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Seismic Fragility of Nuclear Power Plant Components (Phase II)

Switchgear, I&C Panels (NSSS) and Relays

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U.S. Nuclear Regulatory Commission

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ABSTRACT

The Component Fragility Program was initiated in FY1985. In Phase I of this program, a methodology was developed to establish the seismic fragility level of equipment by use of existing test data, and the results were published in 1986. The methodology was further refined in Phase II of the program and was applied to four equipment categories - motor control center, switchboard, panelboard and power supply. The results were published in 1987. The same evaluation methodology is being applied to additional equipment. Information developed under this program is expected to be used for implementation of the external events portion of the NRC's Individual Plant Examination (IPE) Program for all commercial nuclear plants.

This report contains the fragility results and discussions on three equipment classes - switchgear, I&C panels and relays. Both low and medium voltage switchgear assemblies have been considered and a separate fragility estimate for each type is provided in this report. Test data on cabinets from the nuclear instrumentation/neutron monitoring system, plant/process protection system, solid state protective system and engineered safeguards test system comprise the BNL data base for I&C panels (NSSS). Fragility levels have been determined for various failure modes of switchgear and I&C panels, and the deterministic results are presented in terms of test response spectra. In addition, the test data have been evaluated for estimating the respective probabilistic fragility levels. The zero period acceleration and the spectral acceleration averaged over the 4-16Hz frequency range have been used to represent the test response spectra. These two acceleration values have been separately used to estimate the fragility results for each important failure mode. The probabilistic fragility levels are expressed in terms of a median value, an uncertainty coefficient, a randomness coefficient and an HCLPF value corresponding to a high (95%) confidence of a low (5%) probability of failure. The fragility level for the switchgear breaker malfunction is relatively high. However, the relays controlling the breaker operation should be carefully evaluated to preclude a breaker trip due to relay chatter or change of state. Electrical discontinuity occurs in the I&C panels at about the same level as breaker trip in the switchgear. The structural fragility levels are significantly higher for both switchgear and I&C panels compared to the electrical malfunction levels. A detailed generic discussion is provided on the factors controlling the seismic characteristics of relays. Due to a wide variation of relay design and the fragility level, a generic fragility level cannot be established for relays. The relay fragility levels should be identified with model numbers. This issue is being further addressed through a relay test program being conducted at BNL.

EXECUTIVE SUMMARY

S.1 INTRODUCTION

This report presents the results of a study of the seismic fragility of nuclear power plant equipment by use of existing test data as part of the BNL Component Fragility Research Program sponsored by the NRC. The primary objective of the program is to define and quantify the generic seismic fragility of safety-related equipment and to present the results in a format such that they can be readily used in margin studies and probabilistic risk assessments. Seismic margin studies and probabilistic risk assessment are expected to be required for all commercial nuclear plants by the external events portion of the NRC's Individual Plant Examination Program.

The fragility program was initiated in FY1985. In Phase I, a methodology was developed to determine the fragility levels and the results were published in NUREG/CR-4659, Volume 1 [1]. The methodology was further refined in Phase II of the program and was applied to four equipment classes - motor control center, switchboard, panelboard and power supply. The results were published in NUREG/CR-4659, Volume 2 [2]. In addition, dynamic amplification of electrical cabinets were studied based on existing test data and the results are contained in NUREG/CR-5203 [3].

S.2 COMPONENT FRAGILITY PROGRAM - CONTINUATION OF PHASE II

In continuation of Phase II, the following additional classes of equipment have been studied and the results are presented in this report:

1. Switchgear
 - a) Low Voltage
 - b) Medium Voltage
2. Instrumentation and Control Panels (NSSF)
 - a) Nuclear Instrumentation/Nuclear Monitoring System Cabinets
 - b) Plant/Process Protection System Cabinets
 - c) Solid State Protection System Cabinets
 - d) Engineered Safeguards Test Cabinets
3. Relays

The fragility analysis methodology presented in the earlier reports [1,2] was also employed in this report. The seismic fragility level for each major failure mode of an equipment is quantified both deterministically and probabilistically. Test response spectra (TRS) are used as a measure of the deterministic fragility level and two indicators of the TRS are used as parameters of fragility functions to compute the fragility level in probabilistic terms. Zero period and average spectral accelerations are the two TRS indicators. A statistical analysis is performed with each of these two indicators as inputs to obtain a median value, an uncertainty coefficient (β_u) to include modeling uncertainties and a randomness coefficient (β_r) to include performance randomness. These three parameters are used to define the probabilistic

fragility level expressed as HCLPF¹. Judgments are used to estimate the above fragility parameters wherever the data base is considered inadequate for performing a statistical analysis. However, the end results are always checked for reasonableness.

Both the deterministic and the probabilistic fragility results for the low voltage switchgear, medium voltage switchgear and I&C Panels are separately presented in this report. A description of the data base test specimens, a summary of the test results and a discussion of the failure modes are also included for each equipment. A summary of the fragility results is provided in Chapter 5, Table 5-1. The main component of a switchgear assembly, the circuit breaker, can withstand a relatively high level of seismic input. However, the relays controlling the breaker operation malfunction at substantially lower levels. Therefore, a relay screening can enhance the overall electrical fragility level. Electrical discontinuity in the I&C panels (NSSS) occurs at about the same level as the breaker trip in the switchgear. Although minor structural damage such as cracking is observed at the electrical malfunction level, major structural damage such as breaking of bolts and framing members does not occur until a relatively higher (e.g. 50% greater) input motion is applied to the equipment.

A detailed discussion on the characteristics of relays is provided in this report highlighting their electrical functions, design variations, testing techniques, failure modes, controlling factors and acceptance criteria, all in regard to the seismic capacity. The variation of relay designs and their fragility levels is enormous and, consequently, a generic fragility level of relays as a class cannot be established. Each relay model has its own fragility level which again can vary depending on the vintage of the relay and its use in a particular electrical circuit. BNL is addressing these issues through a relay test program as discussed in the following section.

S.3 CURRENT PROGRAM

BNL is conducting a test program primarily to characterize the effects of various parameters on the seismic capacity of relays. The first phase of testing has been completed. The test results are being evaluated and will be published in FY1990. The next phase of testing will concentrate on certain focused issues identified in the first phase and will be conducted also in 1990. BNL will also continue evaluating the seismic fragility of selected additional equipment classes.

S.4 RECOMMENDATIONS FOR FUTURE RESEARCH

Based on the observations made in the course of the fragility study, the following recommendations are provided.

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

S.4.1 Earthquake Experience vs Test Data

The latest version of the IEEE 344 [5] accepted the use of earthquake experience data as a means of seismic qualification. Experience data are being used by the industry and the NRC, directly or indirectly, to resolve important issues such as exceedance of OBE, high frequency content of earthquakes and severe accident issues. It is expected that such data will be used much more in making decisions for numerous applications - from equipment qualification to equipment modification, from eastern seismicity issues to individual plant examinations.

Earthquake experience data are a wealth of information; so are the existing test data. The obvious questions are: Do these two data sources support each other? Are they complementary? Are there any contradictions? These questions should be answered in order to reliably tap the great potential of the experience data.

