's and ECSA's.

2.2.8 Miscellaneous Electrical and Control Devices

Test data have been collected for numerous electrical and control devices in addition to those discussed in the previous subsections. These devices include terminal boards, invertors, square root extractors, formettes, transmitters, remote multiplex units and miscellaneous electrical modules and connectors. Some of these data are presented in Chapter 5 as part of high level test results. Additional test data are expected to be collected during the Phase II study.

2.2.9 Mechanical Equipment and Accessories

As mentioned earlier, the data collection in Phase I has primarily concentrated on electrical and control equipment. However, in collecting such data, test results of some mechanical equipment and electrical accessories have been encountered and incorporated in the BNL data base. It includes a damper assembly, a damper actuator and valve operators.

2.3 DATA EVALUATION

The data discussed in the previous section have essentially been extracted from numerous test reports. These tests were conducted to meet different needs; e.g., qualification purposes, development of the product, determination of fragility levels. Accordingly, the test procedures were different. In addition, a wide spectrum of vibration inputs and techniques were applied to the test specimens studied for collection of data, namely, single-axis, multi-axis, single-frequency, multi-frequency, coherent, incoherent, random, sine beat, sine dwell, etc. Moreover, testing configurations, mountings, additional supports, etc. were not consistent. The test reports which have been reviewed for collection of the data, in general, presented a measure of the vibration input and equipment response in the form of response spectra, and provided a description of the equipment behavior in terms of its functional and structural integrity. The test response spectra, popularly known as TRS, which are the dynamic response amplitudes of a single-degree-of-freedom system subject to the test input time history, were obtained and presented in the test reports for damping values that are not necessarily consistent. In summary, the collected data are the result of a wide variety of test programs and often cannot be compared with each other without further processing. In order to arrive at the generic equipment fragility or performance level from the individual test results, BNL has studied individual test reports, analyzed them using a uniform evaluation technique and presented the data in this report. The methodology employed in evaluating the collected data and the standardization formulae used in comparing them are discussed in the following subsections.

Out of the equipment list provided in the previous section, two components, namely, switchgear and motor control center, have been evaluated for the fragility level, and the results are presented in Chapters 3 and 4. Since the data collected for other components are considered insufficient for a generic evaluation, these components have not been analyzed in Phase I. As discussed earlier, more data for other equipment are expected to be collected and analyzed in Phase II. High level test data have also been analyzed in Phase I, and some examples are provided in Chapter 5.

2.3.1 Methodology

The data from various sources for an equipment family are assembled together in order to assess its seismic behavior. Test response spectra are used to compare and evaluate the performance of an equipment. As expected, with the increase in the response spectra level, the equipment is observed to exhibit various malfunctions or structural damage. Thus, from testing of one specimen with gradual increase in the test input, a number of response spectra curves are obtained corresponding to various failure modes. Depending upon the use of the equipment, some types of malfunctioning or partial structural damage may not be considered to incapacitate the equipment. Consequently, the response spectra level corresponding to such malfunction or damage cannot be termed as the fragility level for that particular application. Therefore, instead of assigning one curve as the fragility level, a number of curves are presented identifying the associated anomalies observed for each response spectra level, so that the user can select the appropriate fragility level of the component by considering its specific application. Thus, the fragility of an equipment is described by a group of response spectrum curves corresponding to various failure modes. The lower-bound curve indicates initiation of malfunctioning or structural damage; whereas, the upper-bound curve corresponds to overall failure of the equipment occurring separately or interactively. Thus, the fragility level used in this report may not necessarily be the ruggedness level, a term that has been used in the industry to indicate the highest available qualification level [1]*.

Once the fragility of a component is thus established by a set of curves for one particular model of a manufacturer, another set of such response spectrum curves is prepared for a second model of the same manufacturer, and compared with the first. This way, fragility of an equipment produced by one vendor is defined for all their models. Fragility of the same generic equipment manufactured by other companies is similarly obtained. At this point, the relative fragility levels of the products from various manufacturers are compared. If the levels are comparable, all the curves are assembled into one set and designated as the fragility level, or more precisely, the fragility region, of the particular generic equipment. In case appreciable differences in the fragility levels are observed for products of one or more manufacturers, fragility levels of such products are separately presented.

It has been observed that some components were tested to high levels, often to the capacity level of the shake table, but exhibited little or no structural damage or malfunction. Test response spectra of such equipment are expected to be used mainly in two different ways depending on the nature of the equipment and its support. If the equipment is generically mounted on a floor slab

*The references are provided in Chapter 8.

or a seismically rigid support, then the test response presented in the BNL analysis might be high enough for all practical purposes, so that the real fragility levels of this type of equipment need not be established. Consequently, they can be excluded from any future fragility test program. On the other hand, if the component is usually mounted on a flexible support (e.g., an electrical device in a motor control center) and the component when tested individually withstood vibration input to the shake table limit without exhibiting any anomalies, then the fragility data should be sought in the test data of the assembly (e.g., motor control center). If fragility testing is required for such components, the possibility of undue fatigue failure by shaking at lower levels, as well as the testing cost, can be substantially reduced by starting with the high level test response presented in the BNL analysis.

Following the guidelines discussed above, the test data collected from various sources are analyzed, and presented by equipment family basis, e.g., switchgear, motor control center. A description of the equipment, mounting conditions, failure modes and limitation of applicability of any test results is also included in each analysis. Therefore, for appropriate use of a fragility curve, it is recommended that the user read the related analysis in the text.

2.3.2 Standardization

As discussed earlier, the collected data are the results of numerous test programs that utilized different testing techniques and vibration inputs, and presented the response spectra for different damping values. However, for comparison of results from different test programs and for development of a generic performance level, a specific vibration technique and a specific damping value are to be used as a standard, and the responses from a different test program or with a different damping value are to be scaled up or down accordingly to convert the results to equivalent responses in the standard system. To this end, random multifrequency biaxial vibration inputs and TRS at the 2% damping value are considered standard in this report, since a major portion of the collected data belong to this group. Consequently, the least amount of conversion is needed for standardization. The conversion factors and the bases are discussed in the following subsections.

2.3.2.1 Damping

In general, the test reports, prepared by testing laboratories, present the vibration input in terms of TRS at certain damping values instead of the time histories used. For comparison purposes, it is immaterial which damping value is used for generation of the TRS from the time histories, as long as the same damping value is selected for the TRS being compared. In this report, a damping value of 2% is selected for comparison of the TRS, since it has been observed that in the collected data a major portion of the time histories were analyzed at 2% damping value. (For ease of comparison with the "ruggedness" spectra generated by EPRI/ANCO [1], a number of selected fragility TRS curves are provided at 5% damping value in Appendix A). However, in the BNL data bank, there are some test results that were analyzed at 1%, 3% or 5% damping value. This necessitated the conversion of such TRS data to those at 2% damping value for inclusion in the generic evaluation of the equipment. For a given time history, the conversion factor to be applied on the response magnitude varies with frequencies as well as damping values. Moreover, at a certain frequency, the conversion factor may not necessarily be the same for two different time histories. Since different time histories are used in different test programs, and sometimes even in the same test program, theroretically there is no single number one can use to convert the test response from one damping value to another, even at one particular frequency. However, for comparison purposes, on a limited basis, one may be satisfied with an approximate converted response at a different damping value, understanding that a majority of the TRS is at the standard damping value. In this report, depending upon the availability of test data, one of the following two methods has been used for standardization of TRS at different damping values.

Method 1 - Suppose, in a particular test program, for one test run, TRS are available at both 2% and 3% damping values; whereas, for another test run, TRS are available only at 3% damping. It is required to standardize the second TRS at 3% to that at 2%. To this end, the conversion factor is obtained as the ratio of the responses at a particular frequency corresponding to the two damping values in the first test run. The conversion factor is then applied to the response of the second TRS at that frequency, and by repeating this procedure, the converted TRS are obtained over the entire frequency range of interest.

Method 2 - If standardization is not possible by use of test data from the same test program as described above in Method-1, the factors shown in Table 2-3 are employed for conversion of TRS to the standard damping value. These factors have been obtained from a BNL study of a large number of test responses at different damping values and at various frequencies, based on numerous vibration inputs used and analyzed by major testing laboratories in this country. Figure 2-1 pictorically depicts how an actual test response spectrum at 2% damping compares with that transformed from 5% to 2% using the conversion factors shown in Table 2-3. Both actual TRS plots, i.e., those at 2% and 5%, are taken from a typical test report.

It should be noted that EPRI/ANCO [1] has used conversion factors inversely proportional to the square root of the damping ratios. The factors discussed in the above two methods and used in this report may be different from those used by EPRI/ANCO at certain frequencies. For example, in conversion from 5% to 2%, the inverse square root formula results in a factor of 1.58 over the entire frequency range. Whereas, Table 2-3 shows three different numbers, namely, 1.4, 1.3 and 1.2 at three separate frequency domains. By comparison with actual TRS plots, it is judged that the above methods provide more realistic and/or conservative response values when converted to 2% damping as evidenced in Fig. 2-3. It is recognized that the conversion factors listed in Table 2-3 are approximate and may need to be further refined as recommended in Chapter 7. It is emphasized that the factors in Table 2-3 have been used for conversion to 2% damping and that they are not recommended for a reverse operation (e.g., from 2% to 5%).

2.3.2.2 Vibration Input

Most of the test programs reviewed for collection of data, employed random multifrequency biaxial vibration inputs. However, a fraction of the collected data corresponds to single frequency and/or single axis testing. For comparison purposes, in this report, random multifrequency biaxial tests are considered standard, and any test results otherwise obtained are transformed to equivalent results compatible with the standard test procedure. Based upon the recommendations provided by Kana [2] while conducting a USNRC research program, a multiplying factor of 0.7 is used in this report to transform a narrowband (e.g., sine beat, sine dwell, etc.), or a single axis response to a standard response over the entire frequency range of interest. When both the narrowband and the single axis inputs are simultaneously employed, the multiplying factor becomes a product of the two i.e., $0.7 \times 0.7 \approx 0.5$. There are a few complex vibration conditions other than those discussed above, for which engineering judgments have been used on a case by case basis to standardize the test results.

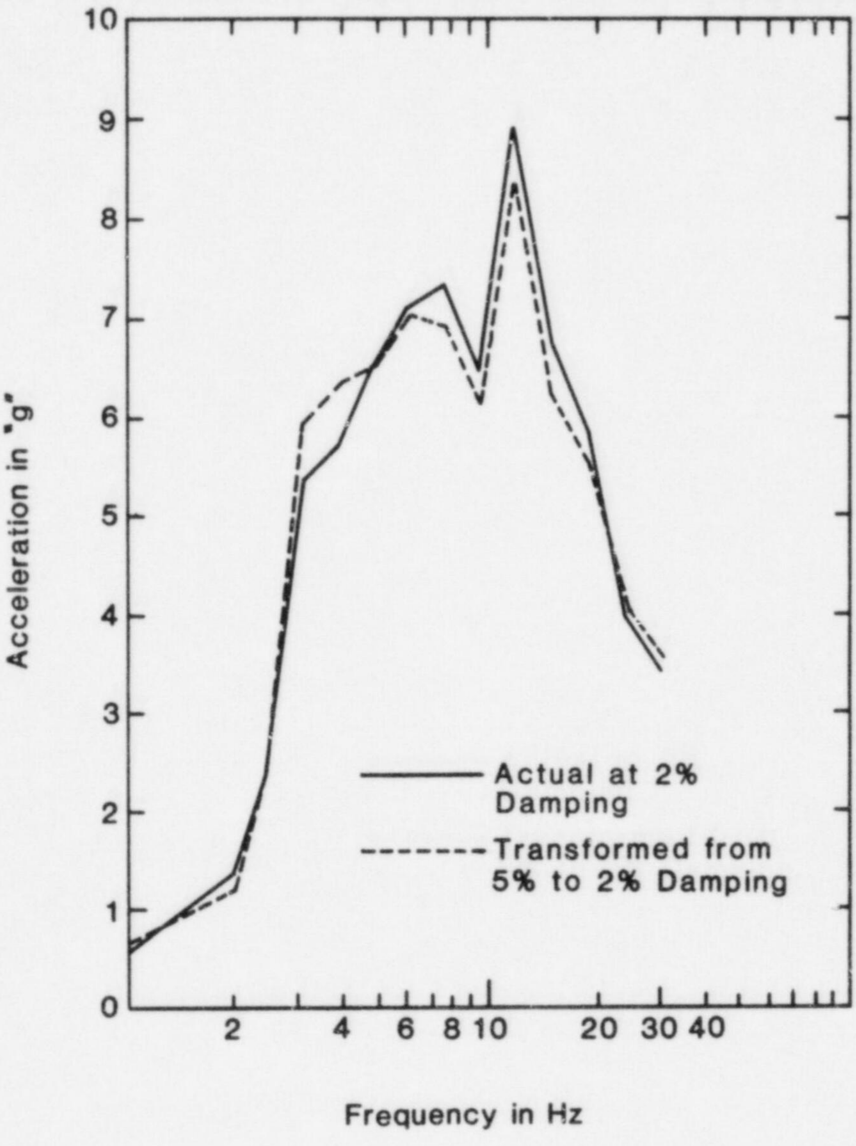


Fig. 2-1 TRS - Actual vs Transformed

TABLE 2-3

TRS Conversion Factors for Various Damping Values

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

[1]The factors in this table are for conversion to 2% damping and are not recommended for a reverse operation (e.g., from 2% to 5%).

CHAPTER 3.

SWITCHGEAR FRAGILITY DATA

3.1 INTRODUCTION

The Class 1E switchgear is an electrical equipment used to provide and control the power supply to various safety-related equipment in a nuclear plant. Fragility level test data have been collected for various models manufactured by four major companies in the USA. These test data are presented in this chapter following the evaluation methodology discussed in Chapter 2. The common failure modes observed at different vibration levels during the seismic tests are enumerated towards the end of this chapter. Descriptions of the equipment and typical tests are also included in this chapter.

3.2 EQUIPMENT DESCRIPTION

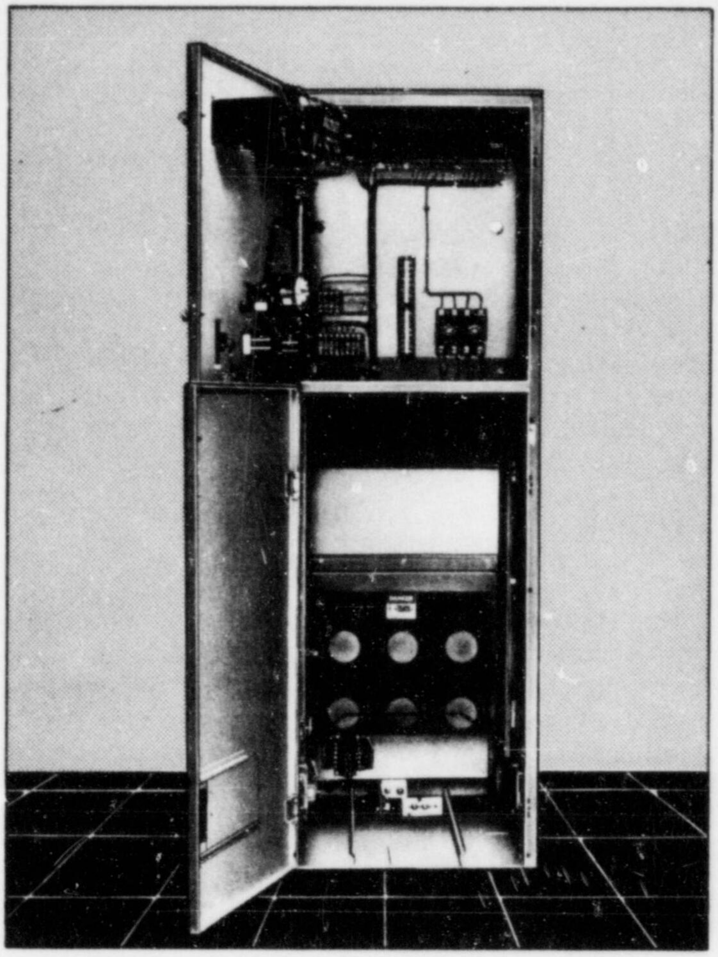
A switchgear unit, called a vertical section (also sometimes called a bay, a frame or a line-up), is enclosed on all sides and top with (steel) sheet metal except for ventilation openings and inspection windows (Fig. 3-1). A typical unit contains primary circuit switching or interrupting devices, or both, with buses, connections and auxiliary devices; e.g., relays, transducers, current transformers, potential transformers. The heavy power breakers are typically mounted on guide rails at the base. Access to the interior of the switchgear enclosure is provided by doors or removable covers. In application, a number (2-20) of such vertical sections are installed side-by-side to form a switchgear assembly (Fig. 3-1).

A switchgear could be metal-clad (i.e., cables are segregated from the bus) or could be metal-enclosed (i.e., cables are not segregated). Depending on the need, it could supply a low voltage (e.g., 600V) or a medium voltage (e.g., 5KV, 15KV). The power breaker can carry as high as 3000 amp and the rating could be as high as 1000 MVA.

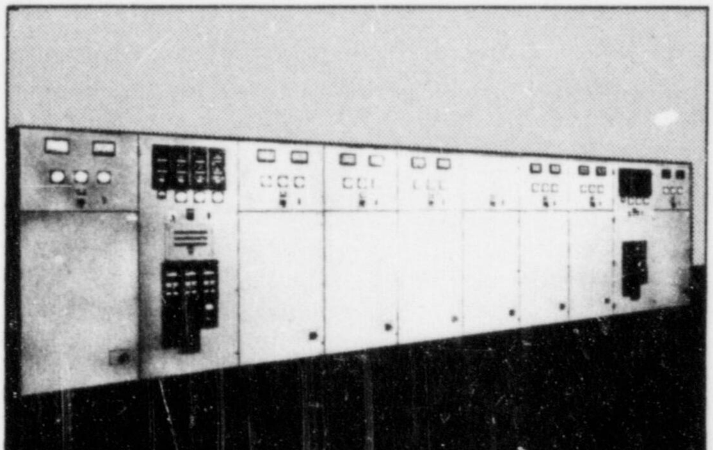
In the field, a switchgear assembly could either be bolted or welded to the floor. The size and weight of the equipment vary with the breaker size and capacity (MVA) rating. One typical vertical section of a 15KV, 500MVA switchgear assembly measures about 91" deep x 36" wide x 90" high and weighs about 2700 lbs.

3.3 TEST DESCRIPTION

For qualification and fragility purposes, the manufacturers and users have traditionally tested a switchgear assembly consisting of one, two or three vertical sections with related control and protective devices in them. A list of electrical devices included in a typical test of a three-frame switchgear and monitored for electrical operation is provided in Table 3-1. The devices included in the switchgear specimens in various test programs are representative of those used in typical nuclear plants. The test results are extended



A Unit with Separate Instrument (Top)
and Breaker (Bottom) Compartments



An Assembly

Fig. 3-1 Medium Voltage Switchgear

TABLE 3-1

Electrical Devices Included and Monitored in a Typical Three-Frame Switchgear Test

6	Test Switches
2	Pushbutton Switches
1	Watthour Meter
1	Ammeter Switch
1	Cell Switch
1	Auxiliary Potential Transformer
3	Lockout Relays
1	Knife Switch
11	Circuit Breakers
10	Auxiliary Relays
10	Overcurrent Relays
2	Negative Sequence Relays
4	Timing Relays
2	Blown Fuse Indicators
1	Voltage Differential Relay
4	Undervoltage Relays
2	Voltage Transducers
1	Frequency Transducers
1	Watt Transducer
2	Voltage Relays
1	Volt Teleductor
1	D.C. Power Supply
2	Backup Relays
2	Underfrequency Relays
2	Air Flow Switches

to multiple line-ups by analysis. Some manufacturers have used dynamic analysis methods, and validated the mathematical model by test results. Devices are sometimes separately tested, and the input response is compared to the vibration level at the device locations. For most tests,random multi-frequency biaxial vibration inputs were used. The test specimens were either welded or bolted to the test table. At least on one occasion, the same specimen was first tested with bolts and then with welds. Of the mounting configurations, the bolted one exhibited higher response amplication.

Additional information regarding test procedures is provided in the following sections along with the test data resulting from individual test programs.

3.4 EVALUATION OF TEST DATA

Test results are presented in the form of test response spectra (TRS) corresponding to various failure modes. The shake table TRS are the response of the table at the equipment base. They indicate the severity of the vibration input, both in magnitude and frequency content. The response curves are plotted for a damping value of 2% of the critical damping. Numerous test programs and their results are discussed separately for medium voltage and low voltage switchgears in the following subsections.

3.4.1 Medium Voltage Switchgear

In a fragility-type seismic test program, a three-frame medium voltage metal-clad switchgear was tested with gradually increasing vibration inputs. The specimen was welded to the shake table and subjected to a 30-second duration biaxial multi-frequency random motion in each test run. Two simultaneous, but independent random signals were used as the excitation to produce phase-incoherent horizontal and vertical motions.

The test specimen exhibited the first natural frequency in the range of 8-10 Hz in the FB direction and 5-6 Hz in the SS direction. A total of forty-five electrical devices were contained in the specimen assembly. Electrical channels were used to ascertain electrical continuity, current/voltage levels, spurious operation, contact chatter, timing of relay operation, etc. before, during and after the seismic excitation. The oscillograph recorders contained galvanometers capable of detecting a discontinuity of 0.5 millisecond or greater, although a chatter up to 2 milliseconds is acceptable for most equipment. The specimen was tested for both electrical conditions, namely, static operation (breakers closed) and dynamic operation (breakers closed-tripped-closed). A synchronism check relay, an auxiliary relay and a power breaker were observed chattering (>0.5 ms) all through the tests. A ground overcurrent relay indicated change-of-state in almost all tests in FB direction.

The resulting table motions were analyzed by a response spectrum analyzer by the testing laboratory. Some of these TRS curves are presented in Fig. 3-2, 3-3 and 3-4. The behavior of the specimen at different vibration levels is discussed by addressing those TRS curves in the following paragraphs.