Therefore, BNL considers that it is timely and expedient to correlate experience data with test data and recommends that research be initiated to study the correlation including the strengths and weaknesses of both. Limited testing may be required to address the issue.

S.4.2 Vintage

A detailed discussion on the possible effect of vintage of equipment on its seismic fragility was included in NUREG/CR-4659, Vol. 2 [2] and a recommendation was made for a study on vintage. Since then additional observations were made in the course of the current fragility study and some of them have been discussed in this report. These observations indicate that improvement of equipment design for upgrading its seismic capacity has occurred. Therefore, it appears that vintage has an effect on the seismic capacity of equipment and research on this subject is again recommended.

S.5 CONCLUSIONS

The Component Fragility Program at BNL has generated "generic" seismic fragility levels of equipment classes that can be directly used for screening purposes in margin studies and probabilistic risk assessments. It has also characterized the performance of equipment in a simulated earthquake environment which can be useful in identifying the weak links of plant specific equipment and for subsequently modifying equipment to enhance the seismic capability. Combined together, the results are expected to be useful in individual plant examinations as well.

TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT.....	iii
EXECUTIVE SUMMARY.....	v
LIST OF TABLES.....	xii
LIST OF FIGURES.....	xiii
ACKNOWLEDGEMENTS.....	xv
1. INTRODUCTION	
1.1 BACKGROUND.....	1-1
1.2 CURRENT RESEARCH SCOPE.....	1-1
1.3 FRAGILITY EVALUATION METHODOLOGY.....	1-2
1.4 SUMMARY.....	1-3
2. SWITCHGEAR	
2.1 INTRODUCTION.....	2-1
2.2 EQUIPMENT DESCRIPTION.....	2-1
2.3 DATA BASE.....	2-2
2.4 TEST RESULTS.....	2-2
2.5 DATA EVALUATION.....	2-7
2.5.1 Dynamic Amplification.....	2-7
2.5.2 Failure Modes.....	2-7
2.5.2.1 Relay Chatter.....	2-10
2.5.2.2 Relay Change of State.....	2-11
2.5.2.3 Breaker Tripping.....	2-11
2.5.3 Fragility Estimates.....	2-12
2.6 HISTORY OF IMPROVEMENT.....	2-13
2.7 LIMITATIONS.....	2-18
2.8 CONCLUSIONS.....	2-19
3. INSTRUMENTATION AND CONTROL PANELS (NSSS)	
3.1 INTRODUCTION.....	3-1
3.2 DATA BASE.....	3-1
3.3 TEST RESULTS.....	3-1
3.4 DATA ANALYSIS.....	3-4
3.5 LIMITATIONS.....	3-4
3.6 CONCLUSIONS.....	3-4

TABLE OF CONTENTS (CONT'D)

	<u>Page</u>
4. RELAYS	
4.1 INTRODUCTION.....	4-1
4.2 EQUIPMENT DESCRIPTION.....	4-1
4.3 CLASSIFICATION.....	4-1
4.3.1 Electrical Function.....	4-2
4.3.2 Design.....	4-2
4.3.2.1 Hinged Armature.....	4-3
4.3.2.2 Rotary Induction Disk.....	4-5
4.3.2.3 Plunger.....	4-5
4.3.2.4 Induction Cup.....	4-5
4.4 DATA BASE TEST PROGRAM.....	4-5
4.4.1 Single Axis, Single Frequency Tests.....	4-5
4.4.2 Multiaxis, Multifrequency Tests.....	4-10
4.4.2.1 Required Response Spectrum Tests.....	4-10
4.4.2.2 IEEE Std Tests.....	4-10
4.4.2.3 Panel Tests.....	4-12
4.5 FAILURE MODES.....	4-12
4.6 ACCEPTANCE CRITERIA.....	4-13
4.7 SENSITIVITY PARAMETERS.....	4-15
4.7.1 Frequency of Vibration.....	4-15
4.7.2 Chatter Duration.....	4-15
4.7.3 Direction of Vibration Input.....	4-15
4.7.4 Electrical Mode.....	4-19
4.7.5 Contact State.....	4-19
4.7.6 Adjustment.....	4-19
4.8 MODEL NUMBER AND VINTAGE.....	4-19
4.9 USE OF TEST DATA.....	4-21
4.10 CURRENT TEST PROGRAM AT BNL.....	4-22
4.11 CONCLUSIONS.....	4-23

TABLE OF CONTENTS (CONT'D)

	<u>Page</u>
5. SUMMARY AND CONCLUSIONS	
5.1 INTRODUCTION.....	5-1
5.2 SUMMARY.....	5-1
5.2.1 Switchgear.....	5-1
5.2.2 I&C Panels (NSSS).....	5-1
5.2.3 Relays.....	5-3
5.3 CURRENT PROGRAM.....	5-3
5.4 RECOMMENDATIONS FOR FUTURE RESEARCH.....	5-4
5.4.1 Earthquake Experience vs Test Data.....	5-4
5.4.2 Vintage.....	5-5
5.5 CONCLUSIONS.....	5-5
6.0 REFERENCES.....	6-1

LIST OF TABLES

<u>Table</u>		<u>Page</u>
2-1	Test Specimens - Low Voltage Switchgear.....	2-3
2-2	Test Specimens - Medium Voltage Switchgear.....	2-4
2-3	Summary of Test Results - Low Voltage Switchgear.....	2-5
2-4	Summary of Test Results - Medium Voltage Switchgear..	2-6
2-5	Fragility Results - Low Voltage Switchgear.....	2-14
2-6	Medium Voltage Switchgear Input Data for Statistical Analysis.....	2-15
2-7	Fragility Results - Medium Voltage Switchgear.....	2-16
3-1	Test Specimens - I&C Panels (NSSS).....	3-2
3-2	Summary of Test Results - I&C Panels (NSSS).....	3-3
3-3	Fragility Results - I&C Panels (NSSS).....	3-6
4-1	Operating Time Required to Change State of a Common Auxiliary Relay.....	4-14
5-1	Recommended Probabilistic Fragility Levels.....	5-2

LIST OF FIGURES

<u>Figure</u>	<u>Page</u>
2-1 Horizontal TRS @2% Damping - Low Voltage Switchgear.....	2-8
2-2 Horizontal TRS @2% Damping - Medium Voltage Switchgear.....	2-9
3-1 Horizontal TRS @2% Damping - I&C Panels (NSSS).....	3-5
4-1 A Typical Hinged Armature Relay.....	4-4
4-2 A Typical Rotary Induction Disk Relay.....	4-6
4-3 A Typical Plunger Type Relay.....	4-7
4-4 A Typical Induction Cup Type Relay.....	4-8
4-5 Single Axis Sine Beat Test Amplitude.....	4-9
4-6 Typical Multifrequency Relay TRS @5% Damping.....	4-11
4-7 Single Axis Sine Beat Test Amplitude Frequency Sensitivity.....	4-16
4-8 Single Axis Sine Beat Test Amplitude Chatter Duration Sensitivity.....	4-17
4-9 Single Axis Sine Beat Test Amplitude Input Motion Direction Sensitivity.....	4-18
4-10 Single Axis Sine Beat Test Amplitude Electrical Mode and Contact State Sensitivity.....	4-20

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CHAPTER 1 INTRODUCTION

1.1 BACKGROUND

The Component Fragility Program at Brookhaven National Laboratory (BNL) was initiated in FY1985 under the sponsorship of the United States Nuclear Regulatory Commission (USNRC). The essential objective of the program at BNL is to establish the generic seismic fragility of nuclear power plant equipment by use of existing test data.

In Phase I of the program, a methodology was developed to determine the fragility levels and the results were published in NUREG/CR-4659, Vol. 1 [1]. The methodology was further refined in Phase II of the program and was applied to four equipment classes - motor control center (MCC), switchboard, panelboard and power supply. The results were published in NUREG/CR-4659, Vol. 2 [2]. In addition, dynamic amplification of electrical cabinets was studied based on existing test data and the results were published in NUREG/CR-5203 [3].

1.2 CURRENT RESEARCH SCOPE

In continuation of Phase II, three additional equipment classes have been studied and the fragility results are discussed in this report. The equipment items are the following:

1. Switchgear
 - a) Low voltage
 - b) Medium voltage
2. Instrumentation and Control Panels (NSSS)
 - a) Nuclear Instrumentation/Neutron Monitoring System Cabinets
 - b) Plant/Process Protection System Cabinets
 - c) Solid State Protection System Cabinets
 - d) Engineered Safeguards Test Cabinets
3. Relays

A relay test program has also been conducted as part of the Component Fragility Program to characterize the effects of various parameters on seismic capacity of relays. The test results will be published in a separate report later in 1990.

1.3 FRAGILITY EVALUATION METHODOLOGY

The methodology used in this report to evaluate the seismic fragility of the above three equipment classes is the same that was employed to study the earlier equipment such as MCC and others. The evaluation methodology is briefly discussed as follows, the details of which were provided in NUREG/4659, Volumes 1 and 2 [1,2].

Existing test data have been collected from various organizations and the seismic fragility level has been measured in terms of the test response spectrum (TRS) corresponding to a defined failure mode. The TRS data have been compiled for each equipment class to develop a uniform data set. A multifrequency, multiaxis TRS at the 2% damping value has been considered as the standard reference data set. Appropriate conversion factors have been used for this purpose to account for the variation of damping values and testing techniques. The lower envelope of the TRS data related to a particular failure mode obtained from different test programs constitutes the "generic" fragility level corresponding to that failure mode for the equipment class. Similar fragility TRS levels for the major failure modes are presented in this report to define the deterministic "generic" fragility levels.

In addition, probabilistic fragility estimates have been made for each failure mode. To this end, the TRS of a test run for a specimen exhibiting a certain malfunction constitutes the basic data. The Zero Period Acceleration (ZPA) and the average spectral acceleration (ASA) averaged over the 4-16Hz frequency band of the TRS are used as the fragility indicators. For each equipment class, such single-valued ZPA and ASA data points have been obtained for all the specimens and for all the fragility level test runs included in the BNL data base. A lognormal distribution of the data has been assumed. The variation of ZPA and ASA values of one specimen for multiple test runs provides the randomness coefficient (β_r), and the variation within the entire data set of an equipment for a specific failure mode quantifies the total coefficient of variation of the population (β_c). The coefficient of variation due to uncertainty of the population (β_u) is computed from the following relationship:

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

Ultimately, a probabilistic high confidence (95%) of a low probability (5%) of failure (HCLPF) value is determined by use of the fragility parameters, i.e. the median fragility value and the randomness and uncertainty coefficients. If the available test data are inadequate for performing a reliable statistical analysis, judgment is used to supplement the limited data base and the HCLPF or the medium value is computed. However the end results are checked for reasonableness. For example, the HCLPF values are kept close to the lowest available data if there exists sufficient confidence in the pertinent data set. Otherwise, the HCLPF value is allowed to go sufficiently below the lowest data point. Therefore, the authors have confidence in the median and HCLPF values published in this report with a slightly higher confidence in the HCLPF value.

This observation is true for all failure modes except for relay malfunctions. Since the relay capacity significantly varies even within the same class and since its ultimate acceptance depends to a great extent on the particular system, the authors do not have as much confidence in the relay fragility results for switchgear presented in this report.

1.4 SUMMARY

Both the deterministic and the probabilistic fragility results for important failure modes are included in this report for switchgear and I&C panels (NSSF). For relays, the generic fragility has been characterized. However, their seismic fragility levels widely vary and are model specific. Therefore, quantitative results are not included for relays. Descriptions of the equipment, data base, test specimens and the failure modes are presented for each equipment item.

Both low voltage and medium voltage switchgear assemblies are discussed in Chapter 2. Chapters 3 and 4 cover I&C panels and relays, respectively. A summary of results and recommendations for future research are included in Chapter 5.

CHAPTER 2 SWITCHGEAR

2.1 INTRODUCTION

In 1986 BNL published preliminary evaluation results of switchgear assemblies [1]. Since then more test results have been collected and further details on earlier data have been obtained for this equipment. In the current evaluation both sets of test data have been used and a comprehensive fragility study has been performed. The evaluation results as well as the test data base are presented in this chapter. For completeness, a description of the equipment and its functions is also included. Both low and medium voltage switchgear assemblies are discussed.

2.2 EQUIPMENT DESCRIPTION

The principal function of switchgear is to safely turn "on" and "off" the power and this is accomplished by means of air circuit breakers in low voltage switchgear and air, magnetic, vacuum or gas circuit breakers in medium voltage switchgear.

Low voltage metal enclosed switchgear assemblies are composed of units that are arranged to suit the user's requirements and are applied on power circuits up through 600 volts. Each unit has three or four compartments which can contain circuit breakers. The low voltage circuit breakers typically incorporate overcurrent trip devices as an integral part of the circuit breakers. An instrument compartment which contains potential transformers, instruments, meters, relays and secondary control devices may also be included. The rear of the unit is allocated for the buses and power cables.

Medium voltage metal-clad switchgear assemblies consist of units with several metal-segregated compartments designed to accommodate medium voltage insulated primary bus bar assemblies, drawout medium voltage circuit breakers, medium voltage cables and insulated connections and low voltage wiring, protective, control and auxiliary equipment. These units and their components are arranged in a variety of combinations to suit user requirements. Switchgear equipment having continuous current ratings of up to 3000 amps and short circuit capabilities to 350 MVA at 5 KV and 1000 MVA at 15 KV has been applied in nuclear stations. The three common nominal medium voltage switchgear ratings are 5, 7.5 and 15 KV.

Medium voltage circuit breakers do not ordinarily incorporate overcurrent devices and therefore require separate protective relays. Switchgear provides all the elements necessary to interface between one or more feeder circuits which distribute power to diverse locations to perform useful tasks. Circuit breakers mounted within the switchgear housings provide the means for switching power "on" and "off", for carrying current under normal loading conditions, for safely closing in, carrying and interrupting short circuit currents when they occur, and for providing isolation between the sources of power and the feeder circuits in a safe manner. Instrument transformers and associated devices within the

switchgear sense the primary voltages and currents within the switchgear and accurately transform them to levels required for activation of low voltage and current devices such as instruments, meters and protective relays. Low voltage wiring conveys the current and voltage developed by the instrument transformers to devices mounted on the switchgear housing or to terminal blocks for connection to devices mounted remotely from the switchgear assembly. Wiring also provides the means for connecting control power to the electrical devices which activate the circuit breakers causing them to close and open in response to commands from control switches, control and protective relays and similar devices. The switchgear assembly may accommodate other devices, but the fundamental components such as primary bus conductors, circuit breakers, instrument transformers and wiring are found in practically all metal-clad switchgear assemblies.