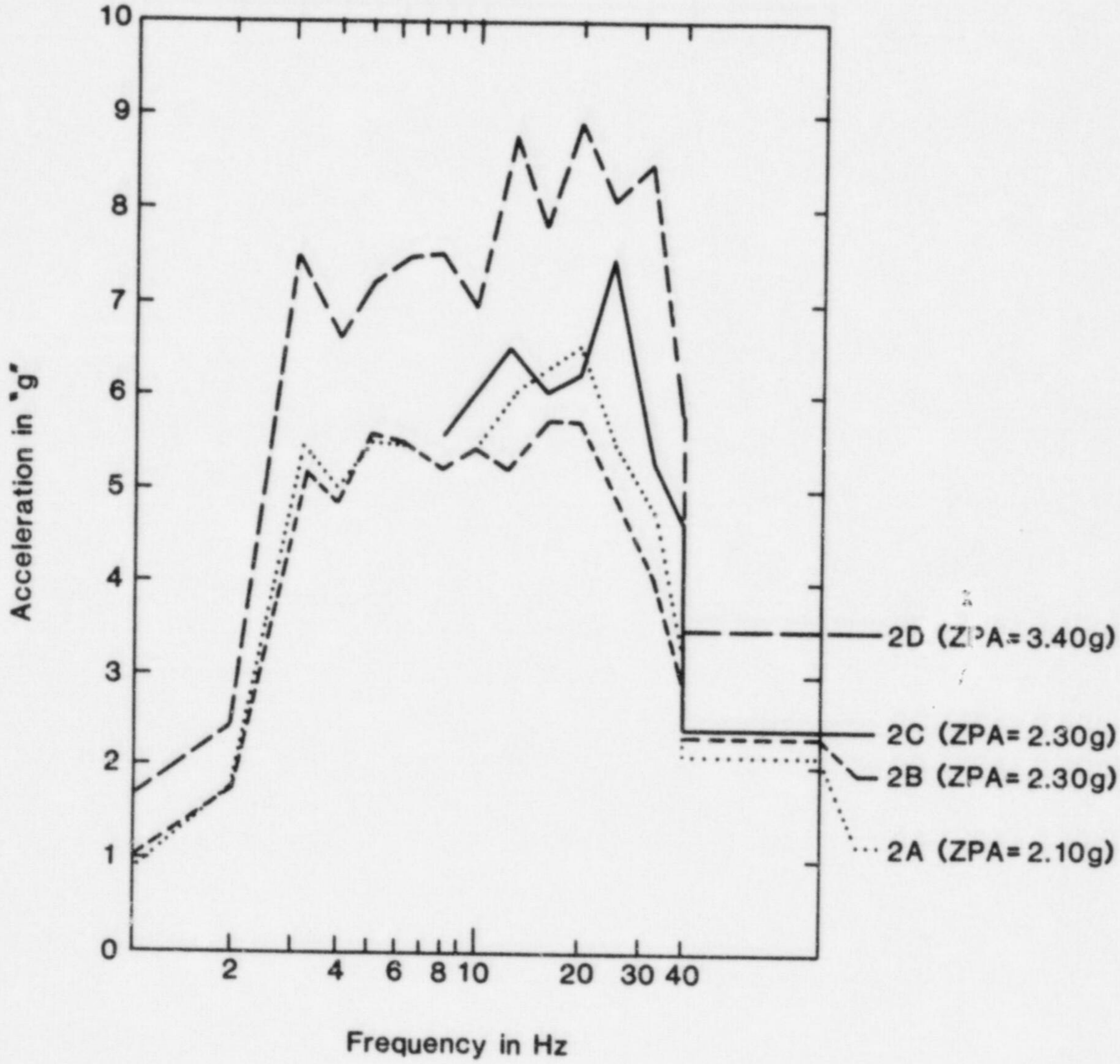


Fig. 3-2 Front-to-Back TRS at 2% Damping, Medium Voltage Switchgear Manufacturer A, Test Program 1

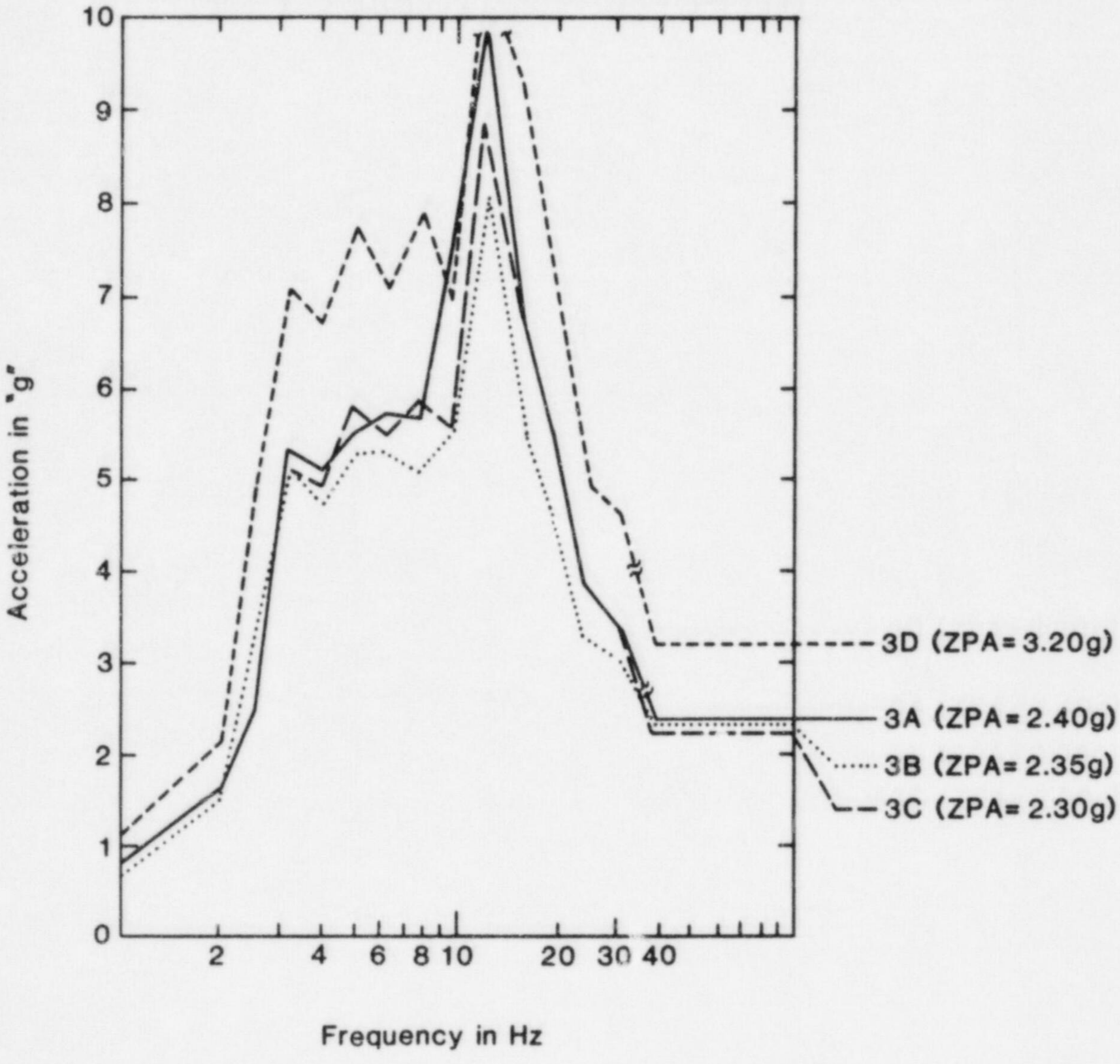


Fig. 3-3 Vertical TRS at 2% Damping,
Medium Voltage Switchgear Manufacturer A,
Test Program 1

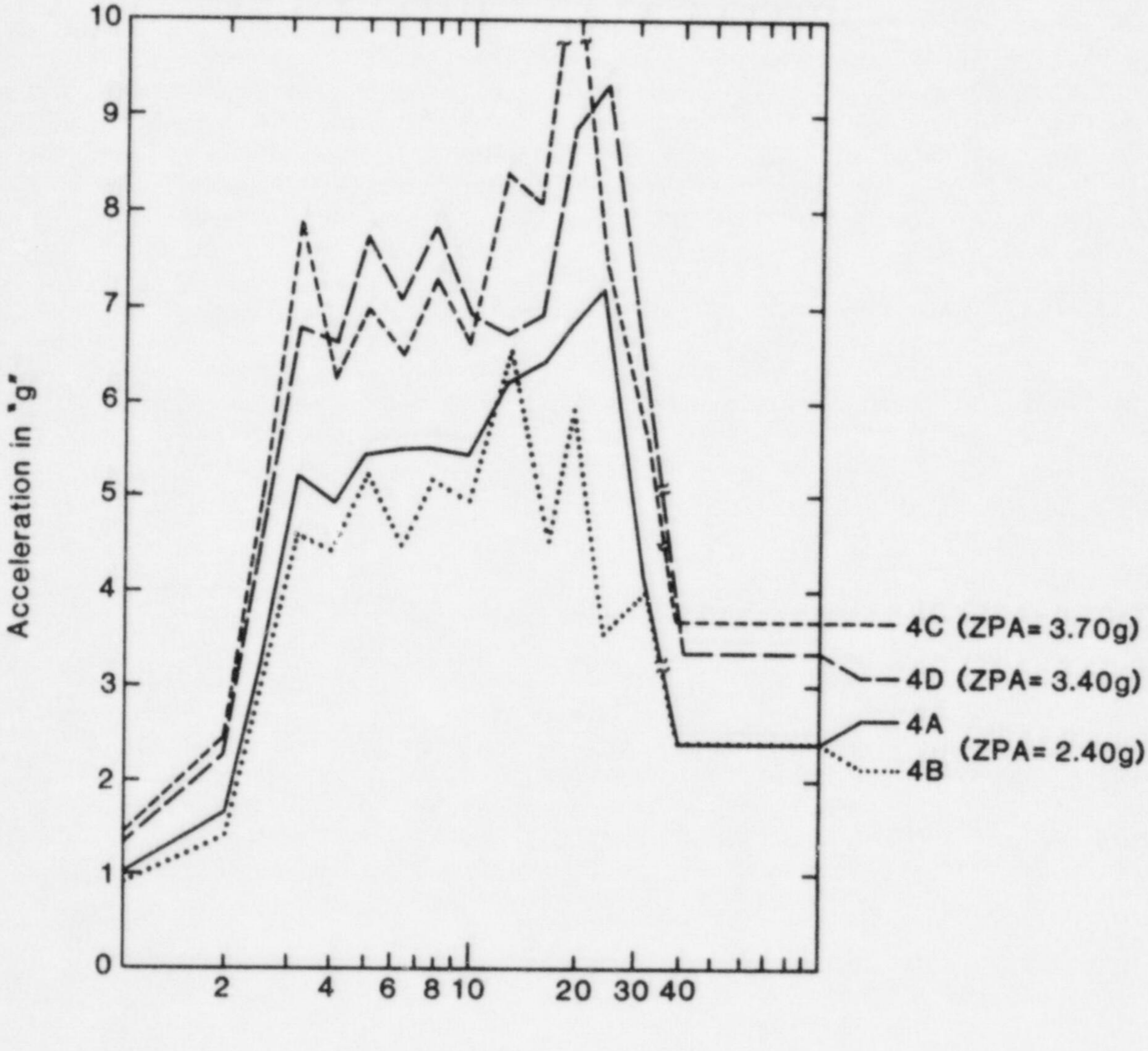


Fig. 3-4 Side-to-Side and Vertical TRS at 2% Damping, Medium Voltage Switchgear Manufacturer A, Test Program 1

Curve 2A shows the FB TRS level corresponding to the electrical static condition for a ZPA value of 2.1g and peak of 6.5g at 20 Hz. Two auxiliary relays, two overcurrent relays, an undervoltage relay, a synchronism check relay, a distance relay and a power breaker switch indicated chattering (>0.5 ms).

Curve 2B is the next test with a slight increase in the ZPA level (ZPA = 2.3 g) although the curve dips below 1A at some frequencies. This test is also for static breaker condition. Two overcurrent relays were observed to undergo change-of-state in addition to the similar chattering that occurred for curve 1A.

The next random test was performed almost with the same vibration input (the TRS plot is not shown in Fig. 3-2). At this point, corners of a "distance relay" were torn. In order to increase the natural frequency of door panels where many devices were mounted, the door frame was stiffened with horizontal angle stiffeners. In the FB direction, the frequency shifted from 8 to 11 Hz at these locations, and in the SS direction, the overall frequency went up from 5-6 Hz to 8-9 Hz.

Curve 2C in Fig. 3-2 corresponds to the level with the minimum electrical disturbance for static breaker condition. Addition of the stiffeners limited the chattering to five devices only (compared to eight for curve 2A). This test did not indicate any change-of-state problem as observed in earlier tests. This curve shows a ZPA of 2.3g with a peak of 7.4g at 25 Hz and another peak of 6.5g at 12.5 Hz. At the low frequency region, curve 2C is close to curves 2A and 2B; hence, for clarity, in Fig. 3-2 curve 2C is not shown in this region.

At almost the same input level, as in curve 2C, the breaker was tested for the electrical dynamic condition. An overcurrent relay was observed not to operate.

The vibration input was further increased to produce curve 2D with a ZPA value of 3.4g and a peak of about 8.9g at 20 Hz. For most of the frequency range, the response exceeded 7.0g. For the breaker closed position, seven devices were detected to chatter and the same ground overcurrent relay changed state. Tests were repeated at the same vibration input level with dynamic breaker conditions. In one test, a momentary short circuit was noticed, and in another test, the same overcurrent relay was observed not to operate.

The last two FB/V tests were performed with the door stiffeners removed to produce TRS comparable to the levels of curves 2A and 2B, and keeping the breaker in the electrically dynamic condition. A number of relays were observed to malfunction (e.g., shorted or did not operate).

A total of nineteen random vibration tests were performed in the FB/V direction at various levels not all of which are shown in Fig. 3-2. The vertical TRS curves of the biaxial tests corresponding to the four FB curves shown in Fig. 3-2, are presented in Fig. 3-3. Twenty-one additional tests were performed in the SS/V direction. The corresponding curves are shown in Fig. 3-4.

Curves 4A and 4B in Fig. 3-4 represent the respective SS and V TRS plots due to a lower-bound SS/V biaxial motion. The same breaker switch, undervoltage relay and the synchronism check relay which were observed to chatter during the lower-bound FB/V tests were also detected to chatter ($\geq$ 0.5 ms) due to this SS/V motion. With an increase in the input level in the SS/V direction, more anomalies were observed similar to the FB/V tests. Intermediate level curves are not shown in Fig. 3-4. Curves 4C and 4D depict the respective SS and V TRS plots due to the upper-bound SS/V biaxial random vibration during which the mounting weld broke and a circuit breaker position rod slipped behind the switch operating lever. However, during all the tests discussed above, both FB/V and SS/V, the power circuit breakers performed their intended function i.e., either remained closed or closed-tripped-closed as directed.

Thus, Fig. 3-2 through Fig. 3-4 depict various malfunction levels for one specimen of a particular manufacturer. The same model was tested in a different test program with some variations of the devices especially with one heavier breaker. Two TRS curves from this test program, one for static and another for dynamic condition of the breaker, are presented in Fig. 3-5.

Curve 5A in Fig. 3-5 corresponds to the static breaker position. It shows a FB ZPA of 2.65g with a peak of about 8.3g at 20 Hz and another peak of 7.4g at 6.3 Hz. The breaker slipped during the run, nine devices chattered and two other devices (switch and relay) experienced change-of-state. The corresponding vertical TRS of the biaxial motion is represented by Curve 6A in Fig. 3-6. The ZPA level in the FB direction was further increased to 3.5g for the same specimen as shown in curve 5B corresponding to dynamic breaker condition. The specimen was first bolted and then welded. The bolted configuration exhibited higher amplification. The mounting weld broke and the specimen became loose on the shake table. Numerous electrical malfunctions followed indicating an upper-bound fragility for this specimen. Curve 6B shows the TRS of the corresponding vertical input of the FB/V test. The same specimen was then subjected to fourteen random biaxial vibration tests in the SS/V directions during which it exhibited bent mounting supports, cracks in structural elements, wearing and movement of a breaker unit, chattering of electrical devices and such anomalies. An upper-bound TRS of the SS input is represented by curve 7B in Fig. 3-7.

Curve 5C in Fig. 3-5 was also for the same model of the same manufacturer, but with further heavier units. The three-frame assembly contained fifty-five devices and was welded to the shake table. In the total of twenty-one random tests, out of which twelve were in the FB/V direction, the specimen experienced various damages and/or malfunctions with an increase in vibration inputs, e.g., the fuse blocks came out, position indicator light broke, shutter arm roller came off, breaker did not trip and undervoltage relay did not reset until fuse blocks were installed. The vertical TRS of this biaxial test is shown as curve 6C. The specimen was then subjected to eight tests with SS/V random biaxial inputs during which breaking of weld, buckling of structural members, tripping and chattering of relays were observed. Curve 7C in Fig. 3-7 shows the SS TRS of one SS/V biaxial test.

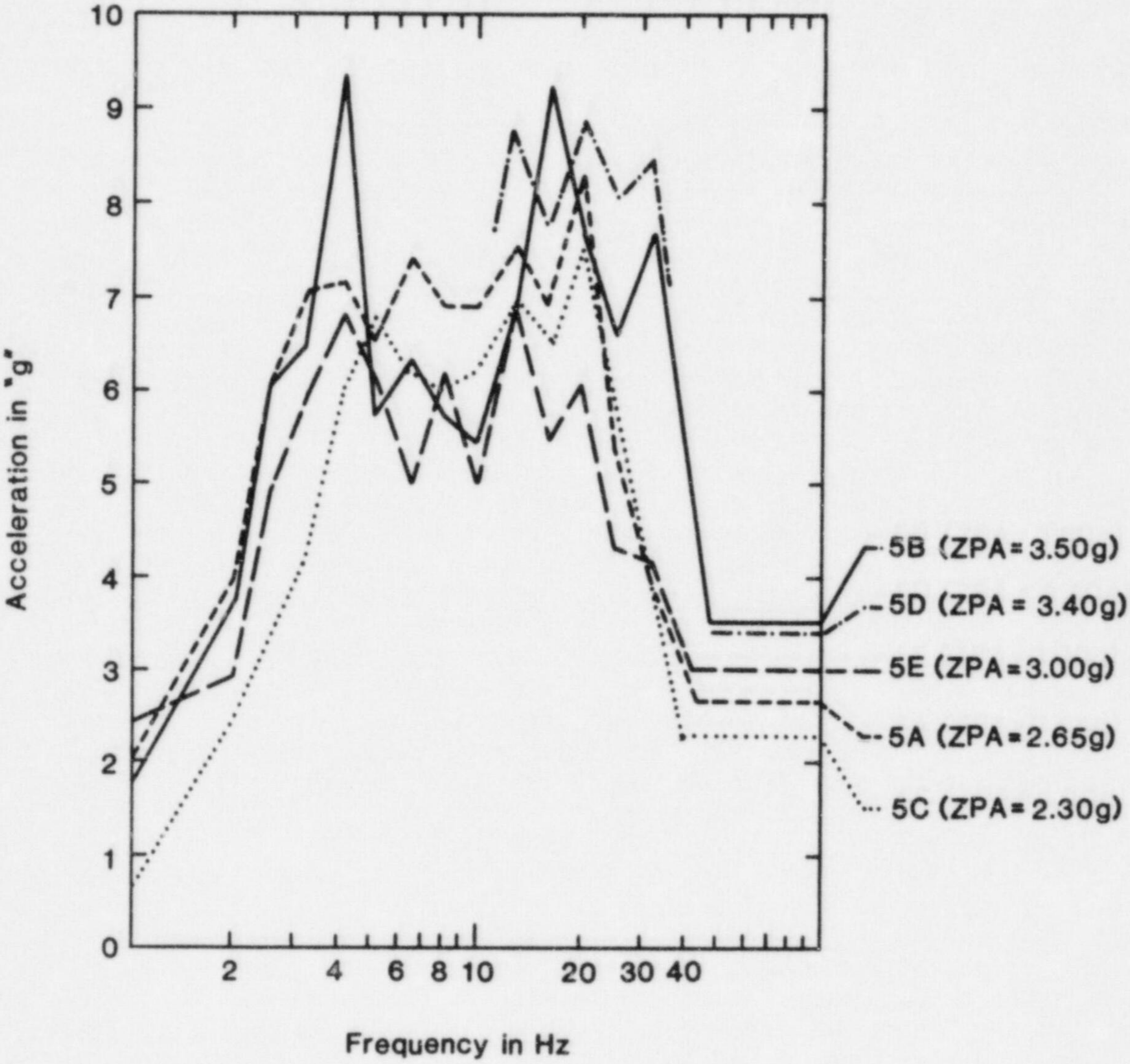


Fig. 3-5 Front-to-Back TRS at 2% Damping, Medium Voltage Switchgear Manufacturer A, Various Test Programs

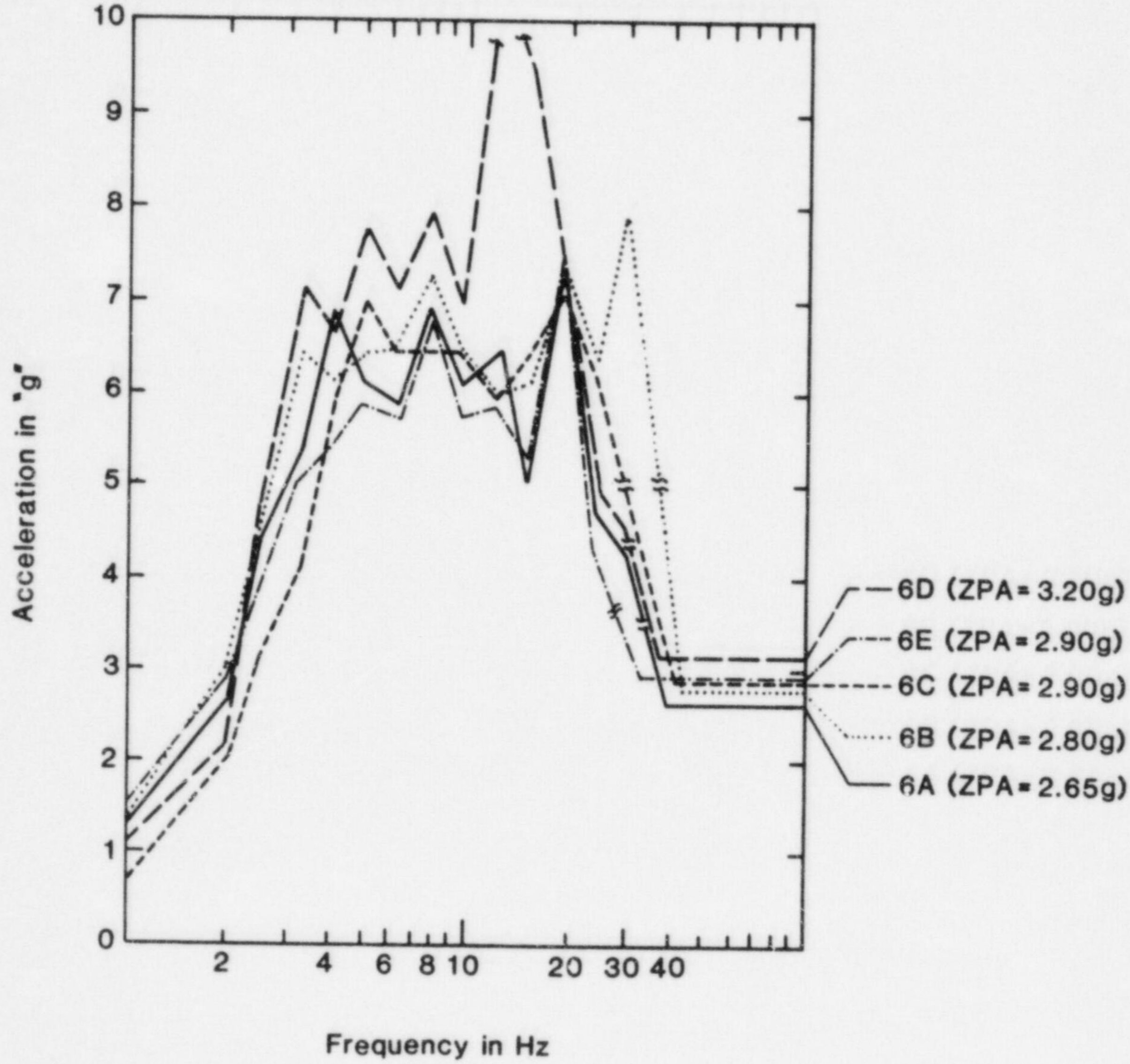


Fig. 3-6 Vertical TRS at 2% Damping,
Medium Voltage Switchgear Manufacturer A,
Various Test Programs

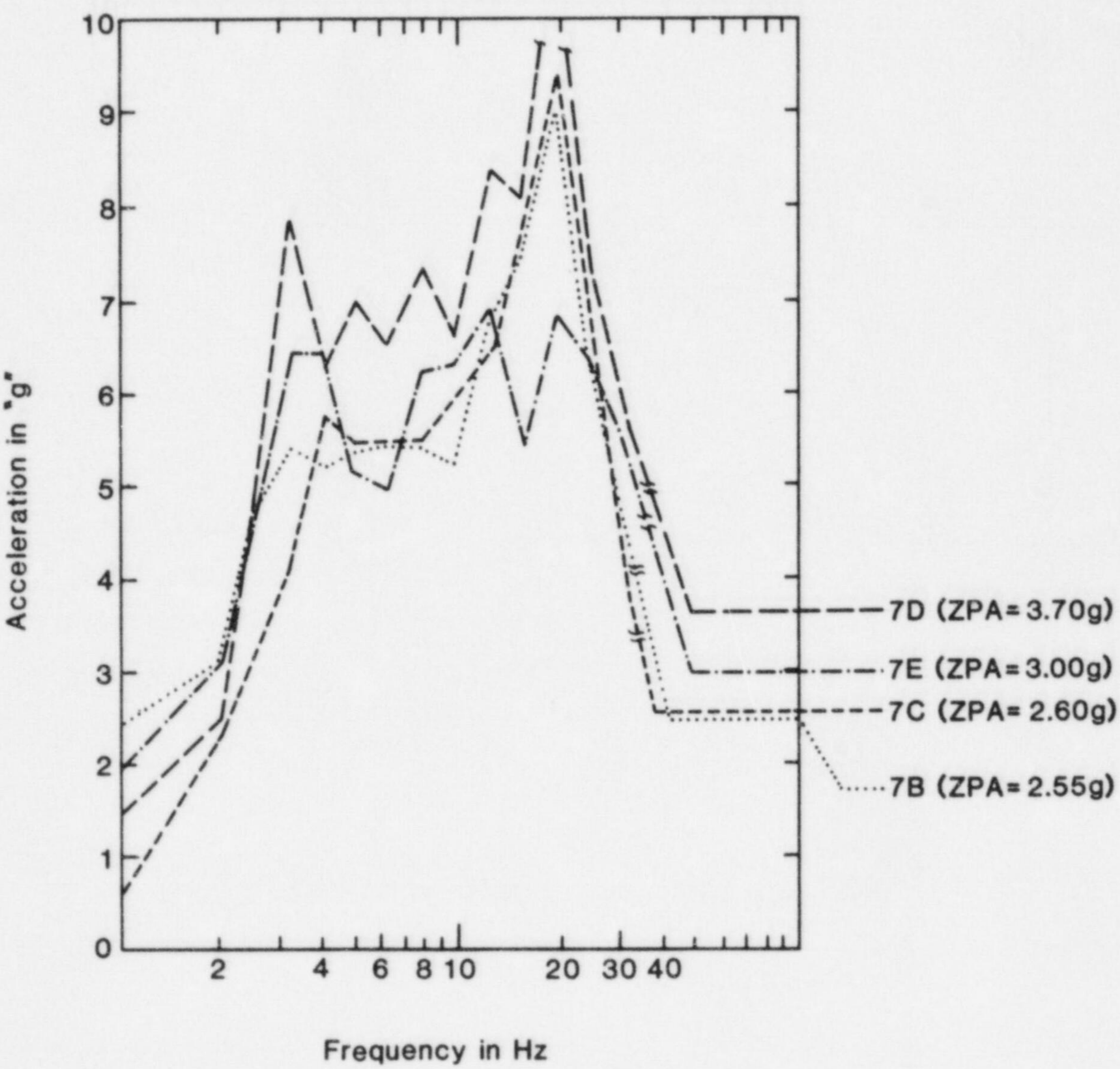


Fig. 3-7 Side-to-Side TRS at 2% Damping, Medium Voltage Switchgear Manufacturer A, Various Test Programs

Curves 5D, 6D and 7D are the same curves as 2D, 3D and 4C, respectively, and are repeated for comparison.