2.3 DATA BASE

The data base includes multifrequency test results of eight low voltage and thirteen medium voltage switchgear assemblies manufactured by five major companies. Reactor trip switchgear is included in the data base and considered as part of the low voltage switchgear family. The tests were performed in the period 1975-81. A description of the data base specimens is provided in Tables 2-1 and 2-2. Typically a switchgear assembly is approximately 90 inches high and 60-100 inches deep. Most test specimens were two to four units (also known as vertical sections, bays or frames) although there were one single-unit assembly and one seven-unit assembly. The specimens were either welded or bolted on the shake table. In a field installation, the switchgear assembly may contain larger numbers of units placed side by side. Many lineups contain more than twenty units.

2.4 TEST RESULTS

The fundamental frequency recorded at various locations in the switchgear assemblies for a sine sweep level of 0.2g varies from 2Hz to 16Hz. A summary of performance of the test specimens and the corresponding vibration levels are provided in Tables 2-3 and 2-4. Performance identified as "highest qualification level" in the "test results" column of these tables indicates the highest acceptance level reported for certain applications where modifications were made and/or devices were replaced for qualification. Detailed information concerning these test results (e.g. chatter) and associated modifications was not available for this study.

TABLE 2-1
Test Specimens - Low Voltage Switchgear

No. of Vertical Sections	Size W x D x H (inches)	Approximate Weight (lbs)	Test Mounting
2	42 x 73 x 94	3400	12 bolts
-	60(D) x 93(H)	-	weld
2	44 x 58 x 90	-	weld
3	65 x 60 x 94	-	weld
7	226 x 68 x 90	15000	weld
-	108(W) x 60(D)	8400	bolts
3	66 x 58 x 90	3600	weld
2	52 x 68 x 90	6000	weld

TABLE 2-2
Test Specimens - Medium Voltage Switchgear

No. of Vertical Sections	Size W x D x H (inches)	Approximate Weight (lbs)	Test Mounting
2	72 x 97 x 91	8300	12 bolts
3	108 x 98 x 90	10300	-
4	104 x 83 x 90	8000	weld
3	-	-	weld
2	52 x 62 x 90	6800	-
2	72 x 88 x 90	10000	bolts
1	-	-	4 bolts
3	108(W) x 104(D)	15800	20 bolts
4	104 x 66 x 90	8000	weld
2	-	-	bolts
3	98 x 66 x 90	7600	weld
2	90(H)	-	14 bolts
3	108 x 91 x 90	8000	weld

TABLE 2-3
Summary of Test Results - Low Voltage Switchgear

Test Specimen No.	ZPA in "g"	ASA @ 2% in "g"	Test Results
1	1.5	3.0	Reported highest qualification level ¹
2	1.5	3.1	Reported highest qualification level ¹
3	0.8	3.4 ²	Breaker failed to close
4	2.9	11.5	Assembly bolts broke
5	0.7	1.0	Relay chattered 170ms
	1.9	2.5	Bent and loose ground connectors; door hinge pins backed out ³
6	3.9	7.2	Mounting welds broke
7	3.4	6.2	Mounting welds and corner angles broke
8	-	7.0	Welds cracked at sill; frame buckled; shunt trip attachment required modification

1. Details not available

2. The ASA of the horizontal TRS has been reduced by 15% to account for the low vertical input which in this case is approximately one-third of the horizontal input.

3. Considered as minor structural damage (see Section 2.5.2).

TABLE 2-4
Summary of Test Results - Medium Voltage Switchgear

Test Specimen No.	ZPA in "g"	ASA @ 2% in "g"	Test Results
1	-	3.2	Breaker actuated prematurely ¹ ; relay chattered and current transformer support broke loose at a lower level
2	2.2	5.0	Reported highest qualification level of a modified specimen ²
3	0.8 1.1 2.4 3.5	2.5 3.5 6.3 6.7	Relay chattered Relay changed state; breaker slipped out Operating arm for breaker bent Specimen broke loose on shake table; relay burnt out
4	1.8	5.2	Breaker tripped
5	1.2 1.4	3.5 4.4	Relay chattered Relay changed state
6	0.3 2.2	0.8 5.9	Relay chattered Relay and breaker chattered
7	-	2.9	Fuse holder became disconnected from panel and fell down on floor ³
8	0.2 ⁴ 1.5 1.4	- 3.7 3.9	Relay chattered and changed state Relay changed state Relay shorted and became inoperable
9	0.5 0.5	1.6 1.7	No malfunction Relay chattered
10	-	2.5	Relay chattered
11	0.5	1.3	Relay chattered
12	-	7.1	Reported highest qualification level of a modified specimen ²
13	1.2	3.3	Relay and auxiliary switch tripped

1. From the available information, it could not be determined whether the premature breaker actuation is acceptable. Therefore, this data was not considered in the fragility evaluation.

2. Details not available.

3. Considered as internal damage in Table 2-7.

4. Sine seep amplitude.

A lower bound of the fragility TRS levels for low voltage switchgear assemblies is shown in Figure 2-1. Relays chattered up to 170 milliseconds in a random multifrequency test at a level as low as that depicted by curve 1A. At the level of curve 1B, a breaker failed to close.¹ Minor structural damage such as bent and loose ground connectors on the breaker panel and backed out door hinge pins was observed at the level of curve 1C. Breaking of mounting welds and structural frame angles occurred at the level of curve 1D.

A lower bound of the fragility levels for medium voltage switchgear specimens is shown in Figure 2-2. Relay chatter occurred almost at all test levels including the sine sweep at 0.2g. Curve 2A shows the lowest random multifrequency TRS available in the data base, and relay chatter was observed at this level. A fuse holder became disconnected from the panel and fell down on the floor at the level of 2B. A lower bound of the TRS levels corresponding to change of state of relays and auxiliary switches is represented by curve 2C. The main breaker tripped and a specimen broke loose on the shake table at the levels of curves 2D and 2E, respectively.

2.5 DATA EVALUATION

The test data discussed above and summarized in Tables 2.3 and 2.4 have been evaluated based upon the available information in the test reports and discussions with experts from the manufacturing companies. The results are presented in the following subsections.

2.5.1 Dynamic Amplification

In a switchgear assembly, devices are typically mounted on door panels or other sheet metal elements which exhibit large amplification of the input motion. A peak amplification value as high as 20 was observed in the data base at the fragility level vibration input in the frequency range 4-16Hz. The amplification data have been separately evaluated and presented in NUREG/CR-5203 [3].