Curve 5E in Fig. 3-5 shows the TRS of another medium-voltage switchgear model manufactured by the same company. This FB curve corresponds to the breaker dynamic condition, and shows a ZPA level of 3.0g with a peak of about 6.9g at 12.5 Hz. The corresponding vertical component is represented by curve 6E. This model has a lower MVA rating, and weighs and measures appreciably less than the previous one. The fundamental frequencies are 8-10 Hz in the FB direction and 12-14 Hz in the SS direction. The three-frame specimen was welded on the shaker table. Chattering of four devices including two switches was observed during the tests. A total of sixty-one tests were performed on the specimen including thirty-one in the FB/V direction. Curve 7E shows a TRS in the SS direction due to an SS/V random biaxial motion.

The test programs discussed so far by use of Fig. 3-2 through Fig. 3-7 were conducted by one manufacturer on their various medium voltage switchgear specimens. A summary of all these tests along with test results of two other manufacturers are presented in Fig. 3-8 and Fig. 3-9. Curve 8AL shows the lower envelop of all the horizontal TRS curves shown in Fig. 3-2 through Fig. 3-7. This indicates the initiation of minor problems e.g., chattering of devices, limited cracking of a plate or a structural element. At this level, the power circuit breaker performs its intended function. Therefore, such minor anomalies could be accepted for some applications. Curve 8AU shows the lower-bound of all the horizontal curves corresponding to which major problems were encountered. As such, this idealized curve indicates the intiation of significant structural damage and/or unacceptable electrical malfunctions, e.g., inoperable breaker or other devices. However, this does not imply that no specimen from this particular manufacturer will withstand a level higher than curve 8AU. For example, curve 8AUU shows a horizontal TRS plot for a product of the same manufacturer, which satisfactorily survived a test at this level with no breaker malfunctioning or any unacceptable structural damage.

Curve 8B in Fig. 3-8 shows a composite horizontal TRS for a medium voltage switchgear specimen from another major manufacturer. The test was performed by applying coherent biaxial vibration inputs. The manufacturer reported that the equipment will survive this test level provided certain relays are not used.

Curve 8C presents the capacity level of a medium voltage switchgear model from a third major manufacturing company. This curve is an envelope of a number of horizontal TRS due to incoherent biaxial random inputs with sine beats at various frequencies. For comparison with other curves, the reported TRS is reduced to 70% of the total response in order to account for narrow band characteristics of the sine beat tests. Major electrical malfunctions and structural damages, including breaker tripping, structural cracks, etc., were reported corresponding to this level.

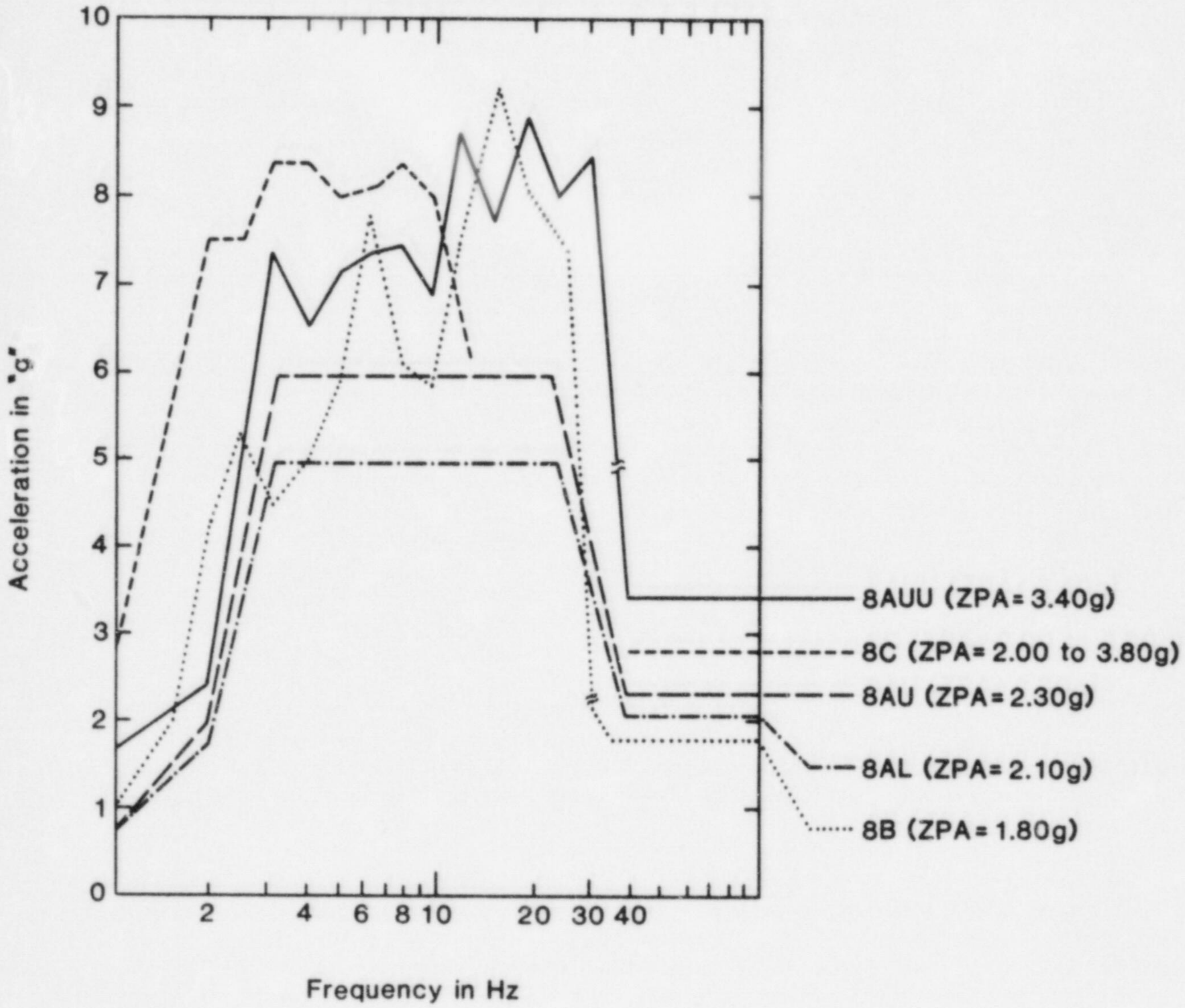


Fig. 3-8 Horizontal TRS at 2% Damping, Medium Voltage Switchgear Various Manufacturers

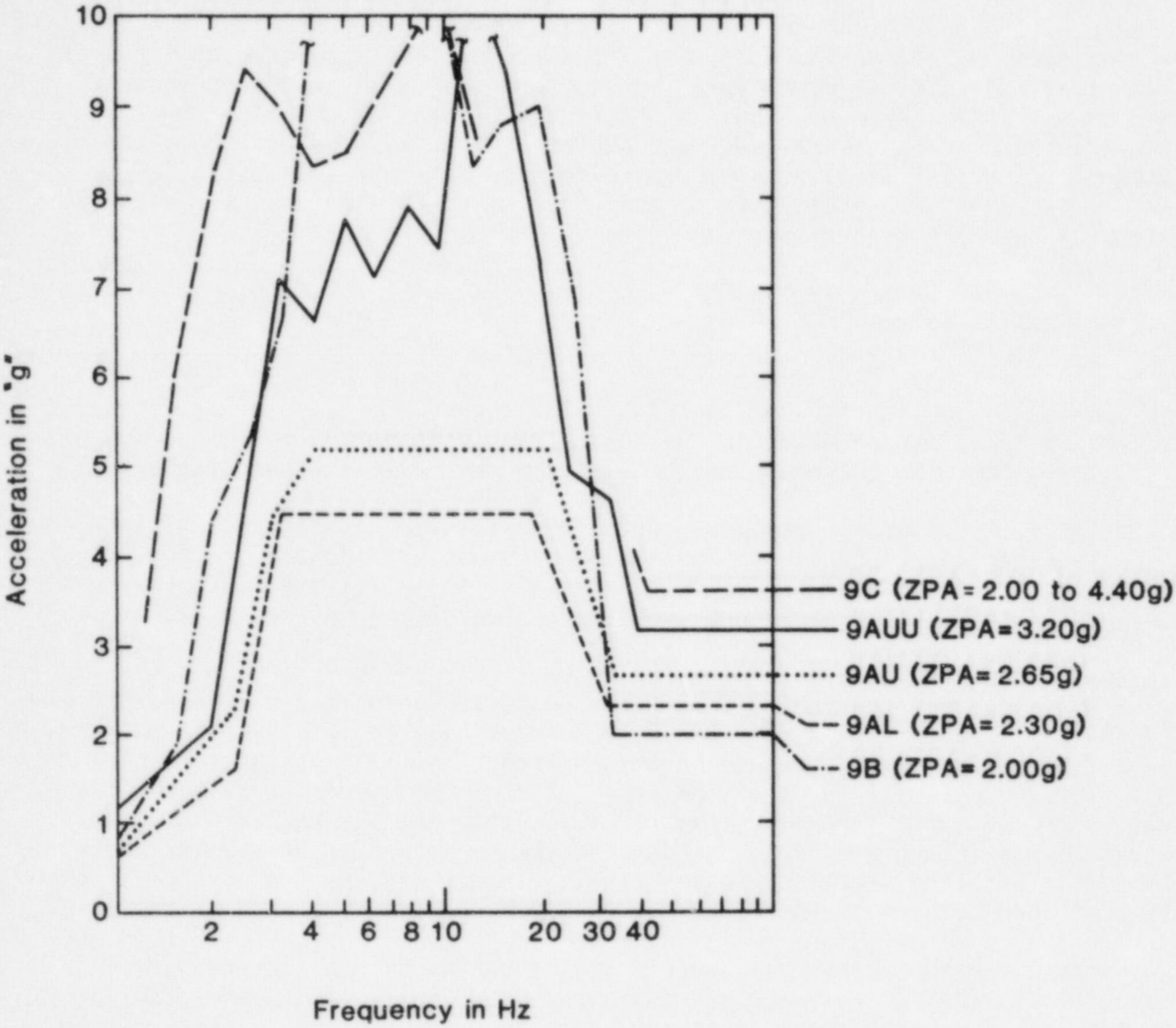


Fig. 3-9 Vertical TRS at 2% Damping, Medium Voltage Switchgear Various Manufacturers

Figure 3-9 shows the TRS of the respective vertical components of the biaxial tests corresponding to the curves shown Fig. 3-8. More data are expected to be collected and analyzed in Phase II, especially for other models from the last two manufacturers.

3.4.2 Low Voltage Switchgear

In a fragility-level test program, a typical low-voltage switchgear specimen was subjected to increasing vibration inputs. The test specimen consisted of three vertical sections with overall measurements of 58 inches deep x 66 inches wide x 90 inches high and weight of 3,600 lbs. It contained twelve circuit breakers and several cell and control switches. The effect of the numbers of vertical sections on the side-to-side motion was investigated by testing two vertical sections in an additional side-to-side test series. The following resonant frequencies were observed during the testing:

FB	12 - 13 Hz
SS (3-frame)	4 - 5 Hz
SS (2-frame)	2.5 - 3 Hz

The two-frame specimen showed about 20% - 30% higher SS response amplification at certain locations relative to the three-frame specimen. The TRS curves are discussed along with the equipment behavior in the following paragraphs.

Curve 10A in Fig. 3-10 is the lower-bound side-to-side capacity of the three-frame specimen corresponding to initiation of structural damage in the equipment (e.g., minor weld cracks). This curve also indicates the SS lower-bound for the two-frame specimen except that the ZPA was 2.4 g instead of 2.75 g.

The test vibration input was increased to the level of curve 10B when the two-frame specimen experienced a severe structural damage and a switch chatter of duration greater than 2 ms. Curve 10C corresponds to major structural damages of the three-frame specimen in the FB direction. At a slightly higher input level (ZPA = 4.7 g), the same specimen exhibited severe structural problems in the SS direction also. The vertical component TRS was as high as curve 10D when numerous structural damages were observed. The breakers were tested for both the static operation (i.e., closed) and the dynamic operation (i.e., closed-tripped). No breaker malfunction was reported.

In summary, for this particular model, 10A is the horizontal lower-bound curve, 10B is the horizontal upper-bound for a two-frame switchgear, 10C is the horizontal upper-bound for a three-frame assembly and 10D is the vertical upper-bound.

Another three-frame low voltage switchgear assembly produced by the same manufacturer was tested with sequentially higher vibration inputs. The TRS curves at 2% damping values are shown in Fig. 3-11. On the random multifrequency biaxial inputs, sine beats at low frequencies were continuously superimposed in the vertical direction. For comparison with other multifrequency random input motions, the resulting spectral values on this low frequency region have been reduced to 80% in presenting the vertical curve in Fig. 3-11. The reduction factor was obtained by judging the test procedure, the response values and other factors (see Section 2.3.2.2).

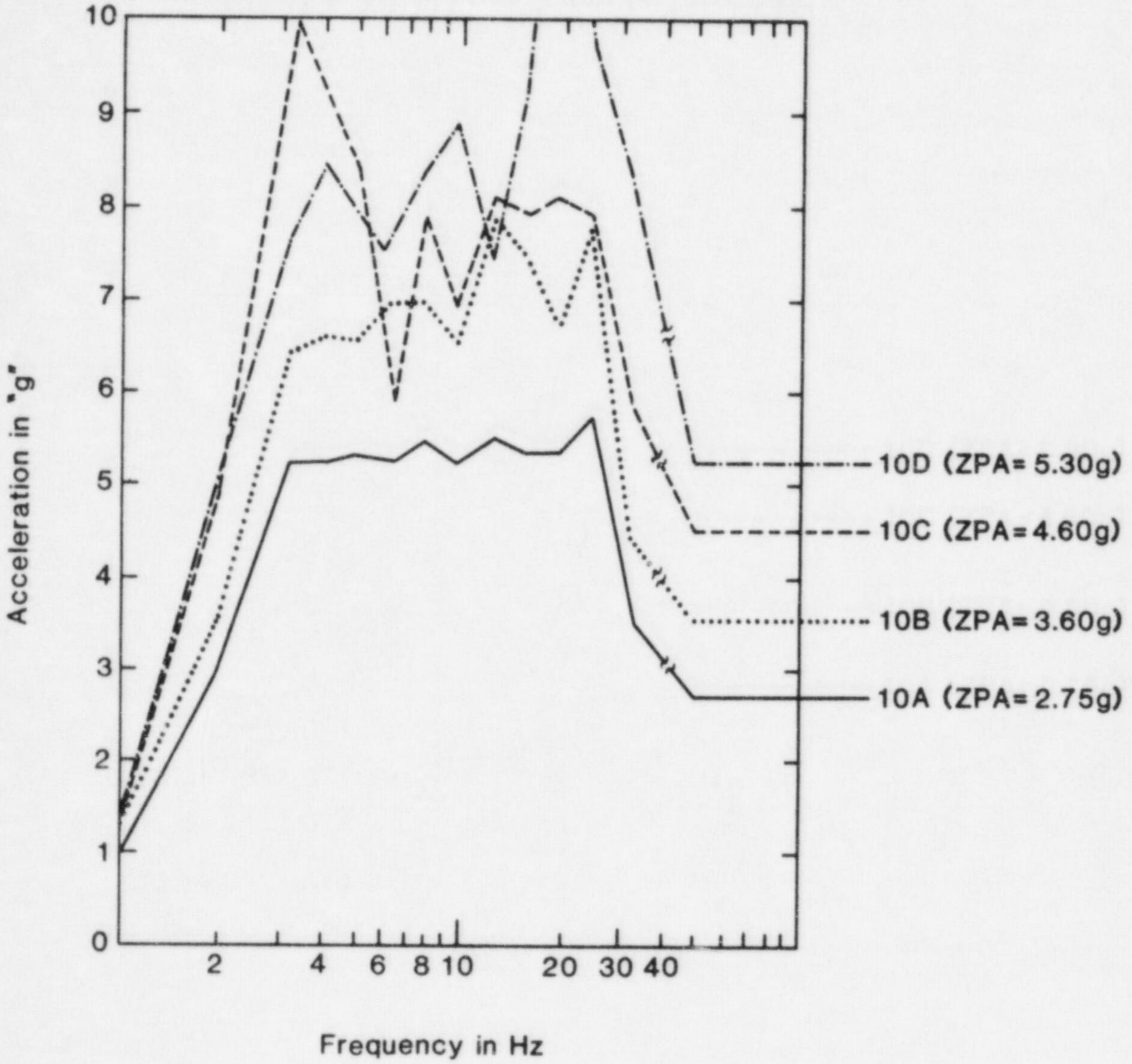


Fig. 3-10 TRS at 2% Damping,
Low Voltage Switchgear Manufacturer A,
Test Program 1

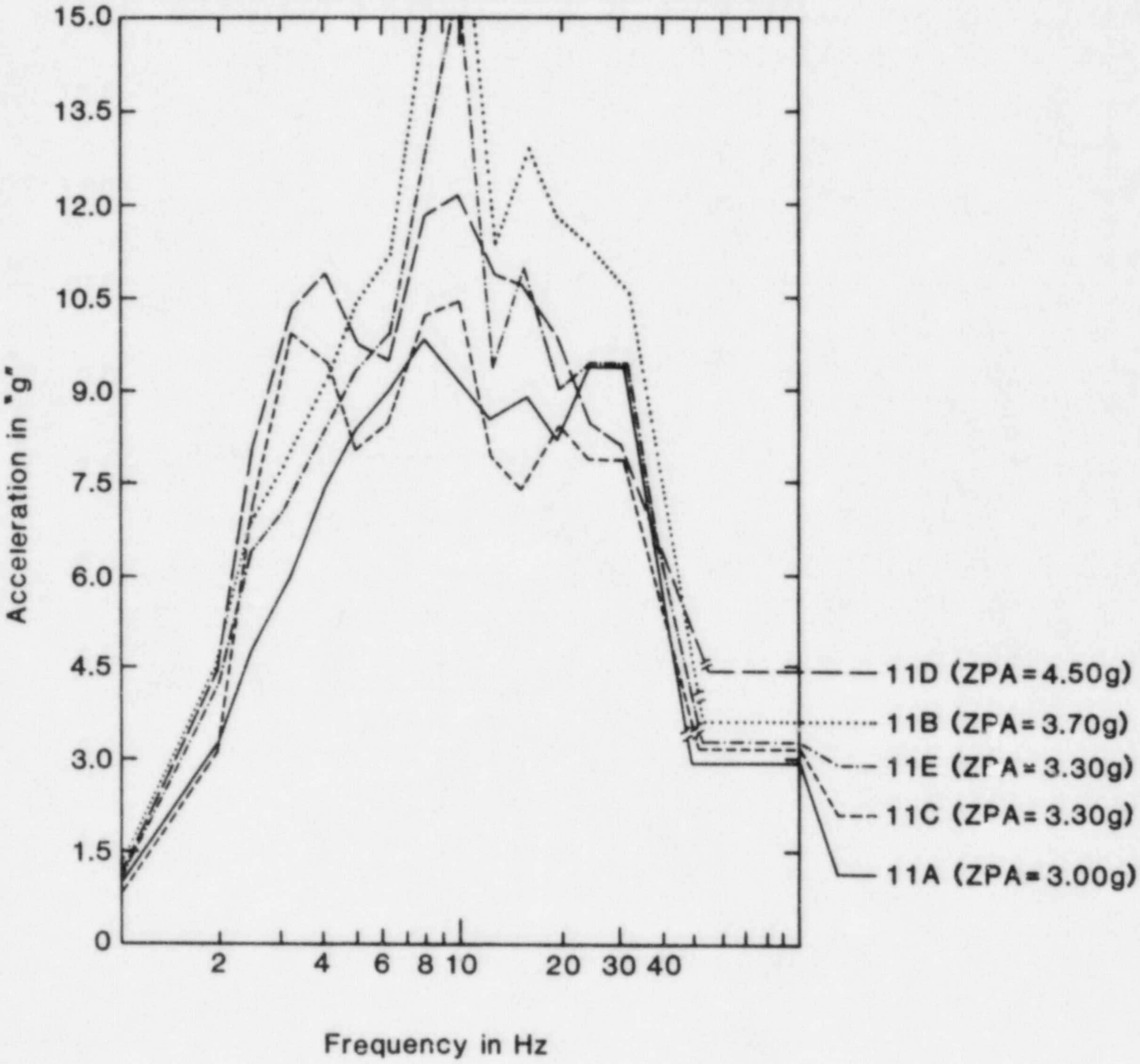


Fig. 3-11 TRS at 2% Damping, Low Voltage Switchgear Manufacturer A, Test Program 2

Curve 11A is an FB TRS with a ZPA value of 3.0 g. This input initiated cracks in the structural frame of the assembly. Curve 11C is the corresponding vertical TRS for the biaxial input. The specimen withstood the level of curve 11E in the SS direction with a ZPA of 3.3g. When the vibration input was increased to the level of curve 11B in the SS direction with a ZPA value of 3.7 g, the specimen exhibited a major structural damage. Curve 11D is the envelope of the two vertical TRS corresponding to the major structural damage. The resonant frequencies were observed at 10-14 Hz in the FB direction and at 6 Hz in the SS direction.

The test specimen was monitored for electrical continuity during the testing. However, in the test report, there was no mention of monitoring breaker operation (i.e., breaker closed, closed-tripped, etc.) or other device performance (e.g., chattering, operability, etc.). Therefore, results of this test program should be limited to the evaluation of structural behavior of the equipment along with its capability to maintain overall electrical continuity.

Neither of the two test programs discussed above indicated that they contained and monitored any relays. A third test program was conducted on the same type of low voltage breakers from the same manufacturer, and this time a number of relays were included in the test specimen and monitored during testing. Figure 3-12 shows the TRS plots from this test program discussed as follows.

The test specimen was a two-frame lineup of a low voltage switchgear containing six power breakers of two different types, and various types and models of protective and time delay relays from two major manufactures. The breakers were monitored for both static and dynamic operations, and no malfunction was reported regarding their closing or tripping. However, chattering of a number of relays was reported to exceed 2 ms and, at some test runs, to approach as high 230 ms. Two undervoltage relays and two time delay relays were observed to chatter during all test runs including the resonance search sine sweep tests with an amplitude of 0.2 g. The switchgear assembly exhibited resonant frequencies of 12 - 17 Hz in the FB direction and 6.5 Hz in the SS direction.

Curves 12A, 12B and 12C in Fig. 3-12 show the level high TRS at 2% damping ratio in the respective FB, SS and V directions. In addition to the device chatter mentioned above, moderate structural damage and chattering of a synchronism check relay were observed as a result of high level tests.