2.5.2 Failure Modes

The failure modes observed in the data base test programs can be enumerated as follows:

- a) Relay chatter
- b) Relay change of state (tripping)
- c) Auxiliary switch change of state (tripping)
- d) Breaker malfunction (e.g. tripping, failure to close)
- e) Fuse holder disconnection
- f) Relay burn out

1 The horizontal TRS has been reduced to account for the low vertical input which is in this case approximately one-third of the horizontal input. The effective reduction in terms of the ASA is 15%.

Fig. 2-1: Horizontal TRS @ 2% Damping – Low Voltage Switchgear

1A – Relay Chattered – 170ms
 1B – Breaker Failed to Close
 1C – Minor Structural Damage
 1D – Major Structural Damage

Fig. 2-2 Horizontal TRS @ 2% Damping – Medium Voltage Switchgear

- 2A – Relay Chattered
- 2B – Fuse Holder Disconnected
- 2C – Relay Changed State
- 2D – Breaker Tripped
- 2E – Specimen Broke Loose

- g) Minor structural damage - buckling and cracking of cabinet frame, crack in arc chute, crack in instrument panel, deformation of bolt washer, weld crack, device connection breaking loose, door hinge breaking, deformation of wire trough, bolt backing off in arc chute, breaking of bus support bracket, deformation of breaker operating arm.
- h) Major structural damage - breaking of cabinet structural frame members and connections.

The oscillograph record for one specimen also appears to contain breaker primary contact chatter. However, this result is judged to be a resistance change at breaker disconnects due to motion, which can have a substantial effect on a low voltage monitor circuit. If rated voltage and higher current levels were used for monitoring during the test, it is judged that there would be no discontinuity in the power. The significance of relay malfunctions and the causes of breaker tripping are discussed in the following subsections.

2.5.2.1 Relay Chatter

Relay chatter is a common phenomenon observed in switchgear test programs. It occurred even at the lowest multifrequency random vibration and sine sweep tests. However, whether a relay chatter will cause a problem (e.g. trip the breaker) depends on the function of the relay in a particular system as discussed in the following paragraphs.

Protective and auxiliary relays are frequently used in switchgear to initiate circuit breaker operations. The conventional application of protective relays is to initiate trip (i.e. opening) of a circuit breaker under conditions that jeopardize the load or the system if the breaker were to remain closed. Typical protective relays sense a parameter (such as current, voltage, frequency) and initiate an output when the parametric value exceeds a preset level for a preset period of time. The output is typically the closing or opening of a contact. The input condition could be an infinitely variable analog from zero (i.e. de-energized) through the entire possible range of a parameter. A portion of this range will cause an output. The conditions associated with a protective relay are therefore de-energized, energized at an input level which does not cause an output, or energized at a level which does cause an output; the latter two are ranges and not discrete conditions. The safety functions of each protective relay are clearly dependent on the system and cannot be accurately identified on a generic basis except by establishing arbitrary normal/abnormal input levels and acceptance criteria.

Auxiliary relays, on the other hand, are used in switchgear to add contacts, change the "sense" of the output, change contact rating/capability and/or add time to the inherent speed of operation. The intent of most auxiliary relay applications is that they function as two state devices - energized and de-energized. The input voltage is ideally constant, but in actual service it can vary.

During a seismic test program, if all the relays were tested with the switchgear specimen in their appropriate locations and if all the protective devices were electrically connected to the trip elements of the circuit breakers or other circuitry per the design, then the protective devices would be qualified

provided they did not initiate an unintended operation or did not fail to initiate an intended operation. However, the relays and other protective devices are not usually tested in this manner. The protective devices are usually separately monitored or sometimes tested as part of a separate seismic test program and their chatter limit is judged based on a predetermined acceptance level for the circuitry in a specific system or, in the absence thereof, based on a generic acceptance criterion, e.g. 2 milliseconds. Similarly, the auxiliary relays that are housed in the switchgear are judged by their functions and acceptable chatter limits for the respective systems or by a generic acceptance criterion. Chattering of relays responsible only for annunciating functions (such as indicating light, alarm) may be acceptable.

In summary, since relays that are responsible for breaker operation (e.g. tripping) were not necessarily electrically connected to the trip element during seismic testing, the acceptability of relay chatter for not causing breaker malfunction should be based on function of the relay in a specific system or a conservative generic criterion such as 2 milliseconds. This approach was used by the nuclear industry in the application of the data base test programs for qualification of specific plants.

2.5.2.2 Relay Change of State

Relays were observed to trip (i.e. change electrical state) in the data base test programs. The seal-in coil of the relay would sometimes sustain the change of state. In some cases the chatter and the change of state were initiated by the seal-in contact. As discussed above, if during testing these relays were connected to the trip elements of the breaker, the breaker also would trip. Removal of the seal-in contact from the circuit can, in some cases, eliminate this seismic effect; however, the design of the relay, the durability of its contacts and the reliability of the relay are dependent on the presence of the seal-in contact. Therefore, in most applications, the seal-in contact should not be removed except as a temporary measure.

2.5.2.3 Breaker Tripping

The power circuit breaker accomplishes the principal function of closing and opening the power contacts, thereby applying and removing power to a load circuit. The closing and opening (i.e. tripping) controls on the circuit breaker are momentarily energized and the primary contacts are mechanically latched into the closed and open positions. The safety functions of a circuit breaker, a simple two state device, are as follows:

- a) Remain closed
- b) Open on command
- c) Remain open
- d) Close on command
- e) Any combination (of the above four)
- f) Any combination with added critical timing requirements

In addition to the relay malfunctions discussed in the previous subsections, the conditions and arrangements that have been found likely to initiate a breaker malfunction are as follows:

- a) The mechanical integrity of the racking mechanism with regard to holding the circuit breaker in the connected position,
- b) The electrical performance of stationary breaker auxiliary contacts (switches) which, since they are mounted on the cabinet but operated by the breaker, monitor the relative locations of the breaker and the cabinet,
- c) The electrical and possibly the mechanical integrity of power and control disconnect devices which interface between stationary and moving connections for circuit breakers, switches and voltage or control power transformer disconnects.

The specific design establishes the likelihood of having a malfunction at these interfaces. The fundamental cause is the relative motion between the moving element and the frame, driven by seismic vibration. All designs of switchgear are vulnerable to these problems to some extent depending on the integrity of the disconnects and racking or locking mechanism and tolerances designed into the interface. Where breakers insert horizontally and rely on the floor for support, improper floor preparation can affect alignment and increase the likelihood of a malfunction. If frame mounted rails or lift mechanisms are used, the strength and tolerances of the structure, mechanisms and latches affect the fragility level.

Frequently, the circuit breaker and its enclosure respond differently to vibration and cause out-of-phase displacement situations which stress all interfaces between the enclosure and the breaker. At a relatively high acceleration level, this condition will cause mechanical damage.

As will be discussed in a subsequent section (2.6), structural modifications were made on both earlier and later products to reduce the effects of the above phenomenon and thus reduce the likelihood of breaker trip and/or damage.