Figure 3-13 and Fig. 3-14 presents the TRS plots for a low voltage switchgear from another major manufacturer as the equipment evolved through successive stages of modifications to meet the needs of a high seismic plant. A 60" deep x 65" wide x 80" high switchgear specimen consisting of structural cabinets and electrical devices of a typical standard model, was first tested with increasing seismic inputs. The test specimen exhibited resonance at 7 - 8 Hz in the FB direction, and withstood without any anomaly a biaxial vibration input corresponding to curves 13A and 13B in the FB and V directions, respectively. Subsequently, the test input was increased to the levels ofcurves 13C and 13D, in the respective FB and V directions. This resulted in both elec-

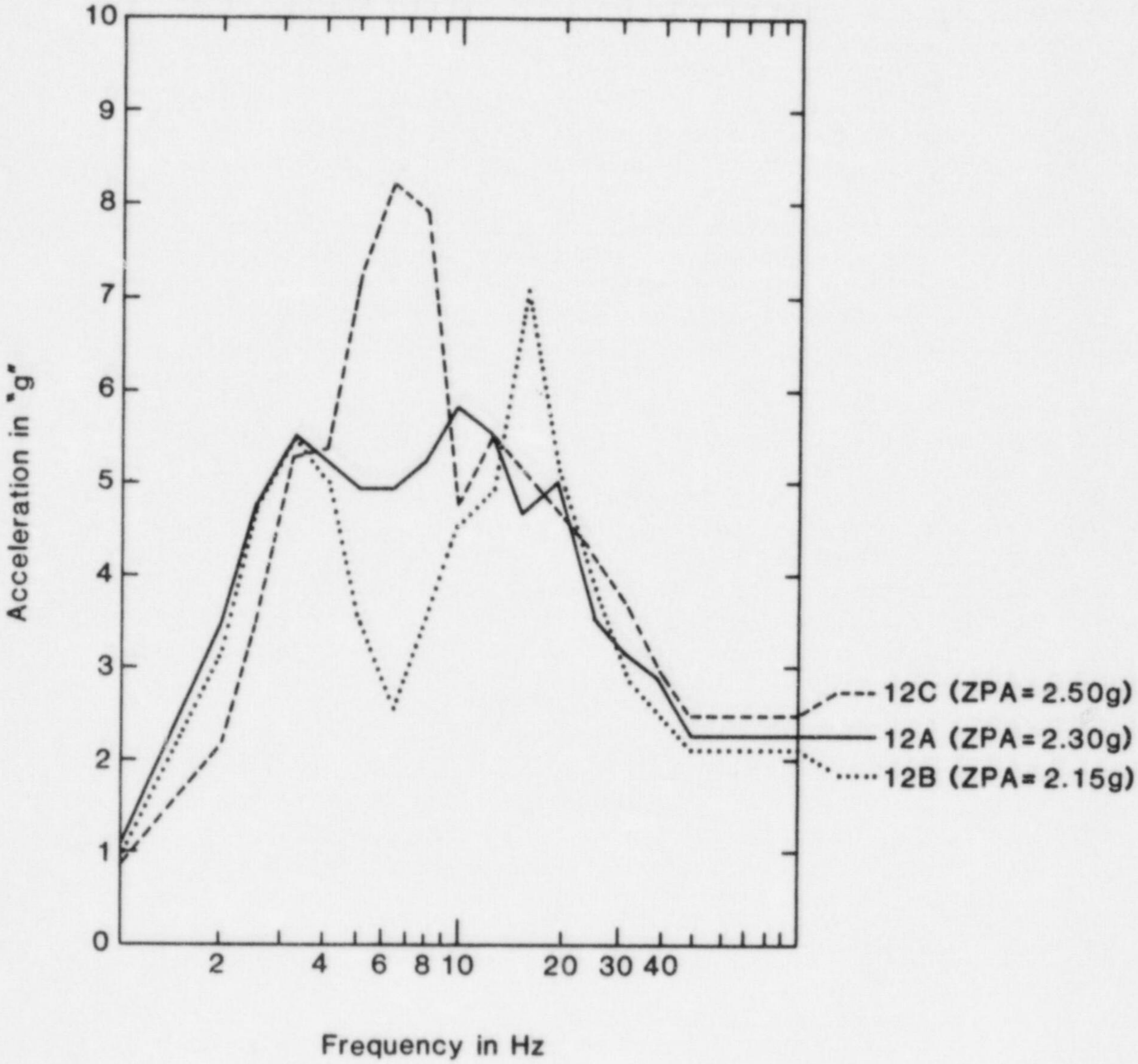


Fig. 3-12 TRS at 2% Damping,
Low Voltage Switchgear Manufacturer A,
Test Program 3

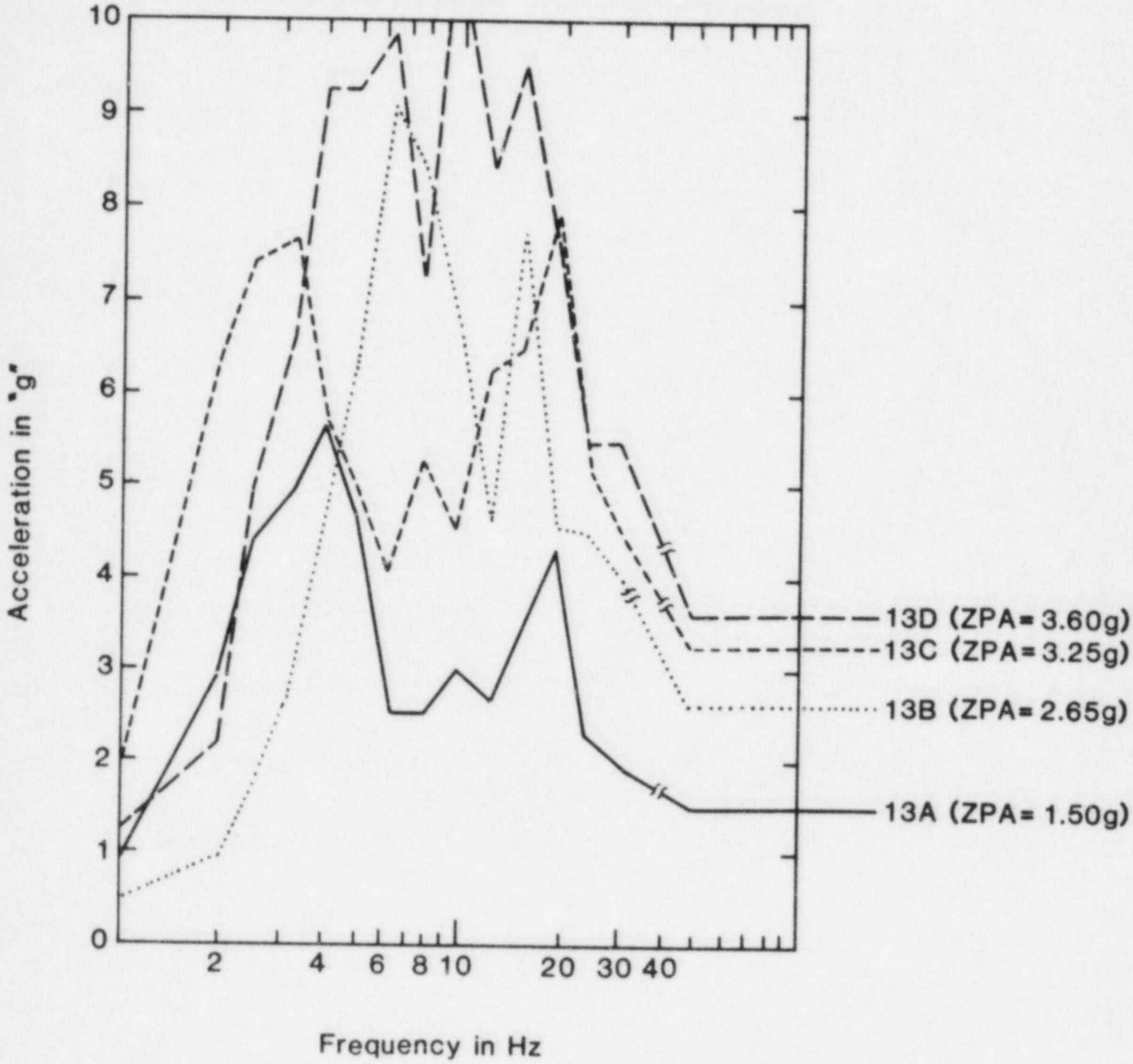


Fig. 3-13 TRS at 2% Damping,
Low Voltage Switchgear Manufacturer B,
Basic Model

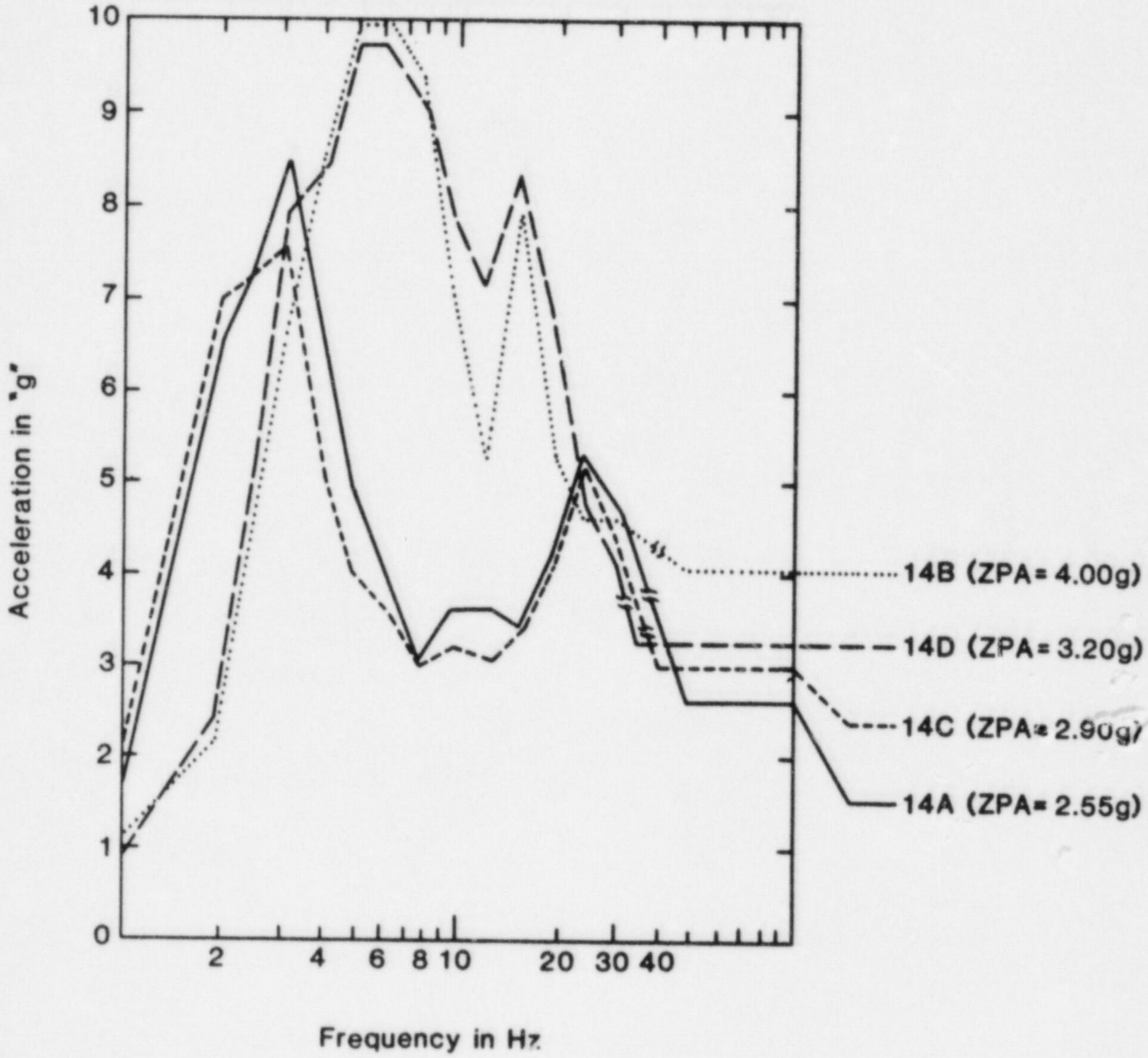


Fig. 3-14 TRS at 2% Damping, Low Voltage Switchgear Manufacturer B, Modified Model

trical malfunctioning and stripping of connecting screws used to attach the rear barrier panel to the main cell structure.

The test specimen was then structurally modified with back-nutted steel bolts to secure the rear panels, and the testing resumed. After several low level aging tests comparable to curves 13A and 13B, the input was again raised to produce TRS close to curves 13C and 13D. This time, no malfunction was reported during the first high level test. However, when a second high level biaxial input with a slightly lower ZPA was applied, the specimen exhibited the same type of structural failure and electrical malfunction. It is of interest to note that the connecting bolts did not fail at the first high level test indicating a metal fatigue failure during the second high level test. Also, fatigue failure at such a low number of stress cycles must be interpreted as a plastic fatigue.

As a result of recurrence of severe structural failures as discussed above, a third configuration of the equipment evolved. Basically, the entire cabinet structure was stiffened with additional framing members and larger size connecting bolts were used for the rear panels. In order to avoid undue fatigue, these modifications were performed on a new specimen which was of the same type and model as the first configuration, and a new series of testing started.

The specimen exhibited resonance at a frequency of 11-12 Hz in the FB direction. It was subjected to several low level seismic aging tests comparable to curves 13A and 13B prior to two high level tests in the FB/V directions. The TRS plots corresponding to these high level tests are shown in Fig. 3-14 by curves 14A (FB) and 14B (V). No structural damage or electrical malfunction was reported for these FB/V biaxial inputs. It should be noted that curves 14A and 14B in Fig. 3-14 are comparable to the earlier high level inputs as depicted in Curves 13C and 13D in Fig. 3-13 except for the dips in curves 14A and 14B around the resonant frequency of 11-12 Hz.

The test proceeded further in the other horizontal direction. The specimen was sufficiently vibration-aged with low level inputs in the SS/V directions prior to application of three successive high level biaxial (SS/V) tests. These high level tests resulted in structural failure of the base framing channels and frame weld, which triggered a series of electrical malfunctions, e.g., change-of-state of a breaker, lockout and excessive chatter of a switch, malfunction and excessive chatter of relays, etc. The TRS plots are close to curves 14A and 14B with ZPA values of 2.4 g in the SS direction and 3.4 g in the V direction.

The specimen was further modified to the final evolved product when new structural supports and base-framing channels were added to the structural base and the mounting frame. A power breaker switch was also replaced by a new one. This modified specimen exhibited the following resonant frequencies:

FB	13 Hz
SS	6.5 Hz
V	31 Hz

The specimen was vibrationally aged at least five times prior to application of the high level biaxial inputs in both the FB/V and SS/V directions. No anomalies were reported. The TRS plots for the FB/V inputs are shown by curves 14C(FB) and 14D(V) in Fig. 3-14. The SS/V TRS plots are very close to curves 14C and 14D with ZPA values of 2.75 g and 3.50 g in the respective SS and V directions.

In summary, the low voltage switchgear type was tested at four stages of evolution. For the basic standard model, the fragility curves are above curves 13A and 13B, but below 13C and 13D (Fig. 3-13) in the respective FB and V directions. The second configuration produced with slight bolting improvement of the basic, model exhibited higher capacity; but still the fragility levels are below curves 13C and 13D. The third configuration which incorporated major stiffening of the cabinet structure had a FB/V capacity levels above curves 14A and 14B in Fig. 3-14. But, its base framing was a weak link, and failed due to SS/V inputs comparable to those for curves 14A and 14B. The fourth configuration, which was the final evolved product, resulted by strengthening the base frame and the mounting supports. This specimen withstood biaxial vibration inputs in both the FB/V and SS/V direction, with TRS levels of curves 14C and 14D. Therefore, the fragility of the final product is higher than these two curves. But from both structural and electrical performance history during the entire test program, the final product is expected to have a fragility level not far above the curves 14C and 14D, and these two curves can be considered as its lower-bound curves.

3.4.2.1 Summary - Low Voltage Switchgear

The bounding TRS for various tests discussed above are presented in Fig. 3-15. Curve 15AFVL represents the lower-bound fragility level enveloping the FB and the V TRS for various models of one major manufacturer; whereas curve 15ASL is the corresponding SS TRS. These curves indicate the input level at which minor structural damage and electrical malfunction e.g., chattering etc. initiated. Curve 15AU is the upper bound for the same manufacturer's products in all three directions. This level corresponds to major structural and electrical malfunctions. However, the breaker was operable even at the level of 15AU. A second manufacturer's basic product withstood the level of curve 15BFL without any damage, whereas it failed completely at the level of curve 15BFU, both in the FB direction. When the unit was modified and stiffened, the evolved product withstood without any anomaly the levels of curves 15BBHL and 15BBVL in both horizontal directions and the vertical direction, respectively.

3.4.3 Failure Modes

The fragility study of both the medium voltage and low voltage switchgears as discussed above, has revealed the following generic failure modes:

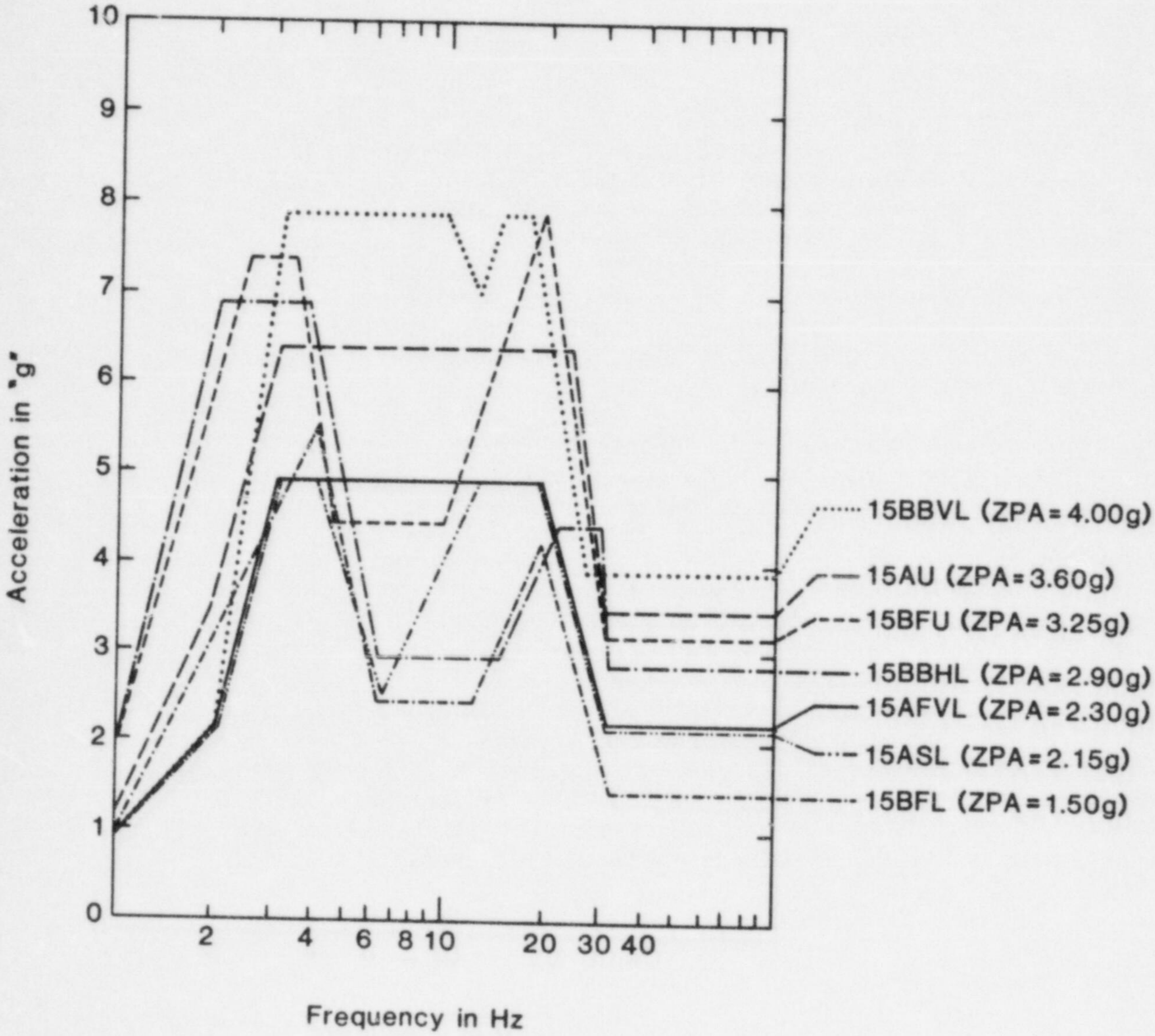


Fig. 3-15 TRS at 2% Damping,
Low Voltage Switchgear
Various Manufacturers

a) Chattering of relays and switches
b) Change-of-state of switches and relays
c) Tearing of device enclosure plate at connection
d) Inoperability of relays and switches
e) Damage of indicating lights
f) Tearing of switchgear enclosure plate
g) Tripping of power circuit breakers
h) Failure of breakers to respond to remote control
i) Sliding of fuse blocks
j) Crack of switchgear mounting weld

3.4.4 Remarks

From consideration of the shake table capacity, usually two or three vertical sections are placed side-by-side on the shake table for testing of this type of equipment. It has been observed that most test specimens are more flexible in the SS direction with lower natural frequencies (FB 10-13 Hz, vs. SS 4-7 Hz). Therefore, the test results may dictate a lower capacity level TRS curve when the SS curve is considered in the envelope. However, the site installation may require more units to be placed together which will increase the capacity of the assembly in the SS direction. In that case, the capacity level in the FB direction may govern.

Another point one should consider in selecting a fragility curve is that the basic unit may have been modified through evolution for a particular plant and the capacity level may have been increased significantly.

For both the medium voltage and the low voltage switchgears, the fragility levels determined above have been compared with those used in the PRA and the Margin Studies. The results are presented in Chapter 7 along with recomendations for proper application of the BNL data in other studies. When compared with the test data provided by EPRI in their interim report [1], the fragility levels for switchgears presented in this report are higher. For example with low voltage switchgears, per Ref. 1, the ZPA of the "Satisfactory" curve is 1.1g, whereas the lowest fragility ZPA in Fig. 3-15 is 1.5g. At the time of publication of their report, EPRI noted that insufficient data had been collected to allow construction of "ruggedness" curves for switchgear. It is expected that such curves will be presented in their Phase II report.

CHAPTER 4.

MOTOR CONTROL CENTER FRAGILITY DATA

4.1 INTRODUCTION

The motor control center, popularly known as MCC, is a floor-mounted indoor-type electrical panel which contains numerous electrical and control devices. Typically, a Class 1E MCC receives 480 VAC, 3-phase, 60 Hertz power and then distributes it through motor starters and circuit breakers to power plant safety-related systems. The specific function and positional location of an MCC in the plant are controlled by its application. Several Class 1E MCC's are needed in a typical nuclear plant.

Test data have been collected for MCC's manufactured by four leading companies in this country. These data are presented in this chapter employing the evaluation methodology described in Chapter 2. The generic failure modes observed in the data analysis are summarized towards the end of this chapter. A description of the equipment is also included in this chapter along with a list of electrical devices contained in a typical MCC assembly.

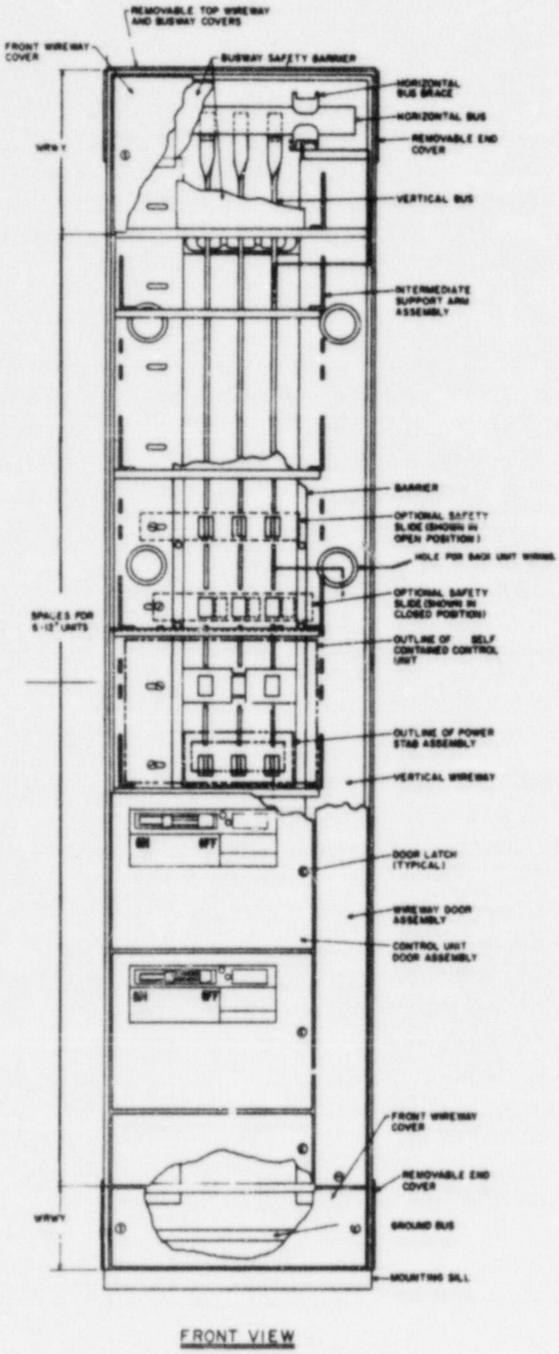
Low level qualification data from additional tests have also been observed while searching for fragility information. For obvious reasons, such data are not included in the fragility analysis presented in this report.

4.2 EQUIPMENT DESCRIPTION

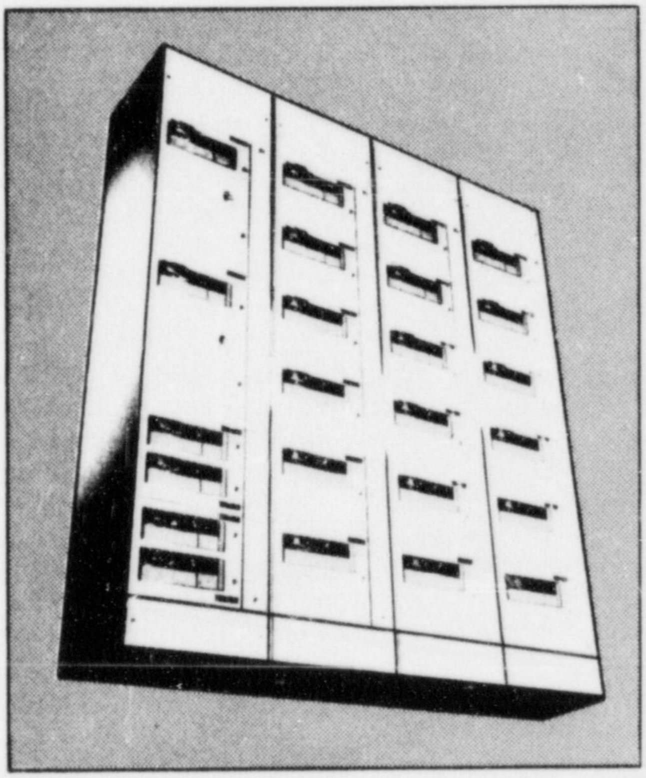
The building block of an MCC is a vertical section which typically weighs 600 lbs. with the devices, and measures approximately 20" wide x 20" deep x 90" high. Several such units (2-6) are placed together side-by-side in a typical application to form an MCC assembly (Fig. 4-1). The frame and housing of an MCC unit incorporate a welded and bolted reinforced steel frame sheathed with steel panels. Latchable steel doors providing access to the electrical devices complete the enclosure. Electrical entrance and egress to the complete assembly are provided by openings in the tops and bottoms of each verticl section. Access to the devices and to the wiring system is typically via doors on the front of each starter unit, and via removable panels at the top, bottom and rear of the MCC assembly. The MCC assembly in its application is either welded or bolted to the floor through a mounting sill.

Typically an MCC may contain the following devices:

- Motor Starters
- Contactors
- Auxiliary Contacts
- Circuit Breakers
- Selector Switch
- Pushbutton Operators
- Indicating Lights
- Current Transformers
- Current Transducers



A Unit



An Assembly

Fig. 4-1 Motor Control Center (MCC)

Industrial Relays
Fuse Blocks
Current Limiters
Reset Assembly
Terminal Blocks
Terminal Boards
Stab Assembly
Overload Heaters
Door Interlock
Miscellaneous

The devices included in the MCC tests are representative of those used in typical nuclear plants.

4.3 EVALUATION OF TEST DATA

The test results have been extracted from six test reports for products from four major manufacturers. In most test programs, more than one specimen or configuration were tested to envelop the device characteristics in different locations in an MCC. The vibration techniques and the electrical monitoring procedure used in a particular test program are presented along with the data analysis. A brief description of each test specimen is also included. The test data have been processed, and are presented on a manufacturer basis in the following subsections. Coded names are used for manufacturers to protect their proprietary information.

4.3.1 Manufacturer A

A widely used MCC model from a major manufacturer was subjected to an intensive test program. The three-frame test specimen weighed approximately 2,000 lbs. and contained numerous electrical devices.

In the test programs the devices were shuffled at different locations in the MCC in order to envelop all possible installations in a plant. The equipment was tested for both electrical states, namely, de-energized and energized, and also for the change of state. In order to encompass all such possibilities along with the environmental aging effects, the specimen was subjected to a total of 159 biaxial random multifrequency tests. The tests included sequentially increasing vibrational inputs up to a certain level beyond which the test specimen started exhibiting different types of structural damages and electrical malfunctions, thereby revealing the threshold of fragility.

The test specimen was bolted to a test fixture which, in turn, was welded to the shake table. The specimen was first tested with four bolts, and later with the usual in-service mounting of twelve bolts. Thus, the effect of mounting on the equipment response can be evaluated. The specimen resonated at the follwoing frequencies:

FB	6 Hz
SS	5-6 Hz
V	35-37 Hz

The TRS plots are presented in Fig. 4-2.

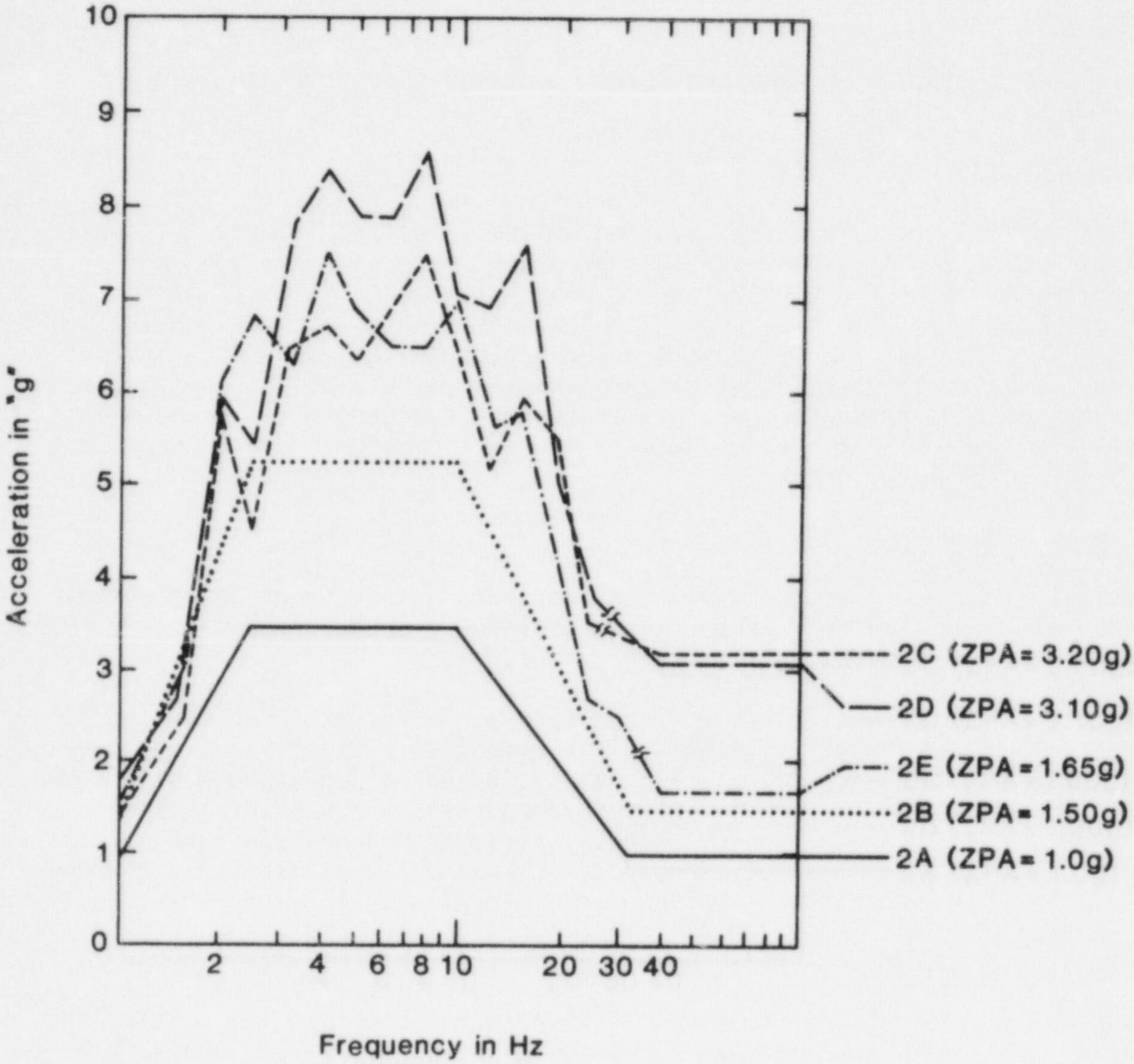


Fig. 4-2 TRS at 2% Damping, Motor Control Center Manufacturer A

The electrical function of the devices was tested by monitoring electrical loads and detecting contact chatter of two milliseconds or greater duration. A summary[1] of the electrical monitoring results indicated that up to the level of TRS shown as curve 2A in Fig. 4-2, (in all three directions), the equipment did not exhibit any malfunction for any of the shuffled positions of the devices and their various electrical states. It was reported that when the test input was increased to envelop the level of curve 2B (in all three directions), the starters experienced various types of malfunctioning, e.g., dropping out load, inadvertently changing state, failing to change state on command, erratic behavior. The structural braces at the bottom of each bay cracked during the test runs intended to envelop curve 2B. The self-tapping screws used to attach the braces also failed at this test level by stripping out.

At certain electrical states and positioning of the devices, the equipment withstood even a higher input level. For example, the specimen was shaken to the level of curve 2C in the FB horizontal direction several times without any starter problem. The input level was further increased to produce the FB TRS shown as curve 2D with no starter malfunction. The vertical TRS corresponding to the biaxial inputs of curves 2C and 2D, are shown as curve 2E. It was also observed that at the same electrical state, a starter exhibited a malfunction during one test run, while it passed without any anomaly during a subsequent run, although the TRS for the two test runs were almost identical.

The observations from the above test program any be summarized as follows:

1. The MCC specimen withstood the level of curve 2A without any starter problem.

2. Starters malfunctioned at the threshold of curve 2B.

3. Starter behavior due to seismic input to unpredicatable near the fragility level.

4. Self-tapping screws are a structural weak link in this MCC model.

5. Low cycle fatigue failure indicates that some structural components reach the plastic strain range at the device malfunction level.

4.3.2 Manufacturer B

A commonly used MCC model from another major supplier was tested in three separate test programs with random incoherent multifrequency vibration

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[1]The details of electrical monitoring, for this test program were not available at the time of publishing this report. The results discussed herein may be changed upon receipt of this detailed information.

inputs. Numerous standard devices were installed in the MCC cabinets in all three test programs. The specimens were powered and monitored for functional operation during testing in energized, de-energized and transition (i.e., energized to de-energized to energized) states. The results are presented as follows.

4.3.2.1 Test Program 1

In the first test program, in 1979, one three-bay MCC and one two-bay MCC were welded on the same shake table, and shaken together using biaxial input motions. The three-bay unit exhibited the first resonance at a frequency range of 6-7 Hz in both FB and SS directions, with a higher amplification in the FB direction. The SS resonant frequency dropped to 5 Hz for the two-bay unit. A total of eighteen random tests was performed with ten in the FB direction. Device chatter of 6 ms or greater was detected in all de-energized FB/V tests with a maximum of 30 ms. No chatter was reported during the SS/V tests. Curve 3A in Fig. 4-3 shows the highest level FB TRS with ZPA value of 1.45 g in the energized state during which no malfunction was observed. However, in the de-energized state, chattering was detected at a lower input motion, even at a low ZPA value of 1.1 g. When the specimens were tested in the FB direction for the transition state at about the same TRS level as curve 3A, terminals were shorted in the normally closed auxiliary interlock compartment in addition to device chatter. In the SS direction, the specimens withstood about the same input in the de-energized state without indicating any malfunction. Mounting weld cracks in both specimens were observed due to the FB/V test series. However, no structural damage was reported due to the SS/V test inputs.

4.3.2.2 Test Program 2

In a second test program, in 1981, a two-bay MCC was subjected to a total of twenty-two random biaxial tests out of which thirteen were in the FB direction. The specimen was tested to the level of curve 3B in Fig. 4.3, with a ZPA value of 2.3 g in the FB direction in the transition state. No device chatter was reported at this electrical state. However, when the specimen was subsequently tested in the de-energized state at about the same input level, normally closed auxiliary contacts chattered (4-8 ms). By increasing the vertical input from a ZPA of 1.7 g to that of 1.9 g while maintainly the same FB input, it was observed that the chatter duration dropped from 8 ms to 4 ms. The chatter was for 6 ms at a level of 1.8 g ZPA. No chattering was reported in this de-energized state when the inputs were further lowered to the ZPA levels of 2.1 g in the FB direction and 1.3 g in the vertical direction. A small fracture was observed in the structure due to the FB/V test series. No malfunction was reported in any electrical state when the specimen was tested in SS direction. In the energized state, no structural damage or electrical malfunction was reported even when the specimen was tested to a ZPA level of 3.4 g in the SS direction.

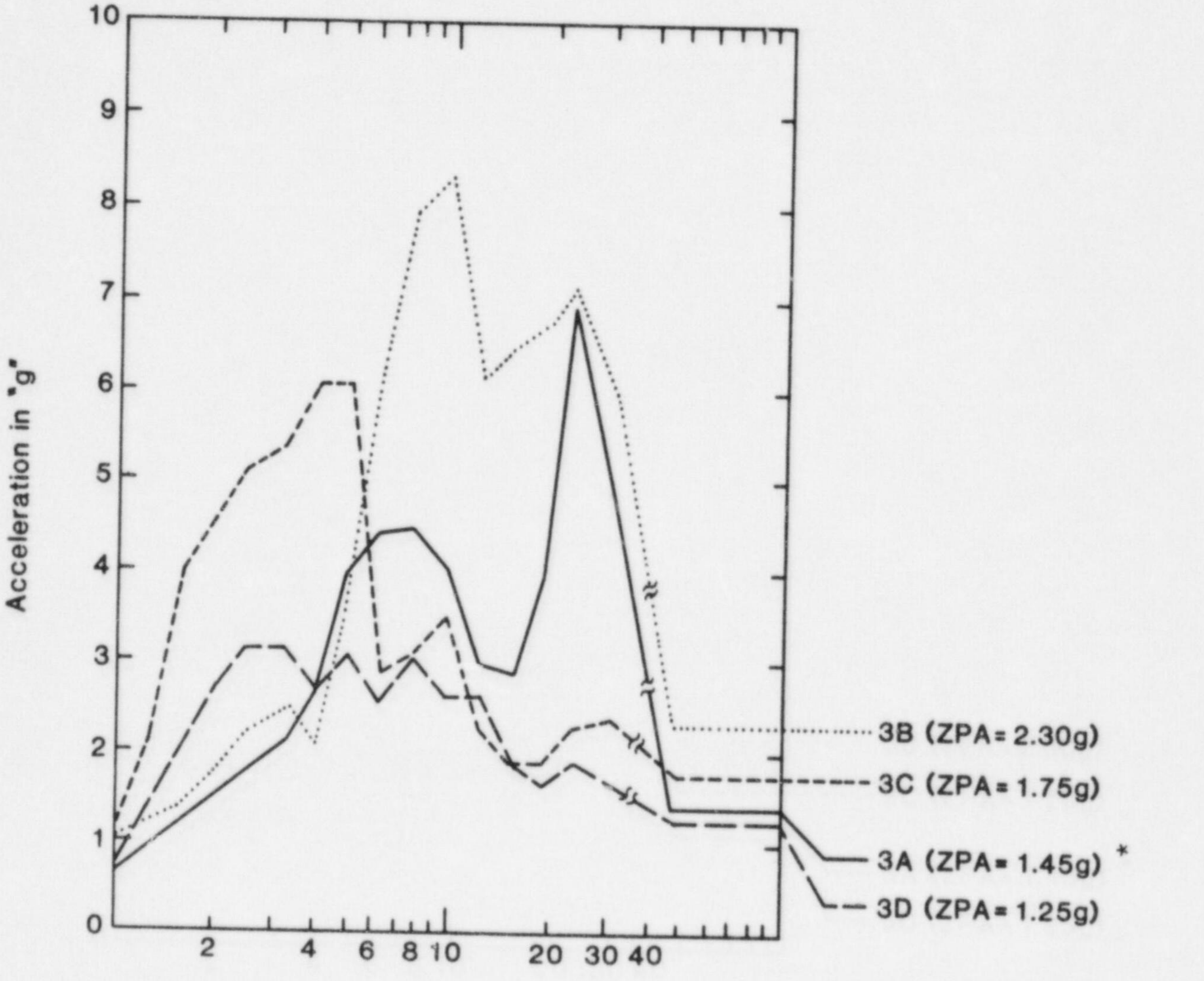

Fig. 4-3 Horizontal TRS at 2% Damping,
Motor Control Center
Manufacturer B

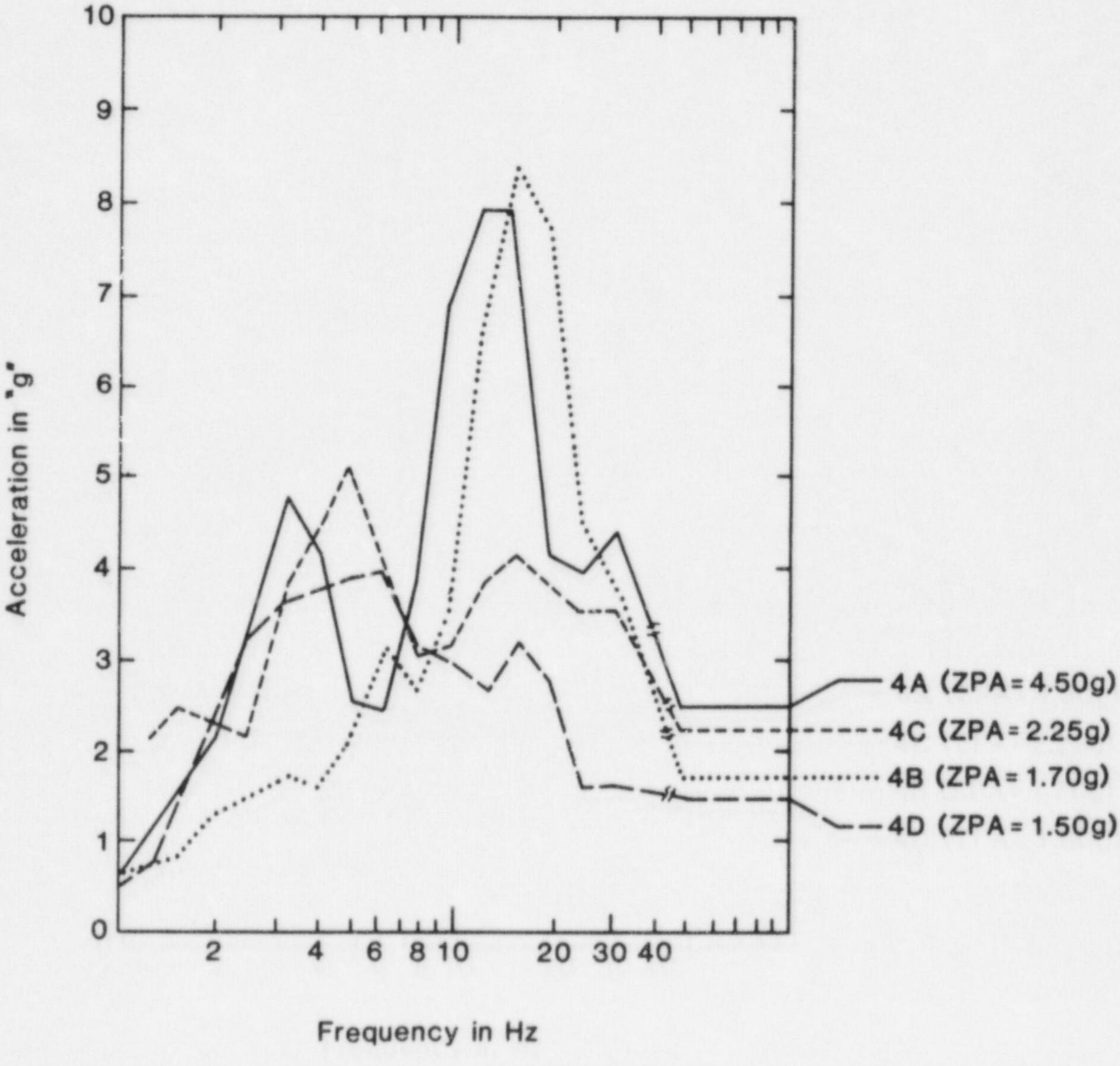

Fig. 4-4 Vertical TRS at 2% Damping, Motor Control Center Manufacturer D

The variation in performance of the specimens in the last two test programs (1979 vs. 1981) is remarkable. For example, in the electrical transition state, the specimens in the first test program indicated major malfunctions at a TRS level shown as curve 3A, whereas the specimen in the second test series withstood an input level of curve 3B without any reported malfunction.

4.3.2.3 Test Program 3

In the third test program conducted in 1983, two MCC specimens - one two-bay and one three-bay - were welded to a triaxial shake table and subjected to nine random multifrequency tests with varying vibration inputs. Each bay measured 20"Wx20"Dx110"H and weighed about 600 lbs. The following fundamental resonant frequencies were detected:

	FB	SS
Two-bay specimen	7.6 Hz	8 Hz
Three-bay specimen	8.5 Hz	9 Hz

During the pretest functional checkout, some latching contactors were generically observed not to latch consistently due to the presence of small pieces of plastic or phenolic material lodged in the area between the pole faces and the coil housing, restricting travel of the mechanism. In order to obtain consistent latching action, it was required to blow out the plastic pieces and to add a flat washer as a shim between each of the latching mechanism's mounting tabs and their respective mounting tabs on the contactor body. The modified contactor was then installed and the test program was continued.

Following several successful low level tests, the specimens were subjected to the level of curve 3C in the FB direction with a ZPA value of 1.75 g for the de-energized state. At this level, chatter longer than 2 ms was detected for the main power contact, and for both the normally open and normally closed auxiliary interlocks of various latching contactors and starters. In addition, a frame-to-mounting-sill bolt snapped during this run. The corresponding SS TRS is similar to curve 3C except that the SS input level is slightly greater with a ZPA value of 2.2 g.

The testing continued with reduction in vibration inputs below 6 Hz until a level was reached at which point no more contact chatter occurred. Curve 3D shows the TRS of the FB input for this lower-bound level. The corresponding SS TRS of the triaxial test was about the same with an identical ZPA value.

The corresponding vertical TRS for the horizontal curves shown in Fig. 4-3 are presented in Fig. 4-4 with the same suffixes.

In summary, the most common failure mode is chattering of auxiliary interlocks in latching contactors in the de-energized state especially for the normally closed contacts. The contactors are more vulnerable at low frequencies (1-7 Hz). In addition, for consistent latching action, cleaning and modifications were required for the latching mechanism as described earlier.

4.3.3 Manufacturer C

The results of testing an MCC from another manufacturer is presented in Fig. 4-5. The three-frame test specimen, 60"Wx20"Dx90"H, weighing approximately 1,700 lbs., was welded to the shake table, and subjected to a total of seventeen independent biaxial random vibration inputs. The MCC exhibited fundamental natural frequencies of 7-8 Hz in the FB direction and 8-9 Hz in the SS direction.

The specimen withstood the level of curve 5A in Fig. 4-5 for the de-energized state in the FB direction, and for the transition state (i.e., energized to de-energized to energized) in the SS direction. However, when the input was raised to the level of curve 5B in the FB direction for the transition state, two motor starters failed to remain in the de-energized state. Curve 5C is the vertical TRS corresponding to the biaxial input of curve 5B. The vertical TRS curve, corresponding to curve 5A, is slightly lower than curve 5C with a ZPA value of 0.8 g.

In summary, curve 5A can be considered as the lower-bound fragility level due to its closeness to the failure curve 5B.

4.3.4 Manufacturer D

The test results of a standard model from a fourth manufacturer are also included in the data base. A five-bay MCC, each bay measuring 20'Wx20"Dx90"H, was welded to a biaxial shake table and subjected to increasing random vibration inputs. The fundamental natural frequencies were detected at 10-11 Hz in the FB direction and 15-17 Hz in the SS direction.

The specimen was shaken several times to the level of curve 6A, Fig. 4-6 in the FB direction. No malfunction was reported, given the fact that the entire test program used chattering upto 20 ms as the acceptable limit.

The vibration level was gradually raised to the level of curve 6B in the FB direction, with the horizontal ZPA value of 3.3 g and the vertical ZPA of 3.6 g, under reduced voltage conditions, at which point chattering of a motor starter and timing malfunction of a time delay relay were detected. In a subsequent test the vertical input ZPA was lowered to 3.0 g maintaining the same horizontal input. Both the chattering and the time delay anomalies increased further. However, in the SS direction no malfunction was reported when the specimen was shaken to the same level as curve 6B, again with the understanding that chattering below 20 ms might not have been reported.