2.5.3 Fragility Estimates

Based upon the test results discussed above, the failure modes have been categorized as follows for the purposes of fragility estimates:

- a) Relay chatter
- b) Relay and switch change of state
- c) Internal damage
- d) Breaker malfunction
- e) Major structural damage

The breaker malfunction is either tripping or failure to close. The breaker malfunction data set does not include the relay chatter or the relay and switch change of state data although the breaker function could have been compromised if during testing the devices were always electrically connected

with the trip elements to simulate the in-service conditions as discussed in the previous section. Typically, the power circuit breakers are seismically strong and it is the controlling devices that cause the breaker malfunction. Instances of breaker tripping in the data base were attributed to relay malfunctions. However, for one switchgear specimen the failure of the breaker to close was attributed to the binding of the closing mechanism. Internal damage data include test results related to disconnection of a fuse holder and breaking of a transformer support.

For the low voltage switchgear, the available fragility data for individual failure modes have been considered inadequate for performing statistical analysis. The fragility parameters have been estimated by judgment based on the data and the HCLPF values have been computed by use of the judged parametric values. The results are shown in Table 2-5.

For the medium voltage switchgear, the fragility data base is shown in Table 2-6 and has been considered adequate for performing statistical analysis for the relay contact chatter and the relay and switch change of state failure modes. The method of moments was employed for estimation of the fragility parameters. The fragility parameters for the internal damage, the breaker trip and the overall structural damage of the switchgear, on the other hand, have been estimated by judgment based on the respective limited data available in the data base. The fragility parameters and the HCLPF values are presented in Table 2-7.

2.6 HISTORY OF IMPROVEMENT

Changes were made in switchgear designs at different times for different reasons whether these were for improvement of the arc controlling mechanism or due to development of better insulating materials or need for a seismically designed product. A brief history of design changes of switchgear is presented in this section with the purpose of acquainting the reader with the evolution that led the product from the pre-nuclear to the nuclear power era and from the pre-seismic to the seismic design era.

Before electricity moved out of the laboratories to become a practical form of useable energy, it was recognized that equipment would be needed for controlling and distributing this new commodity. Even in the simplest installation where power was generated by a single dynamo and carried directly to a single motor, it was necessary to have a switching device to turn "on" and "off" the power. The simple switches performing these "on/off" operations were mounted on hardwood panels which became known quite literally as "switchboards." As devices for performing these functions became more sophisticated and as more functions were added, the mounting board became obsolete and the broader and more inclusive term "switchgear" was adopted.

Beginning with this very rudimentary concept, the switchgear industry has evolved. As the number and size of generators increased, as AC alternators and transformers entered the picture, as systems began to grow, and increasingly large amounts of power had to be distributed, the demand for switchgear to meet the needs of higher power and voltage kept pace. The results have been reflected in a nearly continuous evolution of switchgear designs. Developments in

TABLE 2-5
Fragility Results - Low Voltage Switchgear^{1,2,3}

Failure Mode	Indicator	Median* in "g"	β_u^*	β_r^*	HCLPF in "g"
Relay Chatter ⁴	ZPA	1.0	0.30	0.10	0.5
	ASA @ 2%	1.9	0.30	0.10	1.0
Breaker Malfunction ⁵	ZPA	1.5	0.30	0.10	0.8
	ASA @ 2%	6.6	0.30	0.10	3.4
Major Structural Damage ⁶	ZPA	3.5	0.15	0.06	2.5
	ASA @ 2%	8.5	0.15	0.06	6.0

1. The g-values are measured at the base of the equipment.
2. The results are applicable only within the limitations discussed in Section 2.7.
3. For evaluation methodology and authors' confidence in the results, see Section 1.3.
4. Relay chatter may initiate breaker malfunction.
5. For use of these results, the devices that directly or indirectly control the breaker operation should be qualified to the seismic demand at their respective locations. In the absence of detailed information about the seismic demand it is judged that these devices should be qualified as a minimum to a 3g ZPA capacity rating per ANSI/IEEE Std C37.98 (2ms chatter criterion) provided no seal-in or lockout relays are present in the breaker controlling circuit.
6. For definition of major structural damage, see Section 2.5.2 item h.

* Based on judgment.

TABLE 2-6
Medium Voltage Switchgear
Input Data for Statistical Analysis

Failure Mode	Fragility ZPA in "g"	Fragility ASA @ 2% Damping in "g"
Relay Chatter	0.3, 0.5, 0.5, 0.5 0.8, 0.8, 1.2	0.8, 1.3, 1.7, 1.7 2.5, 2.7, 3.5
Relay and Switch Change of State	1.1, 1.1, 1.2, 1.3 1.4, 1.5, 1.6, 1.6 1.6, 1.9	3.3, 3.3, 3.5, 3.7 3.8, 4.0, 4.0, 4.4 4.5, 4.9

TABLE 2-7^{1,2,3}
Fragility Results - Medium Voltage Switchgear

Failure Mode	Indicator	Median in "g"	β_u	β_r	HCLPF in "g"
Relay Chatter ⁴	ZPA	0.6	0.44	0.10*	0.2
	ASA @ 2%	1.8	0.49	0.10*	0.7
Relay and Switch Change of State ⁴	ZPA	1.4	0.17	0.06	1.0
	ASA @ 2%	3.9	0.11	0.08	2.9
Internal Damage ⁵	ASA @ 2%	4.0*	0.10*	0.10*	2.9
Breaker Trip ^{6,7}	ZPA	2.0*	0.10*	0.10*	1.4
	ASA @ 2%	6.3*	0.10*	0.10*	4.5
Major Structural Damage ⁸	ZPA	3.5*	0.15*	0.06*	2.5
	ASA @ 2%	8.5*	0.15*	0.06*	6.0

1. The acceleration levels are measured at the base of the equipment.
 2. The results are applicable only within the limitations discussed in Section 2-7.
 3. For evaluation methodology and authors' confidence in the results, see Section 1.3.
 4. Relay chatter and relay and switch change of state can cause breaker tripping. In the data base test programs, these devices were not necessarily connected to the trip elements of the breaker to simulate inservice conditions (see Sections 2.5.2 and 2.5.3).
 5. Internal damage includes disconnection of a fuse holder and breaking of a transformer support.
 6. For use of these results, it should be assured that breaker relative movement and slipping out are inhibited by installation of racking and positioning mechanisms as recommended by the manufacturer.
 7. For use of these results, the devices that directly or indirectly control the breaker operation should be qualified to the seismic demand at their respective locations. In the absence of detailed information about the seismic demand it is judged that these devices should be qualified as a minimum to a 3g ZPA capacity rating per ANSI/IEEE Std C37.98 (2ms chatter criterion) provided no seal-in or lockout relays are present in the breaker controlling circuit.
 8. For definition of major structural damage, see Section 2.5.2 item h.
- * By judgment.

materials and improvements in the technology of arc interruption, conductor configuration, dielectrics, bracing against electro-mechanical short circuit forces and control systems all spurred the continuing development of more capable switchgear equipment.

The changes into the 1960's were made primarily for improving electrical performance and for more efficient use of the equipment to meet progressively greater demands. Nuclear plant requirements in the 60's introduced a new issue into switchgear design - seismic motion. The early efforts were involved in establishing proper seismic testing techniques. The manufacturers indicated that early tests did not disclose any "significant shortcomings" in switchgear design except contact chatter compared to the seismic demand of that time.