The manufacturer related the excessive starter chattering mentioned above to the inadequacy of a control power transformer. Subsequently, the MCC was modified by replacement of the transformer by one with 70% higher KVA rating. The time delay relay was also removed from the panel. The modified specimen was then subjected to numerous random biaxial vibration inputs. Curve 6C shows the maximum FB TRS the specimen was tested to (ZPA = 4 g, peak response = 14 g at 40-50 Hz). In the SS direction, the specimen was tested to a TRS

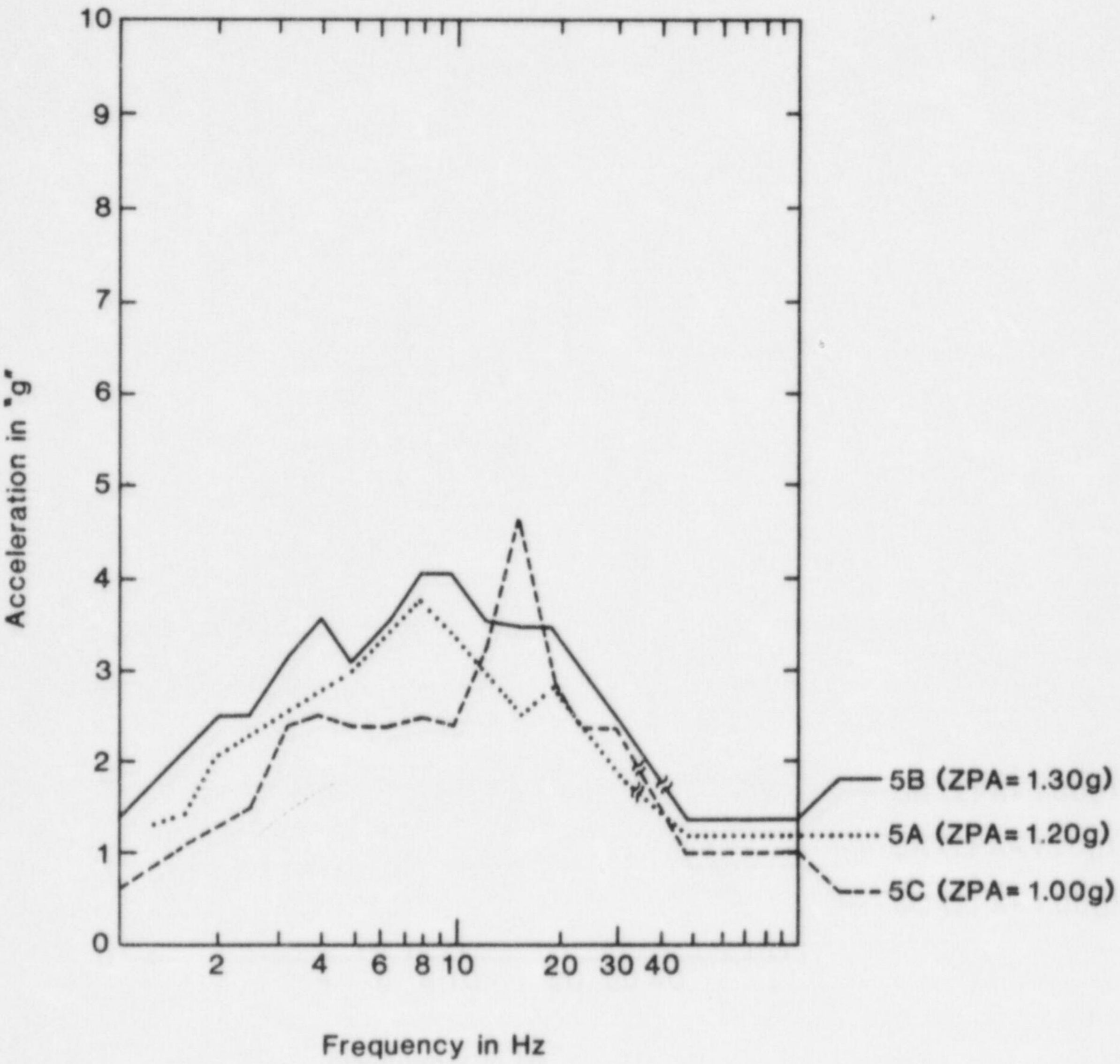

Fig. 4-5 TRS at 2% Damping,
Motor Control Center
Manufacturer C

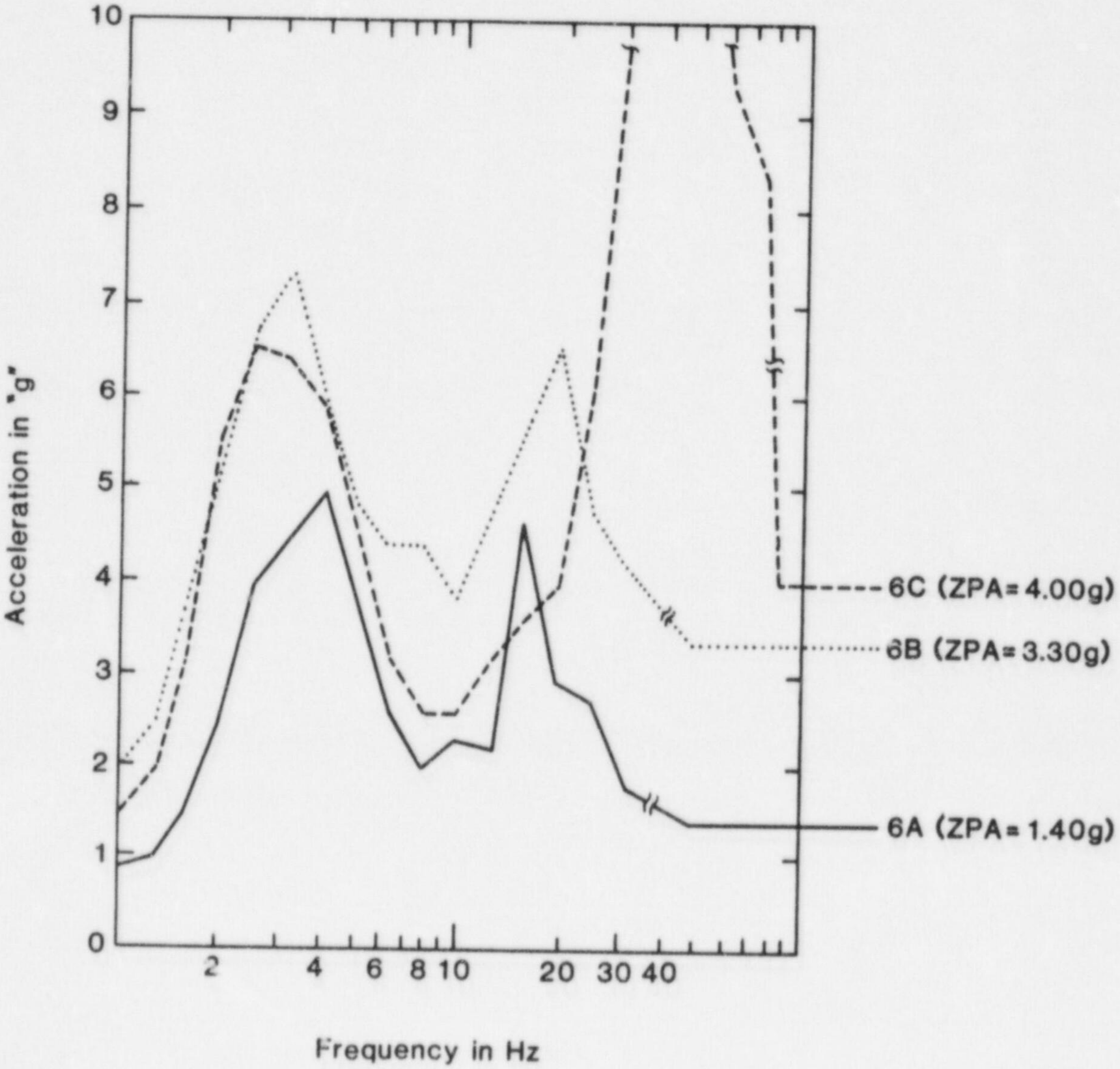

Fig. 4-6 Horizontal TRS at 2% Damping, Motor Control Center Manufacturer D

level slightly higher than curve 6C in the low frequency range and significantly higher in the high frequency range (ZPA = 4.2 g, peak response = 19 g at 40-50 Hz). No anomaly was reported for the modified specimen. Again, chattering below 20 ms might not have been reported.

It is of interest to note that although both the ZPA and the peak response of curve 6C are significantly higher than those of curve 6B, the response levels at the frequency range of interest are lower in curve 6B. In fact, near the MCC resonant frequency, curve 6C is significantly below curve 6B, and is close to, or even below, curve 6A with a ZPA of 1.4 g. This phenomenon is more apparent for the SS TRS discussed in the prevous paragraph. It has been observed that traditionally in an MCC, malfunctions occur at low frequencies. Therefore, the higher ZPA and response values at the high frequency range do not necessarily consitute a more severe test. It evolves from this discussion, then, that specifying a fragility level input by ZPA and/or peak response values, even for comparison purposes, may lead to a serious error and inappropriate conclusions.

In summary, the standard MCC model withstood the level of curve 6A without any modifications, and the level of curve 6C with replacement of a control power transformer and removal of a time delay relay. The vertical TRS curves corresponding to those shown in Fig. 4-6, are presented in Fig. 4-7.

4.3.5 Failure Modes and Remarks

With the increase of vibration levels, the first anomaly experienced by most MCC's is the malfunction of motor starters and contactors. A starter may misbehave in one or more of the following ways:

a) Chattering
b) Dropping out load
c) Inadvertently changing state
d) Failing to change state on command
e) Erratic behavior

Among these, chattering of the auxiliary interlock of the starters and contactors is the most common phenomenon. This is especially true for the normally closed de-energized state. Furthermore, these devices are more vulnerable at low frequencies (usually below 8 Hz).

Another common malfunction is a time setting problem with time delay relays. Stripping out of self-tapping screws has been observed for the MCC structural frame. Crack formation in the frame and in the mounting weld has also been observed at a higher vibration level.

The fragility levels of the MCC corresponding to various failure modes have been compared with those used in the PRA and the Seismic Margin Studies. The results are presented in Chapter 7 along wih recommendations for proper application of the BNL data in other studies. The lowest envelop of the curves presented herein can be used as the lower bound fragility level. Test data of additional MCC models are expected to be incorporated in the Phase II study.

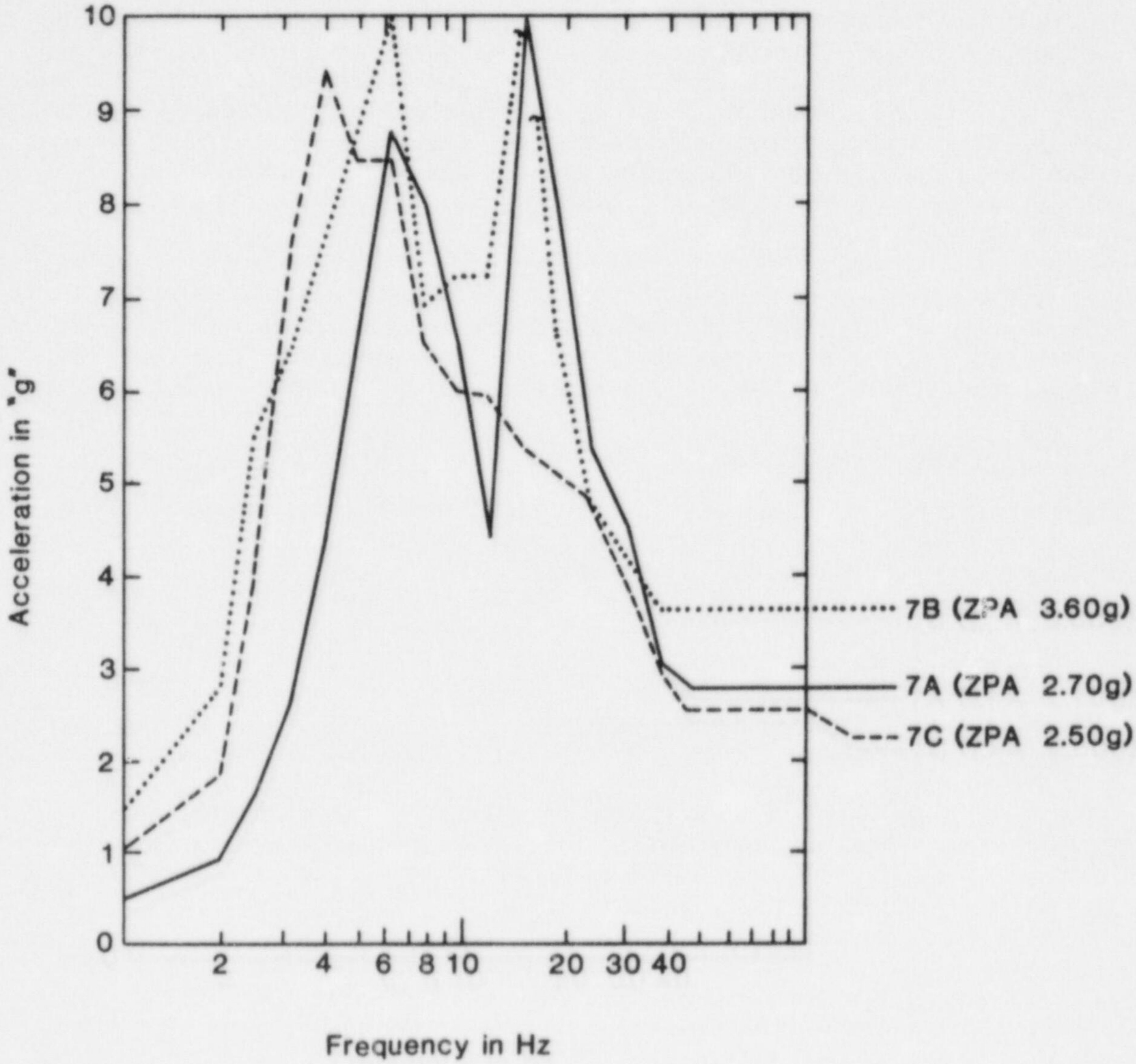

Fig. 4-7 Vertical TRS at 2% Damping,
Motor Control Center
Manufacturer D

CHAPTER 5.

HIGH LEVEL TEST DATA

5.1 INTRODUCTION

During the data collection process, it has been observed that some components were tested to high vibration levels, often to the capacity level of the shake table; but they exhibited no malfunction and little, or no, structural damage. Fragility levels of such equipment are higher than the vibration level used in the tests and, consequently, these test response spectra cannot be considered as the fragility level. However, it has been judged that there is a potential use of these high level test data, and the test response spectrum levels can be used in one of the following ways depending on the nature of the equipment and its support.

If in the field, the equipment is generically mounted on a floor slab or a seismically rigid support, then the test vibration level might be high enough for all practical purposes so that the real fragility levels of this type of equipment need not be established. Consequently, there would be no need to search for fragility level of these pieces of equipment either through data collection or by future testing.

On the other hand, if in the field the component is usually mounted on a flexible support (e.g., an electrical device in a motor control center) and the component was tested separately to the shake table vibration limit without indication of any anomalies, then additional analysis would be required, and the fragility data for such component should be sought in the test data of the assembly (e.g., motor control center). Moreover, if, in the future, fragility testing is required for such equipment, the possibility of undue fatigue failure by shaking at lower levels as well as the testing cost can be substantially reduced by starting with the high level test data collected for these components.

High level test data of five electrical and instrumentation components are presented in this chapter. More data are expected to be collected in Phase II for some of these components as well as for additional components.

5.2 ELECTRICAL PENETRATION ASSEMBLY (EPA) AND ELECTRICAL CONDUCTOR SEAL ASSEMBLY (ECSA)

EPA's and ECSA's are basically electrical conductors sealed in tubular modules. They protect the conductors in adverse environments and assure electrical continuity. EPA's, in addition, maintain the environmental boundaries in that they provide electrical continuity without leakage of pressure, radiation, etc., through the penetrations.

Test results from a leading manufacturer were obtained for three EPA models and two ECSA models. The lowest natural frequency for the EPA's was detected as 8 Hz. High level random biaxial seismic tests were performed on prototype

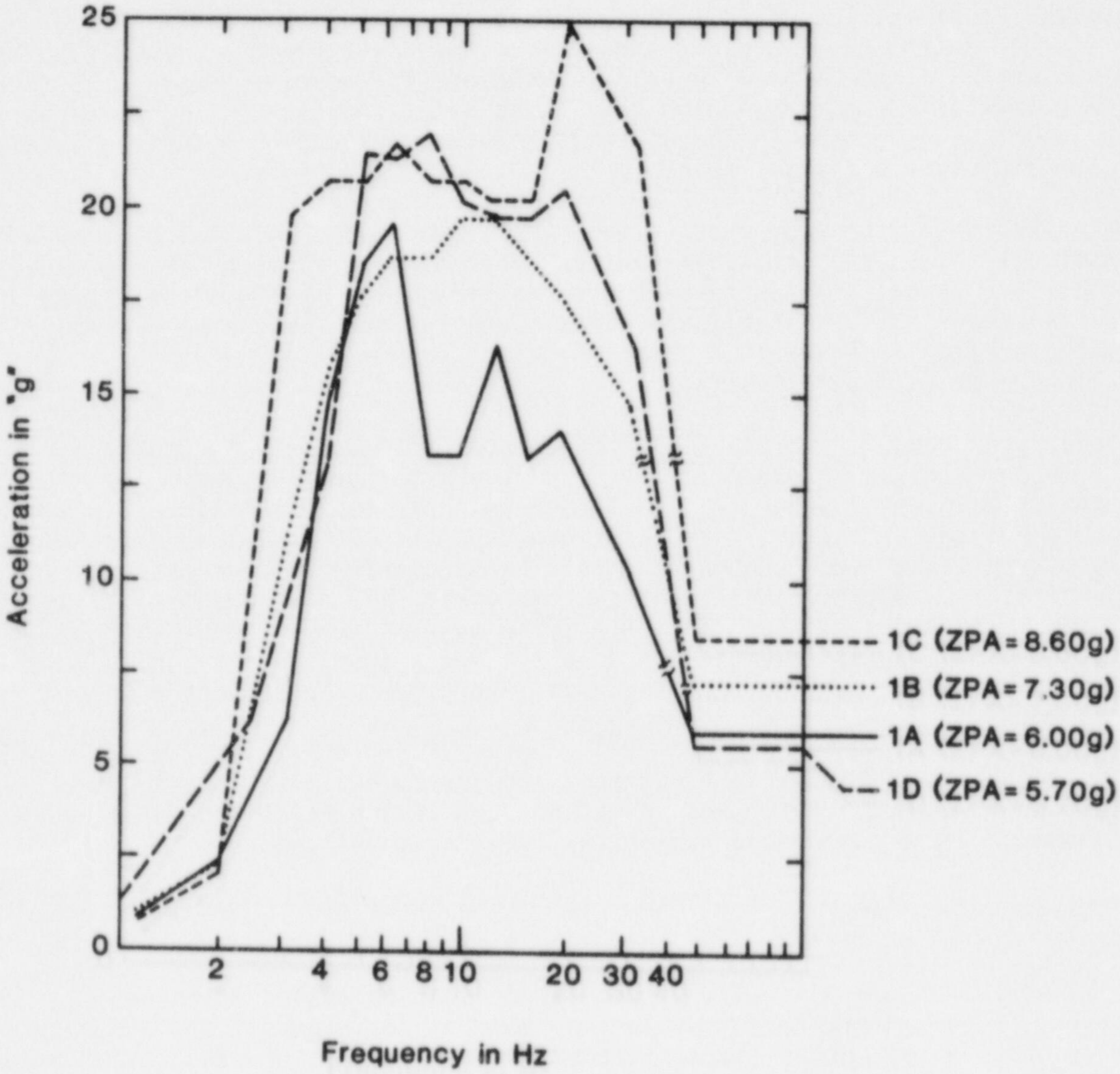

Fig. 5-1 TRS at 2% Damping, EPA, ESCA, RTD, Thermocouple and Terminal Board - High Level Test Data

specimens. No failures or anomalies were reported. Curves 1A and 1B in Fig. 5-1 show the lower envelops of the TRS in three orthogonal directions for various models of the EPA's and the ECSA's, respectively.

It should be noted that the above EPA test specimens did not contain electrical junction boxes mounted on header plates as sometimes used in field installation. In such cases, the seismic capability of the assembly might be limited by the strength of the junction box. Test results of EPA's from another major manufacturer indicate anomalies at a lower seismic level. These results will be incorporated in the component fragility study in the future.

5.3 RESISTANCE TEMPERATURE DEVICE (RTD) AND THERMOCOUPLE TEMPERATURE SENSOR

RTD's and thermocouples are long electrical modules used to electrically and remotely measure temperature to a high range. Nine specimens of RTD's and thermocouples from one major supplier were biaxially tested to a high seismic level. No malfunction was reported. The lower envelop of the TRS in three orthogonal directions is shown as curve 1C in Fig. 5-1.

5.4 TERMINAL BOARD

Six different models of terminal boards from five major manufacturers were mounted on a rigid test fixture and shaken to the capacity of a triaxial table. The specimens were vibrationally aged with 50%, 60%, 70%, 80% and 90% of the input capacity prior to the full capacity level test. Electrical continuity was nonitored. No malfunction or damage was reported. The TRS plot enveloping both horizontal components is presented as curve 1D in Fig. 5-1.

CHAPTER 6.

A DISCUSSION ON RELAYS

6.1 INTRODUCTION

Relays are one of the most common groups of devices that are extensively used in a power plant. By maintaining the continuity or discontinuity of contacts in an electrical circuit, they sense some electrical variables, e.g., current, voltage, frequency, protect the circuit or perform similar indispensable functions. A complex electrical equipment, such as, a main control board, a switchgear or a motor control center, typically contains numerous relays for its multifarious functions. Based upon their designs and functions, relays are divided into a large number of groups. The relays used in nuclear plants in this country are mostly supplied by three companies, although there are three or four other manufacturers. Regardless of the type of relays or their manufacturers, relays have been proven to be one of several weak links in an electrical equipment (Ref. Chapters 3, 4 and 7). However, unlike other weak devices, the relay family is large, diverse and complex. Therefore, a discussion on relays is presented in this chapter highlighting the complexity of the issue, data collection in Phase I, additional data required for a generic analysis and recommendations for further study.

6.2 COMPLEXITY OF RELAY FRAGILITY STUDY

As mentioned above, recent studies increasingly indicate that for most electrical equipment assemblies, the seismic capacity is limited by the functional capability of relays along with a few other devices. However, a complete understanding of relays is not easily gained due to the large family size, varied design patterns, inherent behavioral complexities when subject to seismic vibration, controversies over acceptance criteria and various testing methods. Three broad categories of factors obscuring the relay fragility study are discussed in the following subsections. In summary, the study of relay is complex, and deserves special attention before its seismic fragility is fully understood.

6.2.1 Design and Behavior

The relay family can be broadly categorized into four groups, namely, auxiliary, protective, general purpose and time delay relays. Again based on its specific function and use in a circuit, a relay may be called under or over voltage, frequency, lockout, reverse power, ground, voltage balance, current balance, instantaneous overcurrent, synchronism check, etc. On the other hand, it can be divided into several groups based upon its fundamental design concept, i.e., electro-mechanical, solid state, pneumatic, etc. Again, a relay configuration could be normally open or normally closed. Furthermore, a contact relay may exhibit substantially different capacity levels under an identical seismic vibration input depending on whether it is energized or de-energized. It has also been observed that a relay capacity determined by an independent test does not always correlate with its behavior when tested in an assembly.

6.2.2 Acceptance Criteria

Perhaps, all of the above problems are overshadowed by a single issue, i.e., the acceptance criteria. With the increase in seismic vibration, the first malfunction exhibited by most relays is the uncalled-for electrical discontinuity or continuity at the contacts for a short duration, technically known as "contact chatter." For most applications, if not all, it has been a practice to accept chatter up to a 2-millisecond duration without the need for a system study. Unfortunately, a large number of relay groups reach this chatter limit at a comparatively low vibration level, thereby disproportionately and uneconomically reducing the capacity of the entire equipment system in which the relay is located. In search for the alleviation of this problem, circuits and systems have been studied to determine the true chatter limit that they can withstand without any compromise of the safety functions. It has been observed that in many applications, a chatter duration significantly higher than 2 milliseconds is acceptable. However, this may require a study of the individual systems or circuits.

6.2.3 Testing Methods

In recent years relays have been tested following the guidelines of ANSI/IEEE C37.98-1978, "Standard Seismic Testing of Relays." This standard recommends broad band multifrequency testing with a 250% ZPA level in the frequency range 4 to 16 Hz linearly reduced to the ZPA level at 33 Hz on the high frequency side and to 25% ZPA at 1 Hz on the low frequency side for a damping value of 5%. Both phase coherent and incoherent test inputs have been used in different test programs. However, in older test programs, single frequency testing, i.e., sine dwell and sine beat, has been extensively used.

Both the multifrequency and the single frequency test methods discussed above are individual testing of relays. However, another important source of relay test data is assembly testing. A typical equipment assembly test specimen contains a number of relays. Since relays are a weak link, the vibration level at relay locations are mostly monitored and analyzed to generate response spectra at these locations. This becomes a large source of test data for relays. The significant factor in this form of testing is that ultimately the relays would be mounted in an assembly, and therefore in an assembly test they are subject to the proper vibration level filtered through its structure. In addition, any possible interaction with the system is accounted for in such tests.

In all the above tests, the contact chatter and the electrical continuity are typically monitored for both the energized and the de-energized states. In an assembly testing, the relay operation is further verified in a transition state and/or by letting it perform its intended function.

It has been observed that the performance of a relay and its fragility level determined by separate individual testing may be different from that observed in an assembly test. This complicates the interpretation, evaluation and use of the relay test data and introduces further complexity in establishing fragility levels of relays.

6.3 DATA COLLECTION

Test data have been extracted from ten reports for auxiliary, protective, general purpose and time delay relays manufactured by four companies. The data collection covers both single frequency and multifrequency tests. However, the current data base is not adequate for a generic evaluation of any of the relay groups. Much more test data are believed to be available with various source organizations. Contacts have been established in Phase I with some of these source companies, and the data collection from them are expected to be accomplished in Phase II of the Component Fragility Research Program.

Some of the collected test data are presented in Fig. 6-1 and Fig. 6-2. Figure 6.1 shows horizontal vibration inputs in a fragility test of a hinged armature double pole auxiliary relay. The test was performed with single frequency sine dwell vibration inputs at 1, 5, 10, 15, 20, 25 and 30 Hz. Both the electrical operation and the contact chatter were monitored. The vibration amplitudes were increased at each frequency to reach a specified chatter duration unless the excitation limit of the shaker machine had been reached prior to contact chatter. Curves 1A, 1B and 1C are for the normally closed contacts corresponding to 0.1, 1 and 10 ms chatter limitations, respectively. Curve 1D shows the vibration amplitudes for the normally open contacts corresponding to 0.1, 1 and 10 ms chatter limits. Basically, curve 1D shows the capacity of the exciter and any deviation from this curve in Fig. 6-1 indicates a fragility level of the device at that frequency for the particular chatter acceptance limit. All four curves shown in Fig. 6-1 are for the de-energized condition of the relay. For the energized condition, no chatter up to 0.1 ms was observed while testing up to the shaker limit, represented again by curve 1D.

Figure 6-2 shows a FB TRS plot obtained from testing of some models of time delay relays manufactured by one leading company. The test program was termed as a fragility test program for those relays.

6.4 CONCLUSIONS

The study of the fragility level of relays is a complex phenomenon requiring the collection of a large amount of test data for various types of relays. A small amount of these data has been collected in Phase I and, as such, a generic fragility study of relays is not possible at this stage. Additional source organizatons have been contacted in Phase I to facilitate collection of adequate data in Phase II.

One important factor in establishing the fragility limit of a relay group is the proper definition of its performance requirement, especially, that related to contact chatter. Separate studies are currently in progress by various research groups to identify the relays requiring stringent contact chatter limits, and those for which a high value of contact chatter can be acceptable. A coordinated and consolidated research study to explore and determine meaningful and useful fragility levels in relation to the individual electrical circuits, appears to be very timely.