A new category of switchgear (Class IE) evolved through the early 1970's, to meet increasingly more rigorous seismic qualification criteria and higher seismic levels. Early test data are not included in the BNL data base and therefore, the fragility levels of early unmodified equipment may not be represented by the results of the current study. In addition to possible earlier generic improvements, equipment for specific applications was sometimes further modified during a test program to meet a specific set of seismic criteria.

In summary, the switchgear products manufactured in the 1960's and early 1970's are expected to demonstrate a reasonable amount of seismic resistance. Products made after that time are expected to perform better due to the modifications incorporated with a view to meeting more rigorous seismic criteria and higher demands. Since BNL's data base covers test data generated only in the late 1970's, the results presented in this report are applicable for the modified equipment. The details of the early modifications were not available to BNL; however, some of the specific types of later modifications are as follows:

- o Breaker racking and positioning mechanisms were improved.
- o Anchor bolt hole reinforcements or heavier members were introduced.
- o Local gussets and stiffeners were added to avoid fracture.
- o Better subassembly welding was introduced.
- o Mountings of coils, latches, switches etc. were modified.
- o Members were added to panels to reduce local flexibility.
- o Device substitutions were made.
- o Structural members were strengthened.
- o Additional hardware (studs, bolts, lockwashers and nuts) was used.
- o Welding became the preferred method of anchorage.

- o Members were added to stiffen the equipment structure and improve anchorage.
- o Material thickness of removable plates was increased.
- o Positioning materials were added to reduce displacements of vulnerable components.
- o Use of high strength hardware increased.
- o Requirement of bolt torquing was introduced.

Available documents indicate that some of the above modifications were needed directly or indirectly for proper functioning and qualification of the breaker, and other modifications were made to improve overall structural resistance and capability.

Modifications continued through the 1970's and further modifications were made generically or for specific applications as a result of test programs some of which were used in the BNL study. Therefore, it is emphasized that the products specifically qualified and supplied since the tests in the data base, are expected to perform significantly better in a seismic environment than the picture depicted by the generic results presented in sections 2.4 and 2.5.

2.7 LIMITATIONS

Due to the limitations of the data base and possible earlier modifications, the fragility results presented in Sections 2.4 and 2.5 are applicable provided the following limitations are satisfied:

- o The switchgear is manufactured after 1975.
- o The equipment rating and configurations are comparable to that in the data base as discussed in Sections 2.2 and 2.3.
- o Since some relay models are known to be very weak in seismic environments, such relays should be carefully screened.
- o The equipment is installed in the field in accordance with the testing as discussed in Section 2.3 and presented in Tables 2.1 and 2.2. Uneven floor preparation increases the likelihood of problems where breakers insert horizontally and rely on the floor for support.
- o The switchgear is in the operating (i.e. connected) position only.

2.8 CONCLUSIONS

The data base indicates that the fragility level corresponding to the relay chatter failure mode is low. This does not mean that a switchgear qualified based on the test results of the data base has a low seismic capacity. On the contrary, results of the test programs similar to those in the data base were used to characterize a standard product and then, with that knowledge, evaluations were made for specific applications. For example, the specific systems were analyzed for determination of the acceptable chatter limit, relays were relocated within the cabinet, devices were replaced with seismically stronger ones, device mounting and instrument panels were improved, cabinet structure was stiffened and/or strengthened. As a result, although the qualification of a switchgear for a specific application was derived from the results of test programs similar to those in the data base, the seismic capacity of such equipment used in a specific application is expected to be significantly higher than that depicted by the results presented in this chapter provided a seismic qualification program was implemented for that application.

On the other hand, in order to improve the seismic capacity, modifications were made to the standard products in the period 1968-76. Since the data base test programs were conducted after this period, the "generic" fragility results presented above may be larger than the actual fragility for certain earlier products, and should be carefully used for these earlier products. However, since with increasing vibration levels breaker malfunction is first caused by malfunction of controlling devices, replacement of certain weak devices may significantly improve the seismic capacity of early vintage switchgear.

CHAPTER 3 INSTRUMENTATION AND CONTROL PANELS (NSSS)

3.1 INTRODUCTION

The instrumentation and control (I&C) panels supplied by the reactor vendors are discussed in this chapter. The panels included in the fragility study are floor mounted and typically furnished as part of the following systems:

- a) Nuclear Instrumentation System/Neutron Monitoring System (NIS/NMS)
- b) Plant/Process Protection System (PPS)
- c) Solid State Protection System (SSPS)
- d) Engineered Safeguards Test (EST) Cabinets

The NIS/NMS cabinets process input from the nuclear detection system around the core and monitor the power system. In the reactor protection system, these cabinets provide an alarm function, a secondary control function of indicating reactor states during start-up, power operation and overpower trip protection. The NIS/NMS cabinets contain smaller cabinets or drawer assemblies which house power ranges, source ranges, flux deviation and miscellaneous control and indicating devices, remote preamplifiers, remote loud speakers, etc.

The PPS cabinets contain various signal conditioning devices for monitoring reactor coolant flow, temperature and pressure, pressurizer level and pressure, safety injection flow, and steam generator feedwater level and pressure. The devices include power supplies, process control cards and termination panels. The SSPS cabinets in the reactor protection system provide reactor trip and safeguards actuation. The engineered safeguards test cabinets provide testing capability during power operation.

3.2 DATA BASE

The data base covers test results of thirteen I&C panels from four vendors. Test inputs were either single frequency sine beats or multifrequency random. Tests were performed in the period 1971-81. Most test specimens were 90 inches high and 30 inches deep (Table 3-1). Each bay of the panel assembly was mounted to the shake table with four 3/4-inch or larger diameter bolts torqued to 100-500 ft-lb. For multiple bay specimens, adjacent bays were bolted together.

3.3 TEST RESULTS

The data base test specimens exhibited the fundamental frequency in the range of 4-12Hz at low level sine sweep tests (e.g. 0.2g). A summary of the highest qualification and/or fragility level test results is shown in Table 3-2. The lower-bound fragility results corresponding to various failure modes

TABLE 3-1
Test Specimens - I&C Panels (NSSS)

No. of Bays	Size W x D x H (inches)	Approximate Weight (lbs)	Test Mounting
4	89 x 30 x 90	2800	16 bolts
2	45 x 30 x 91	-	8 bolts
3	90 x 36 x 90	-	- bolts
4	150 x 54 x 100	14000	- bolts
1	22 x 30 x 90	-	4 bolts
-	50(D) x 95(H)	-	- bolts
3	81 x 30 x 95	4000	12 bolts
3	66 x 30 x 92	2000	12 bolts
2	-	-	8 bolts
2	60 x 30 x 91	2900	8 bolts
-	-	-	12 bolts
3	90 x 30 x 91	4300	12 bolts
2	60 x 30 x 91	-	8 bolts

TABLE 3-2
Summary of Test Results - I&C Panels (NSSS)

Test Specimen No.	ASA @ 2 $\frac{1}{2}$ ¹ in "g"	Test Results
1	7.5	Drawer latch mechanism failed.
2	4.7	Highest qualification level.
3	11.0	Cabinet screws loosened; cabinet disfigured; threshold of instrument accuracy problem.
4	6.5	Circuit breaker and power supply cards were shaken loose and caused malfunction at a lower level. Hold down strips were mounted before this test. Capacitor failed causing trip during this test.
5	4.1 5.0	Cable connectors became disconnected. Highest qualification level with redesigned connectors.
6	6.3	Structural integrity test.
7	7.4	Structural integrity test, yielding at connection of cabinet to base.
8	6.4	Structural integrity test.
9	7.0	Distorted door latches and fasteners.
10	8.9	Highest qualification level.
11	10.0	Power supplies lost input; equipment modified prior to this test.
12	7.4	Modified cabinet - number of bolts connecting cabinet to the base was doubled.
13	8.9	Highest qualification level.