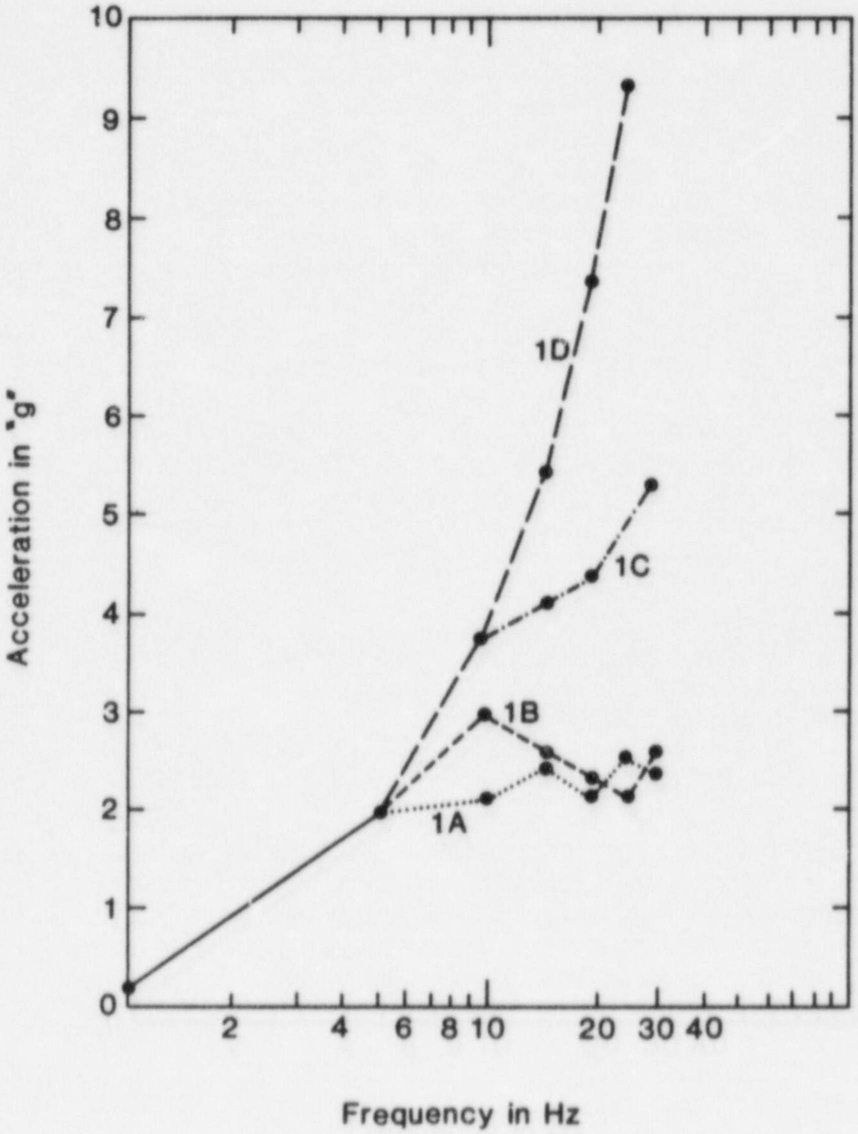

Fig. 6-1 Single Frequency Test Amplitude, Auxiliary Relay

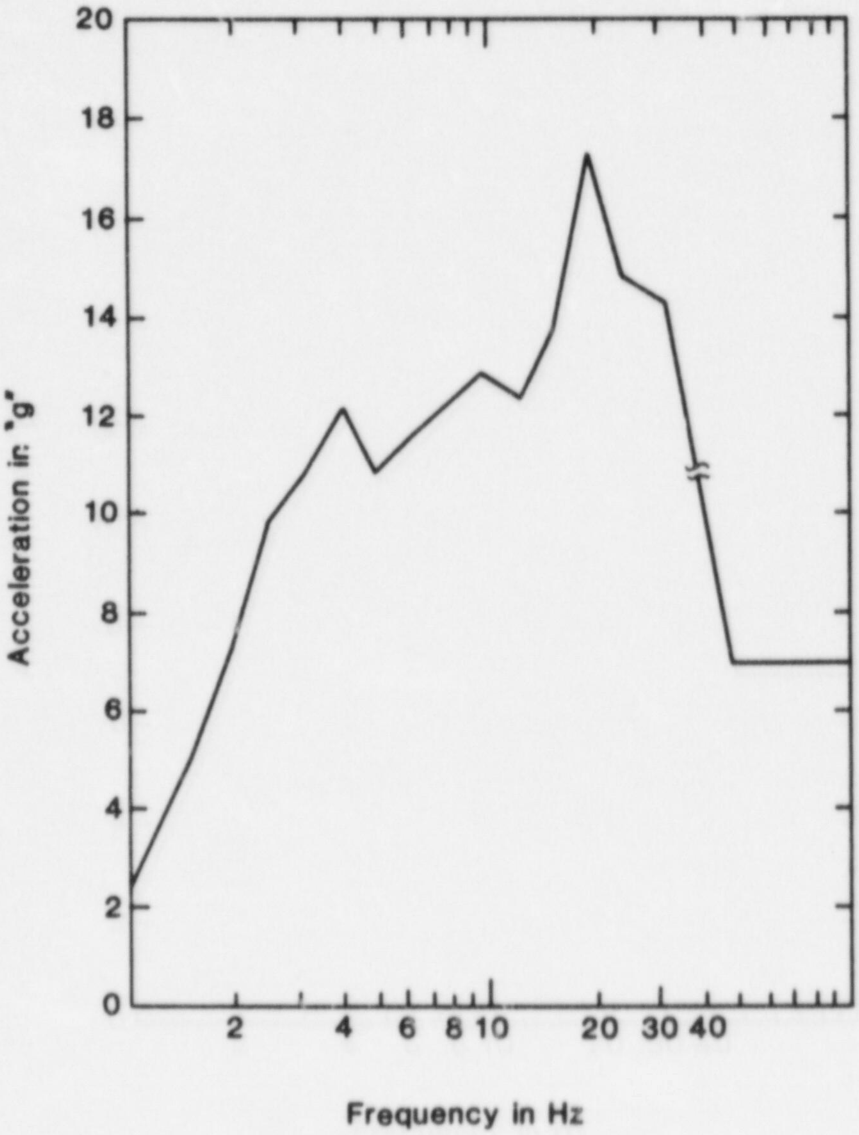

Fig. 6-2 TRS at 2% Damping (Biaxial Test)
Time Delay Relay

CHAPTER 7.

SUMMARY AND RECOMMENDATIONS FOR FUTURE RESEARCH

7.1 INTRODUCTION

The primary objective of the Component Fragility Research Program is to define the seismic fragility level of safety-related equipment such that the information can be included in the overall safety evaluation of a nuclear plant. The first and most important step toward this goal is to obtain and analyze a sufficient amount of test data. The next step is to present the data in a useful way to compare with, and possibly upgrade, the fragility levels being used in various contemporary studies, since all such studies have increasingly indicated the need for correlation with the fragility test data. This chapter provides a summary of what has been achieved by BNL in Phase I towards these steps. Also included in this chapter is an assessment of the remaining tasks in reaching the goal of defining the seismic fragility in quantitative terms. In this context, recommendations are provided for future research.

7.2 SUMMARY AND OBSERVATIONS

Test data have been collected for switchgears, motor control centers, other electrical and control panels, small transformers, relays, switches and contactors, electrical penetration and conductor seal assemblies, other electrical and control devices and valve operators (Ref. Table 2-1). The collected information has been stored in a computerized data bank at BNL in summary forms. For switchgears and motor control centers, the collected data are considered adequate to generically represent a majority of the respective equipment family. As such, a detailed fragility analysis of these two types of equipment has been performed and presented in this report (Ref. Chapters 3 and 4). Some high level test data have also been studied (Ref. Chapter 5) that have expectedly revealed that for some equipment the real fragility level is very high, and for all practical purposes (e.g., PRA's, margin studies) such high level data are sufficient. For other equipment, not enough data have been collected for a generic analysis. More importantly, however, the foundation for the completion of the fragility work has been laid by establishing contacts with various source organizations for collection of additional test data.

The following observations have been made in collecting and analyzing the fragility data:

- A large amount of fragility data exists in the industry, residing especially with the manufacturers who conducted tests in the process of developing and improving their equipment. This information, if it can be made completely available, will greatly enhance the fragility data base and dramatically reduce the need and cost of any future fragility testing. This information is difficult to obtain due to proprietary constraints; however, some organizations are willing to release these data provided they are properly protected and used as part of a generic data base.

- In an equipment assembly (e.g., switchgear, motor control center) some devices are more vulnerable to seismic environment than others. Thus the overall fragility level of the equipment is limited by malfunction of these devices. Some of these devices and their malfunctions are enumerated as follows:

  a) Contactors - chattering
  b) Motor Starter - chattering, dropping out load, changing state, erratic behavior
  c) Time Delay Relays - time setting
  d) Other Relays - chattering, non-operability
  e) Switches - chattering

  The presence of these devices and their effect on the fragility level should be carefully judged.

- Among the sensitive devices, certain types may withstand a substantially higher vibration level than that of another. Therefore, in evaluating the seismic margin or the risk of a specific plant, consideration should be given to the type of device used.

- Equipment design has evolved with time. Due to emphasis on stringent seismic qualification criteria since the mid-seventies, the later products have been observed to withstand higher vibration inputs. Therefore, plants utilizing later products should not be unduly penalized by limiting the capacity level to that determined based on earlier products.

- Self-tapping screws have been observed to strip at a much lower vibration level than what the equipment frame can otherwise withstand. Proper consideration should be given if such screws are present.

- Sometimes in a fragility test the capacity level of a specimen in the horizontal direction is governed by the excitation level in the side-to-side direction. However, in application such equipment might be stiffened by the presence of a larger number of units or by some other means. Therefore, in such cases, the front-to-back vibration level, although higher, might be the governing fragility level in the horizontal direction in the actual installation.

- In multiaxis vibration tests, simultaneous test inputs in different directions should be considered while defining one input as the fragility level in that particular direction. For example, in a typical test program it has been observed that for the same input in one direction, the test specimen passed one test run but failed a subsequent run, due to the fact that the input in the second axis had been doubled. This is especially true for complex equipment for which a strong coupling effect is expected.

- Many electrical devices are frequency-sensitive. In a test program, the malfunction of a device was eliminated by reducing the low frequency content of the vibration input. In another test run, the vibration amplitude was very high at a high frequency band with a high ZPA level; while a low frequency-sensitive device withstood this level without any sign of malfunction. These facts indicate that frequency content of the vibration input must be incorporated in the definition of a fragility level. Obviously, defining the fragility by the ZPA level alone would not address this issue.

Phase I of the Component Fragility Research Program is a step toward the goal of quantifying fragilities of all risk-contributing equipment. As a result of Phase I tasks, it is believed that the direction of future efforts should be to collect and analyze more existing test data. Data for additional models of the equipment families for which generic analyses could not be performed in Phase I, should be collected. Still, there are other equipment families for which no test information has been collected in Phase I; consequently, such information should be sought to enrich the data bank. Based on this discussion and the experience gained in performing the Phase I tasks, recommendations are provided in the following section for future research efforts.

7.3 RECOMMENDATIONS FOR FUTURE RESEARCH

To successfully complete the Component Fragility Research Program, the following recommendations are provided for further research in the respective fields.

7.3.1 Data Collection

The collection of test data should continue to enable generic study of the components that could not be fully analyzed in Phase I due to insufficient data (Ref. Chapter 2). Also, data should be collected for other components not covered in BNL Phase I but listed as priority items in the LLNL studies conducted as part of Phase I. Additional data should also be sought for switchgears and motor control centers from at least one other manufacturer.

Since the BNL Phase I Study indicated that in a seismic environment, some devices in an equipment are more vulnerable than others, special emphasis should be given to collecting test data for these devices. Some of these devices are as follows:

- Contactors
- Motor Starters
- Time Delay Relays
- Other Relays
- Switches

The collected data should be incorporated in the existing computerized data bank. Since the success of the Component Fragility Program depends largely on the quantity and the diversity of the test data studied in establishing the fragility data levels, it is imperative that contacts be maintained with outside computerized data sources (e.g., EPRI) for transfer of fragility data.

7.3.2 Data Analysis

The analysis of all collected data should continue and be completed following the guidelines discussed and illustrated in this report. The analysis must identify the failure modes and the modifications, if any, performed on the test specimen corresponding to different fragility levels. Such information is essential for application of the fragility data since some malfunctions may not pose a problem for a specific system, and some modifications, if not implemented in the field, may substantially decrease the fragility level of the equipment.

7.3.3 Special Studies

In the process of data collection and analysis performed in Phase I, it has been observed that additional studies are needed in a few specific areas in order to better evaluate and utilize the fragility data. Limitations of the state-of-the-art knowledge and recommendations for remedial studies in these areas are discussed in the following subsections.

7.3.3.1 Vulnerable Devices

The BNL Phase I study has indicated that the fragility phenomenon is mostly initiated by the presence of any of the following devices in an electrical equipment (Ref. Sections 7.2 and 7.3):

- Contactors
- Motor Starters
- Time Delay Relays
- Other Relays
- Switches

These devices are widely used in numerous types of equipment. Therefore, a separate study of these devices is recommended.

A common failure mode for most of the above devices is "chattering", i.e., electrical discontinuity for a very short duration (on the order of milliseconds). However, an acceptable duration of chattering of a particular device depends on the system in which it is located. Therefore, even though the device exhibits a chattering of a certain duration at a certain vibration level, that level is not necessarily the fragility of the equipment for all applications. Therefore, the chattering phenomenon and its effect on these devices should be studied further to define acceptance criteria. Some studies on this subject have been and are being performed by the industry for licensing purposes. Future research efforts should be carefully coordinated with these activities to maximize the benefits gained from these studies and avoid any duplication of effort.

One special area of interest is the study of relays. Due to their varied nature, in both design and performance, a future comprehensive study is recommended for this particular class of devices (Ref. Chapter 6).

7.3.3.2 TRS Damping Value

It has been observed that the test response spectra (TRS) available in the existing test results were not necessarily analyzed at a particular damping value. Therefore, for correlation of the data and for development of a generic fragility TRS plot using the existing TRS results, a technique must be utilized to transform the TRS at one damping value to that at another damping value. An approximate transformation technique has been suggested and used in this report (Ref. Chapter 2). However, future research should determine whether further accuracy is needed and, if so, a better approach should be sought.

7.3.3.3 Equipment Mounting

The usual form of mounting used for testing an equipment is a specified detail of weld, bolts or on occasion clamps. However, experience indicates that in most occasions, due to various practical reasons, the field installation differs from the test mounting. Therefore, the validity of the fragility level established based upon test results from a specific mounting condition becomes questionable when used for the equipment installed in service conditions. The specific concerns to be investigated are as follows:

- Frequency shift
- Amplification of response
- Effect on devices through filtration, etc.
- Mounting as a fragility mode, if a weaker mounting is used in the field

Fortunately, test data are available for various mounting conditions. A study of the pertinent transmissibility and TRS plots, as well as some structural analyses would probably be sufficient to address these issues.

7.3.3.4 Application of Fragility Data in PRA and Margin Studies

The major and immediate application of the fragility levels determined by the Component Fragility Research Program will be in the overall safety analyses of the plants. The following two types of analysis are currently being performed or discussed:

1. Probabilistic Risk Assessment (PRA)
2. Seismic Margin Studies

Both of these analysis techniques in their current forms require the input of the equipment fragility level in terms of ZPA or PGA. ZPA, or the zero period acceleration, is the highest amplitude of a given time history and PGA is the peak acceleration of the ground motion[1]. Moreover, the ZPA or the PGA used in PRA and Margin Studies is a statistical number with a standard deviation. On the other hand, the fragility level data presented in this report, based on results, are in the form of test response spectra (TRS) including the ZPA of the test vibration time history. The reasons for selecting TRS as the indicator of a fragility level can be summarized as follows:

1. The test results are available in the form of TRS, and rarely in any other forms.
2. TRS, as opposed to ZPA alone, provide a better measure of the severity of the test vibration since it includes the effects of frequency content.
3. A TRS plot is a basic data source and the information needed for a specific application can be extracted from it. Thus, the fragility level defined by TRS is expected to serve the needs of various users.

Nevertheless, there is a gap between the fragility format being used for the PRA and Margin Studies and that presented in this report. Therefore, it is recommended that further study be pursued to determine how and in what format the fragility level data presented in this report can be best utilized in the PRA and Margin Studies. If needed, a conversion methodology should be developed. In this regard, a discussion is provided as follows, which identifies several aspects for consideration in future research.

First, current PRA and Margin Studies derive their basic inputs regarding component fragility from a table of fragility "g"-values based primarily on expert opinion and some test data. Many of these tests were "shock tests"; therefore, a g-value was used as the indicator of fragility level vibration input. The PRA and the Margin Studies were accordingly developed to accept one number, i.e., one g-value, as the fragility input for the overall safety analysis. The effect of frequency content in the test vibration was apparently not included in these studies. However, it has been observed that the operability of electrical devices is very sensitive to the frequency content of the vibration input. By maintaining the same ZPA level and by only changing the response at some critical frequency levels, a component has been observed to pass or fail a test. On the other hand, by maintaining the same response levels at the critical frequency range and by largely increasing the ZPA level a component has been observed to withstand the level. Consequently, for the same equipment there could exist a number of ZPA levels corresponding to one specific failure mode. The use of one of these ZPA numbers, therefore, is not sufficient to describe the fragility phenomenon. In conclusion, a future study should explore whether the fragility input in the form of TRS data can be accepted and incorporated in the PRA and Margin Studies thus reflecting a more developed picture of the fragility phenomenon by use of evolved seismic data.

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[1]Therefore, ZPA of the ground motion in the PGA.

Second, if incorporation of the entire TRS in the PRA and Margin Studies, as discussed above, is found to be prohibitive for practical reasons, the next attempt should be to explore the possibility of inclusion of several key parameters of the TRS rather than only one parameter (i.e., ZPA or PGA) in the safety analysis. As a minimum the following parameters are recommended to be considered in such simplification of the TRS:

1. Peak response
2. Frequency at peak response
3. ZPA
4. Fundamental frequency of the equipment
5. Response at the fundamental frequency
6. Consideration of possible presence of frequency-sensitive devices

Third, if neither of the above two options proves to be feasible, and future studies indicate that the PRA and Margin Studies cannot be modifed to accept more than one fragility indicator (i.e., a g-value), the following course of study is recommended. In order to retain the information regarding frequency content in the fragility level TRS, a standard time history should be used as the reference time history, and a comparative number should be assigned to the testing time history (analyzed as the TRS) with respect to the reference time history. This number should basically indicate the severity of the test vibration compared to the reference time history. The ZPA, the peak response of the TRS, an equivalent ZPA, or any other comparative parameter can be selected for this purpose. An analysis technique or the judgment of an experienced engineer will probably be the tool to arrive at this number. Two illustrations are pictorically provided in Fig. 7-1 to demonstrate the process of arriving at one g-value, e.g., an equivalent ZPA, using TRS data. Curves 1A and 1C are horizontal TRS plots of two different electrical equipment assemblies. Fundamental frequencies are in the range of 5 to 12 Hz in different directions for both equipment. Assume for the sake of discussion that the standard response spectrum recommended by ANSI/IEEE C37.98-1978, "Standard Seismic Testing of Relays" are the aforementioned "reference" response spectrum. This standard recommends a response spectrum with an amplification of 250% ZPA for the frequency band of 4 to 16 Hz, decreasing linearly to 25% ZPA at 1Hz, and to ZPA at 33 Hz for a damping value of 5%. By use of these "reference" spectrum data, curves 1B and 1D are drawn for reasonable comparison. Thus, the fragility levels defined by TRS plots 1A and 1C can now be represented by one indicator g-value for each curve, i.e., the equivalent ZPA values of 1.7g and 0.9g, respectively. It is observed that for curve 1A, the equivalent ZPA value is close to the TRS ZPA value; whereas, for curve 1C the equivalent ZPA is 25% lower.

Fourth, the fragility level by TRS describes the vibration level at the location of the equipment. In other words, if the equipment is installed on a floor in a plant, the floor response spectra should be compared with the fragility TRS to evaluate the component's ability to withstand a specific earthquake. However, if the PRA and Margin Studies can only accept the vibration parameter at the ground level and not the amplified response at the floor level of a particular plant, a further evaluation should be made to transform the fragility level of the equipment from its location to the ground level.

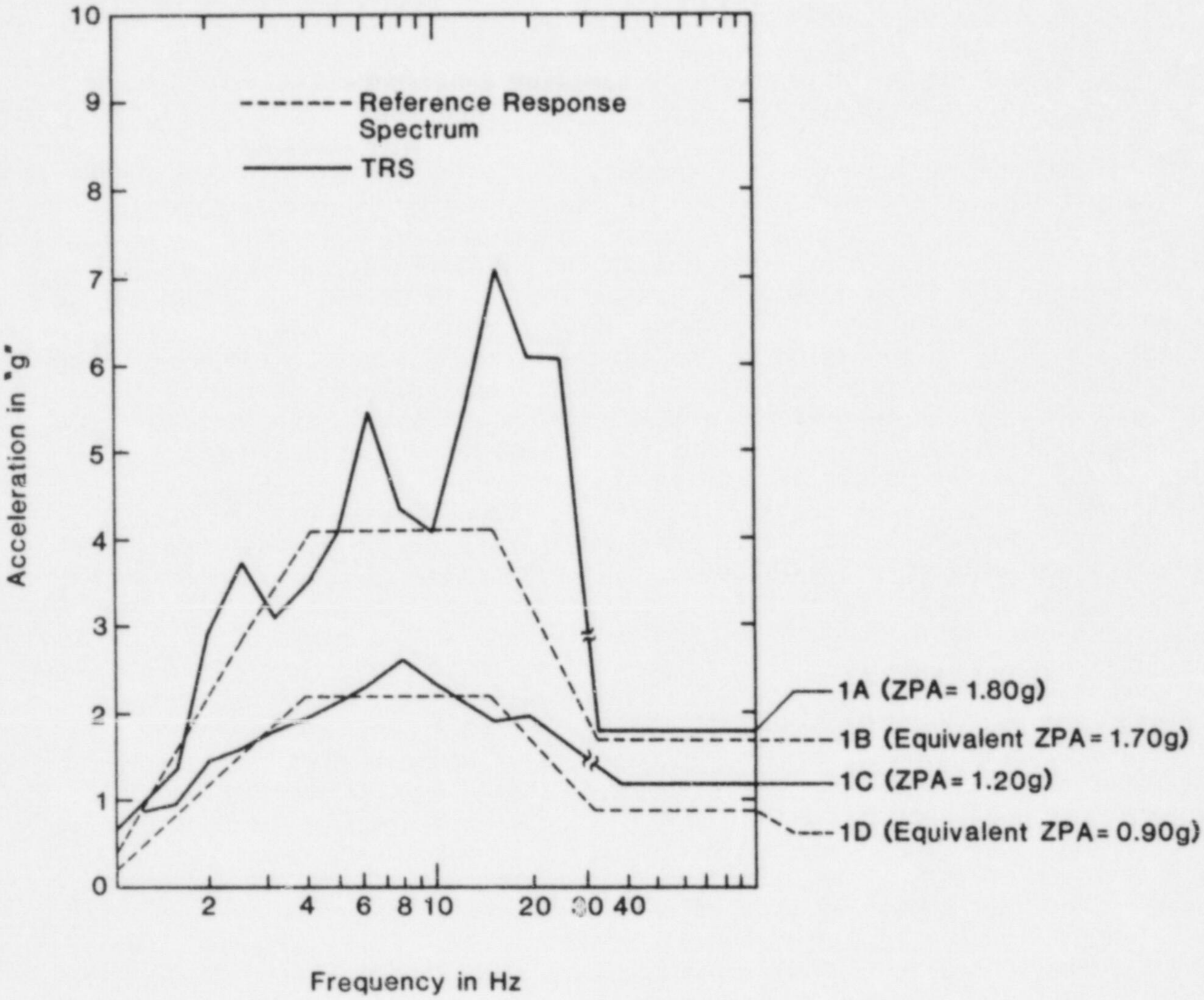

Fig. 7-1 Representation of TRS by "Reference Response Spectra" and Equivalent ZPA (All Curves at 5% Damping)

As further clarification of the above discussions, the PRA and the Margin Studies performed for the Zion Nuclear Plant are considered as an example, and the results of the studies are presented in Table 7-1. Low and medium voltage switchgears and motor control centers are used for comparison of the results obtained from various studies. In Table 7-1, column 2 shows the median values (A_m) of the fragility level corresponding to recoverable failure modes used in a PRA of the plant and expressed in terms of "the effective-peak ground acceleration" (i.e., peak ground acceleration/1.23). Column 3 indicates the "high-confidence-of-a-low-probability-of-failure" (HCLPF) levels corresponding to recoverable failure modes suggested by the Seismic Margin Group and expressed in terms of the peak ground acceleration. Information in both these columns are extracted from Reference 3. Column 3 shows the component fragilities developed in the Seismic Safety Margin Research Program (SSMRP). These component fragilities are expressed as "median values for local accelerations" and are extracted from Reference 4. The corresponding fragility levels developed by the BNL Component Fragility Program are discussed in Chapters 3 and 4. Reference of the applicable lower-bound TRS with the ZPA values is provided in Column 4 of Table 7-1. As mentioned above, the formats of the fragility levels in Table 7-1 do not match and, consequently, the results cannot be directly compared. However, a qualitative assessment can be made. For example, assuming an amplification factor of 3 for the PGA to reach the MCC location in the Zion Plant[1], the equivalent PGA value for the BNL fragility level is 0.37 g (i.e., 1.1g/3) compared to the HCLPF value of 0.23. With the same amplification value, the conservativeness of the HCLPF values for switchgears is even greater.

In conclusion, it appears that the BNL fragility data correlate better with the HCLPF levels, and that these levels can be further improved and enhanced by use of the BNL fragility analyses, provided a proper application technique is developed as recommended above.

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[1]Per Zion FSAR, the maximum floor ZPA is 0.45g compared to the PGA of 0.17g.

TABLE 7-1

COMPARISON OF BNL FRAGILITY EVALUATION WITH PRA AND SEISMIC MARGIN STUDIES

	Fragility Level for Zion			Generic
	A_m* (effective pga)	HCLPF* (pga)	Median** (local accn.)	Fragility level per BNL Study ZPA,TRS
(1)	(2)	(3)	(4)	(5)
Low Voltage Switchgear	0.89g	0.23g	2.33g	1.50g Fig. 3-15
Medium Voltage Switchgear	0.89g	0.23g	2.33g	1.80g Fig. 3-8
Motor Control Center	0.89g	0.23g	7.63g	1.10g Sect. 4.3.2.1

* Reference 3
** Reference 4

CHAPTER 8.

REFERENCES

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2. Kana, D.D. and Pomerening, D.J., "A Research Program for Seismic Qualification of Nuclear Plant Electrical and Mechanical Equipment", prepared for USNRC, NUREG/CR-3892, August 1984.

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

4. Cover, L.E., et al., "Handbook of Nuclear Power Plant Seismic Fragilities Seismic Safety Margin Research Program", prepared for the USNRC, NUREG/CR-3558, June 1985.

APPENDIX A

Selected TRS Curves at 5% Damping

APPENDIX A

A.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 [1]. Six fragility curves summarizing the performance of switchgears and motor control centers 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, using the same conversion factors as used by EPRI/ANCO. Specifically, for conversion from 2% to 5%, the responses are divided by a factor of $\sqrt{5/2}$, e.g., 1.58, with no high-frequency response values lower than 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 factor (e.g., 1.58) is 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 (Ref., Section 2.3.2.1). A further study of damping value conversion factors is recommended (Ref., Section 7.3.3.2).

For convenient reference, a suffix is used to the figure numbers at 2% damping to present the figure at 5% damping. The curve numbers in any figure are identical. For description and use of these curves, one should refer to the appropriate text provided in Chapters 3 and 4 of this report.

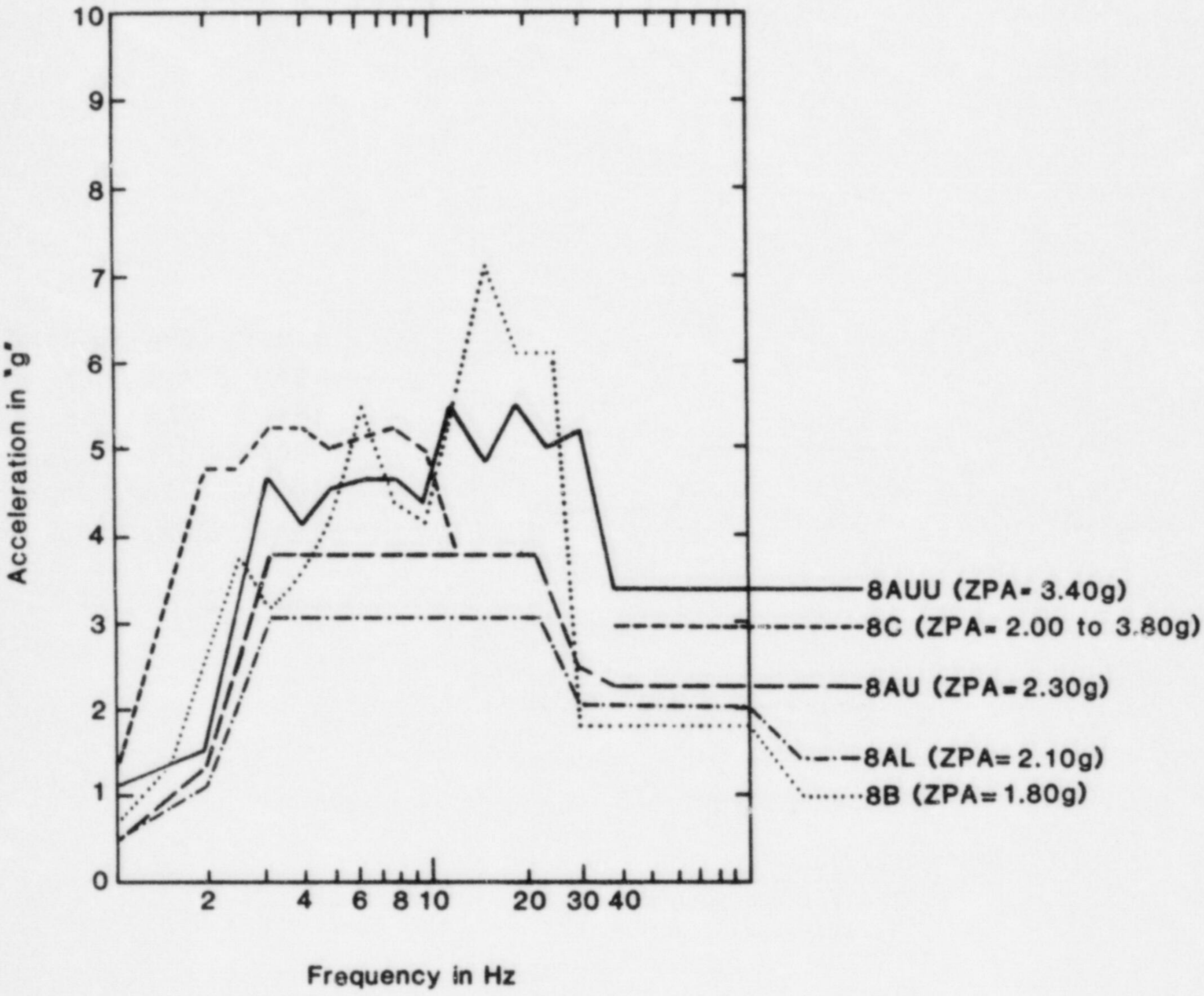

Fig. 3-8a Horizontal TRS at 5% Damping, Medium Voltage Switchgear Various Manufacturers

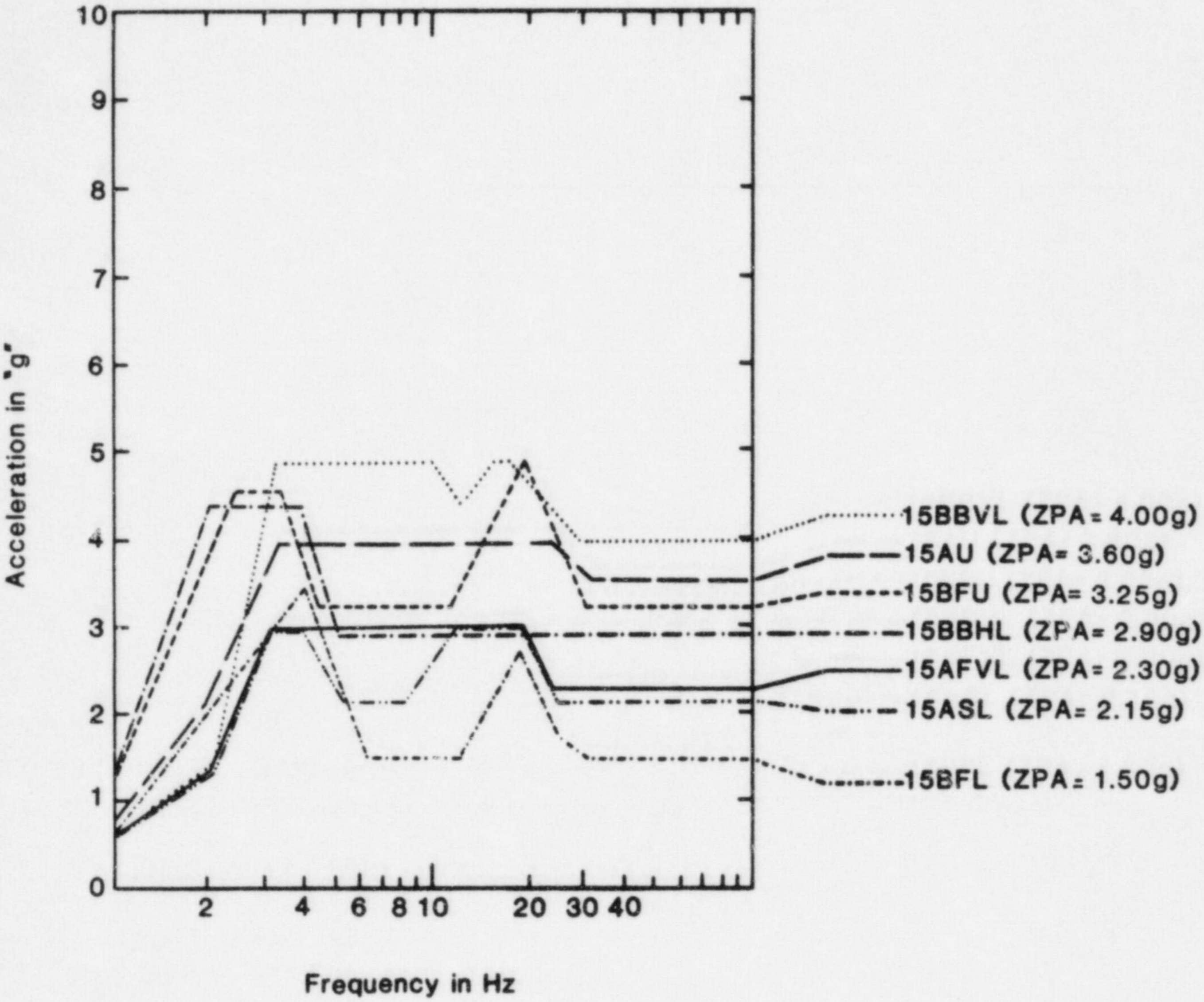

Fig. 3-15a TRS at 5% Damping,
Low Voltage Switchgear
Various Manufacturers

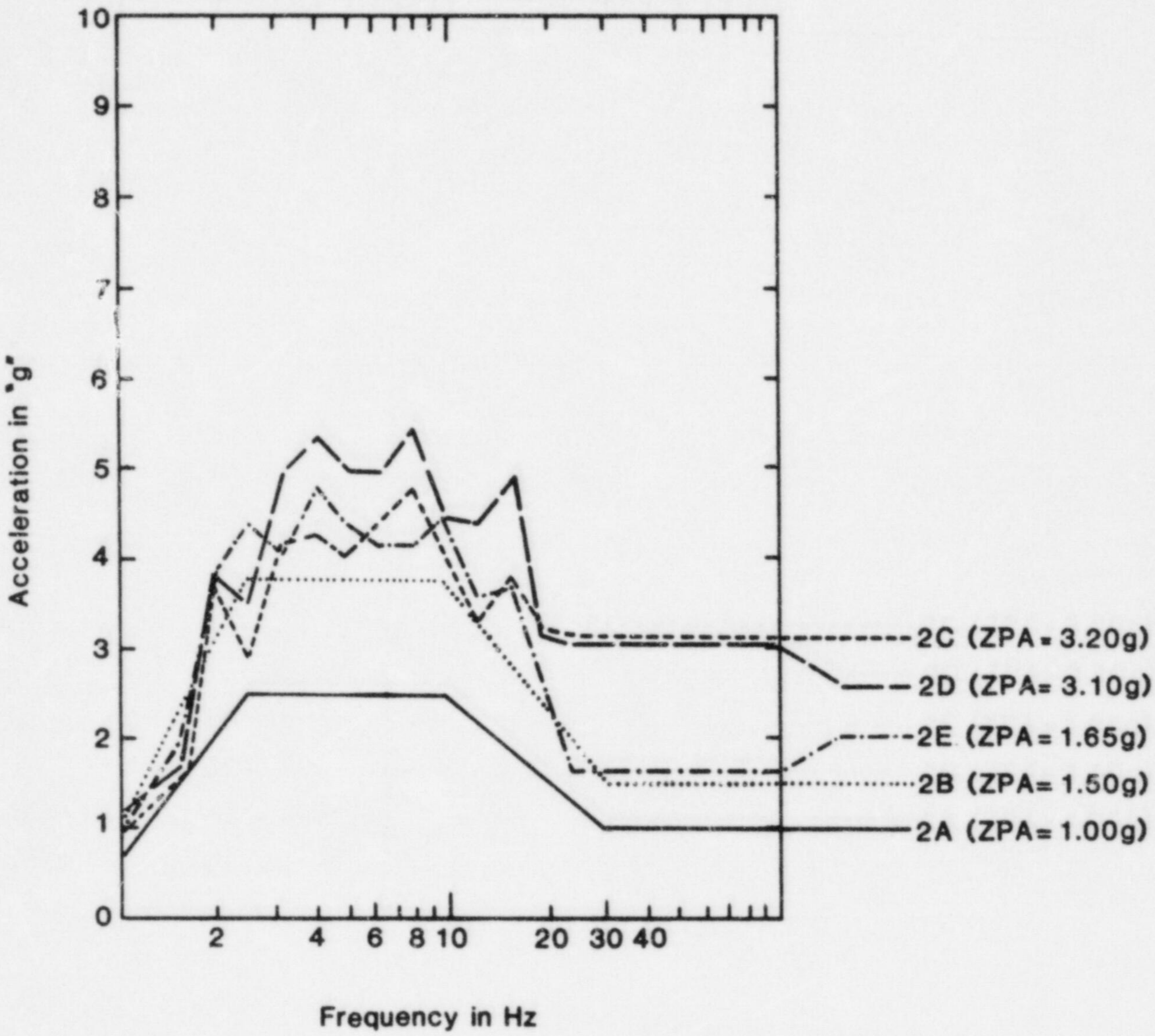

Fig. 4-2a TRS at 5% Damping,
Motor Control Center
Manufacturer A

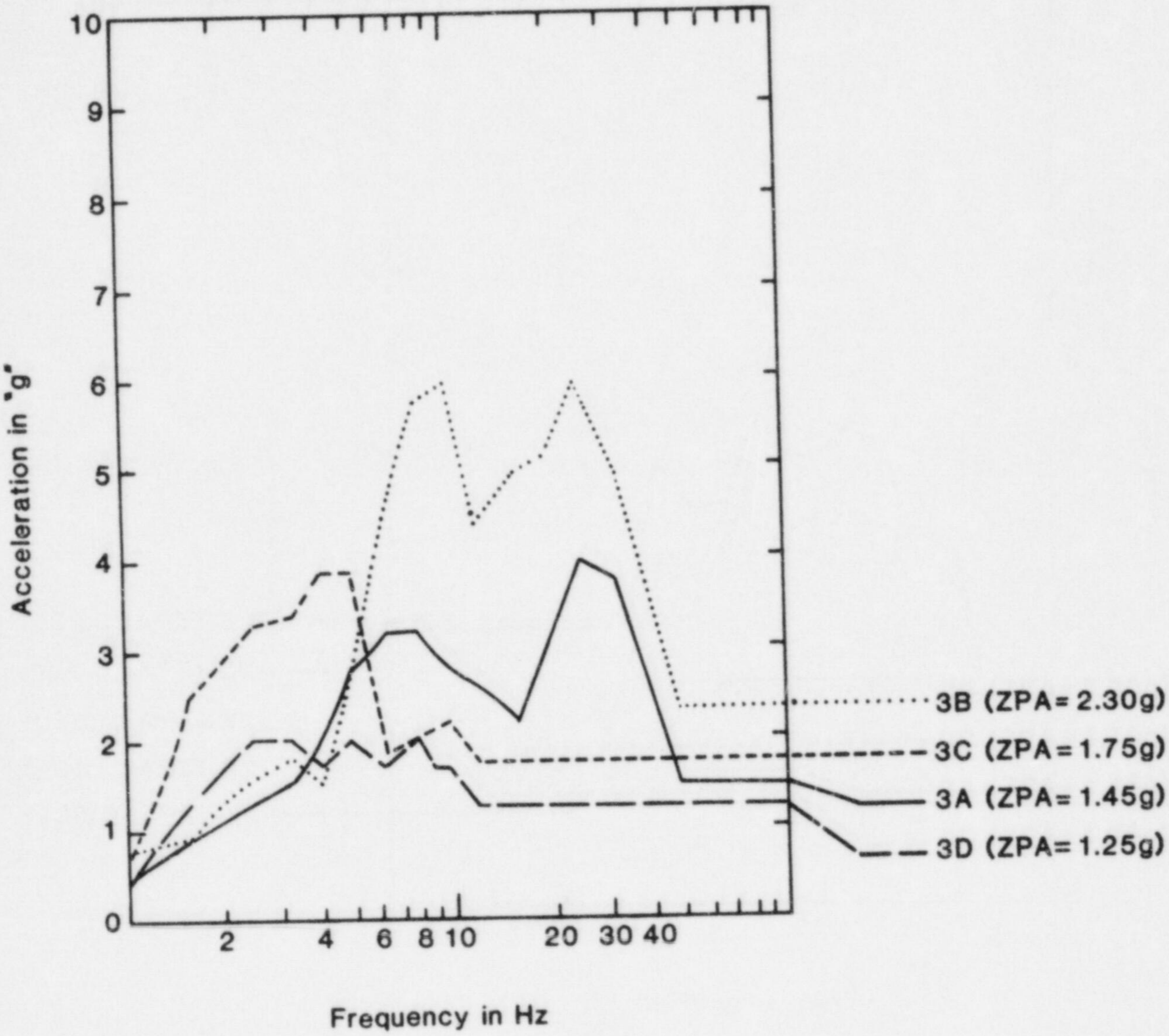

Fig. 4-3a Horizontal TRS at 5% Damping, Motor Control Center Manufacturer B

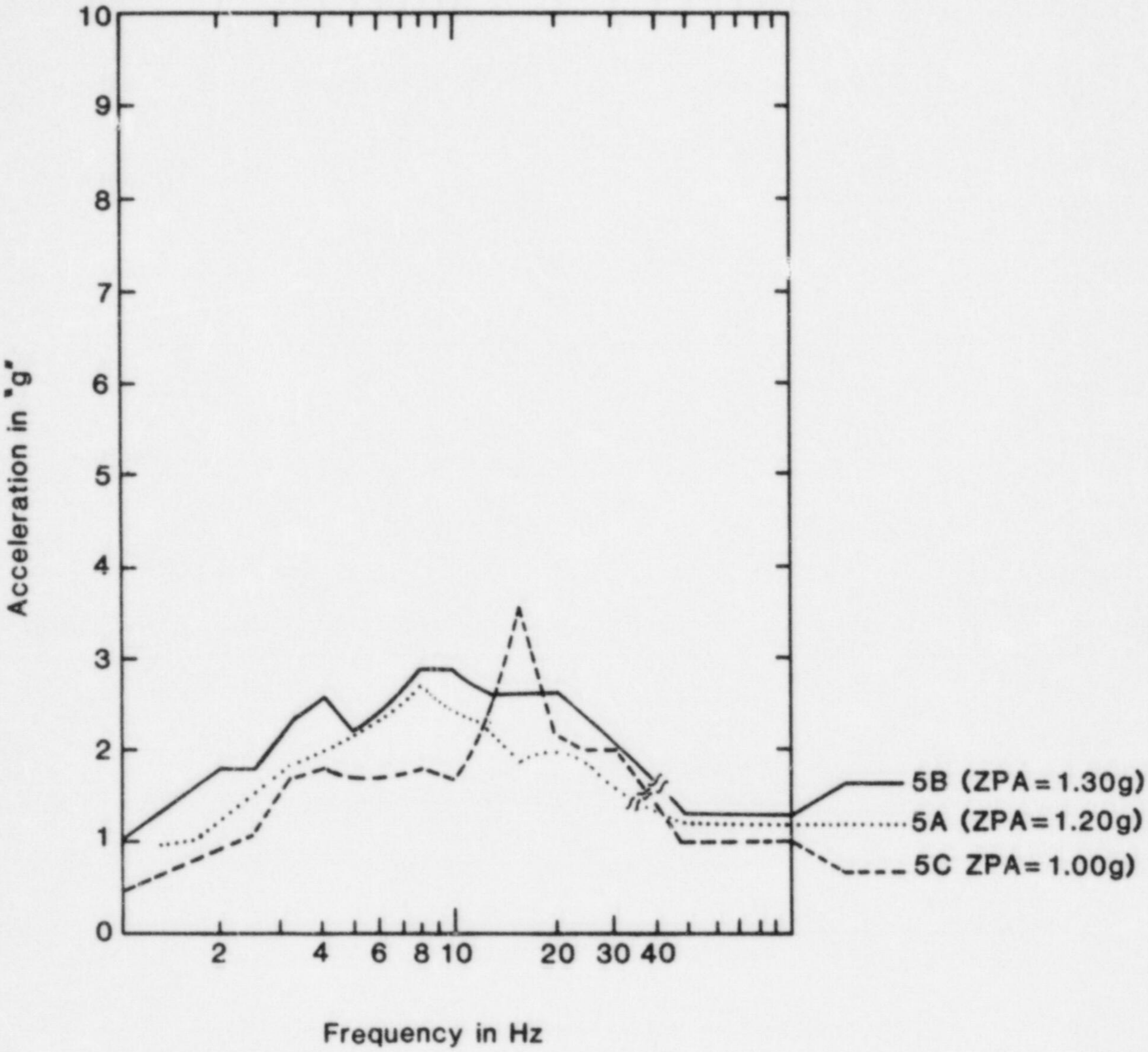

Fig. 4-5a TRS at 5% Damping,
Motor Control Center
Manufacturer C

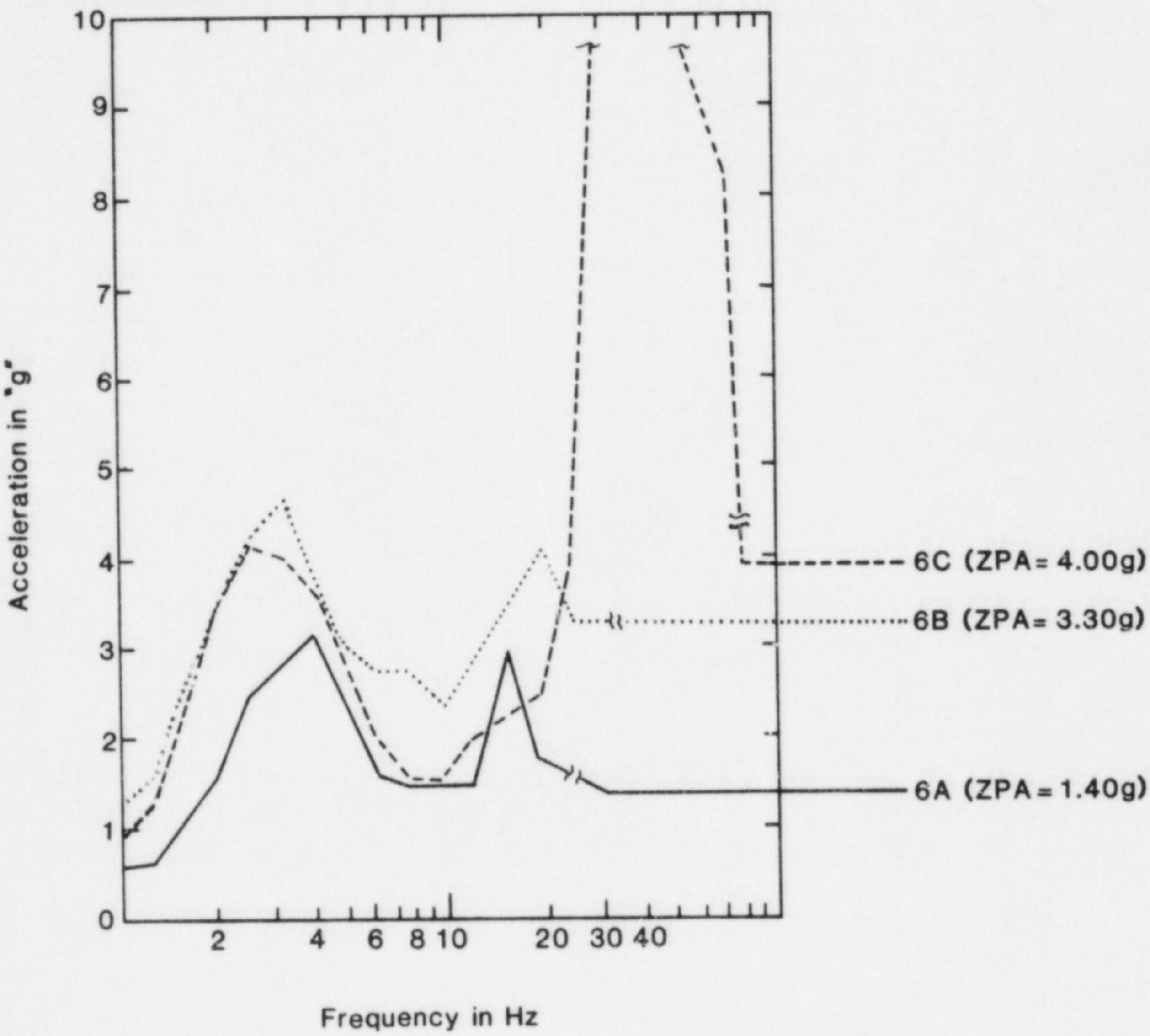

Fig. 4-6a Horizontal TRS at 5% Damping, Motor Control Center Manufacturer D