¹ ZPA values could not be reliably estimated from the information available in the BNL data base

are shown in Figure 3-1. At the level of curve 1A, two cable connectors became disconnected and the equipment lost tripping function. The connectors were redesigned by incorporating vibration locks and the equipment successfully withstood the vibration level corresponding to curve 1B. For another specimen, a capacitor failed and a trip occurred at the level of curve 1C. The specimen was modified prior to this test program since earlier "preliminary" testing had indicated loosening of circuit boards and power supply cards resulting in electrical malfunction. Hold down strips were mounted for remedying the loosening. Curve 1D corresponds to the onset of structural damage, e.g. distorted door latches and fasteners.

3.4 DATA ANALYSIS

Test data indicate a wide variation of the fragility levels. Some of the data base test programs were performed for demonstration of structural integrity only. Moreover, some specimens were modified as a result of preliminary testing for which sufficient information was not available. Therefore, the fragility values have been judged based on the available test data and estimates of the median, β_u , β_r and HCLPF values are shown in Table 3-3. The electrical discontinuity failure is estimated to occur at a median value of 6.8g and a HCLPF value of 3.5g. The structural fragility levels are estimated at 9.0g median and 4.7g HCLPF.

3.5 LIMITATIONS

The limitations of the fragility results presented above are as follows:

- a) The I&C panel is manufactured after 1971 and supplied by a reactor vendor.
- b) The equipment and mounting description should conform to the data base information presented in Table 3-1.
- c) Modifications¹, if any, recommended by the supplier as a result of seismic testing have been implemented in the field.
- d) Relays should be separately screened.

3.6 CONCLUSIONS

Test reports indicated that modifications were performed on the equipment as a result of malfunctions observed during earlier "preliminary" testing but did not include sufficient details of the preliminary results and the modifications. Therefore, the results presented above should not be used for unmodified panels.

¹ Examples: improved supports for circuit boards and power supply cards; additional bolts for connecting devices, for connecting frame members and for mounting the panel.

Fig. 3-1: Horizontal TRS @ 2% Damping – I and C Panels (NSSS)

- 1A – Cable Connectors Disconnected, Tripping Function Lost
- 1B – Qualification Level With Redesigned Connectors
- 1C – Capacitor Failed Causing a Trip
- 1D – Structural Damage

TABLE 3-3
Fragility Results - I&C Panels (NSSS)^{1,2,3}

Failure Mode	Indicator	Median in "g"	β_u	β_r	HCLPF in "g"
Electrical discontinuity and trip	ASA @ 2%	6.8	0.3	0.1	3.5
Structural damage	ASA @ 2%	9.0	0.3	0.1	4.7

1. The acceleration levels are measured at the base of the equipment
2. These results are based on judgment and are applicable only within the limitations described in section 3.5.
3. For evaluation methodology and authors' confidence in the results, see Section 1.3.

CHAPTER 4

RELAYS

4.1 INTRODUCTION

An introduction to relays and a discussion on the complexity of their fragility were included in the 1986 report [1]. Since then more relay test data have been collected. Relays, like other devices, are mounted in cabinets and, consequently, subjected to an amplified motion compared to that at the base of the housing cabinet. Therefore, for an appropriate use of the relay test data obtained from separate testing measured at the base of the respective specimens, the amplifying characteristics of the housing cabinets must be taken into account. To this end, the dynamic amplification of motor control center and switchgear cabinets have been studied as part of the Component Fragility Program [3]. In addition, a relay test program has been initiated as part of this project for gaining more knowledge regarding the effects of parameters on the fragility levels such that the existing data can be properly interpreted and used. The results of the test program will be published in a separate report in 1990. This chapter presents the characteristics of relays learned from existing test data.

4.2 EQUIPMENT DESCRIPTION

Many relays fit in an envelope of a 6-inch cube; longer relays usually affect only the height dimension. The weight is in the range 1-12 pounds. A relay may be mounted in a socket, directly on a panel surface or in a cutout in the panel (called semi-flush mounting). Typically four screws are used for mounting a relay. It could have AC or DC coils for actuation of contacts which may be either normally (i.e. when de-energized) open or normally closed. Normally open contacts can usually be converted to normally closed contacts and vice versa. Improper adjustment may affect the performance of the contact when subjected to vibration.

In addition to the main contacts, relay assemblies frequently contain one or more auxiliary units, such as an instantaneous trip unit or a target and seal-in unit. The auxiliary units add more functions to the relay. Both main and auxiliary contacts can affect electrical performance and consequently must be competent in the required seismic environment. For many relay models, as discussed later, the auxiliary contacts have lower seismic ratings than the main contacts.

4.3 CLASSIFICATION

Relay performance in a seismic environment is associated with its electrical function and design and hence a categorization of the wide varieties of relays is needed as a tool for discussion of the fragility mechanism and the fragility level. A broad classification of the relay family based on these two aspects can be made as discussed in the following subsections.

4.3.1 Electrical Function

The traditional approach to classify a relay is according to its electrical function and application. All relays can be broadly categorized into two groups, protective and auxiliary. The protective relays protect a circuit, a system or an equipment from an undesirable electrical condition, for example, by initiating a trip of a circuit breaker under conditions that would otherwise jeopardize the circuit, system or the equipment if the breaker were to remain closed. A protective relay senses an electrical parameter such as current, voltage or frequency, and initiates an output when the parametric value exceeds a preset level for a preset period of time. The output is typically the closing or opening of a contact. Depending on its specific function, a protective relay may be an undervoltage, overvoltage, overcurrent, frequency, reverse power, etc.

Protective relays cannot be classified as two state devices (i.e. energized and de-energized) except regarding the output. The input condition is an infinitely variable analog from zero (de-energized) through the entire possible range of the monitored parameter. A portion of this range will cause an output. The input conditions associated with a protective relay are de-energized, energized at an input level which does not cause an output or energized at an input level which does cause an output; the latter two are ranges and not discrete conditions. The operating conditions and safety functions of a protective relay are dependent on the system and cannot be accurately identified on a generic basis except by establishing arbitrary normal/abnormal input levels.

On the other hand, auxiliary relays are used to add contacts, change the sense of the output, change the contact rating/capability and add time to the inherent speed of operation. The intent of most auxiliary relay applications is that they function as two state devices - energized and de-energized. The input voltage is ideally constant. Under some conditions this may not be true and the reliability of pick-up or timing may not be consistent at varying voltage levels. Thus the operating conditions and the required safety functions for auxiliary relays are also dependent on the system requirements.

Two types of output contacts are available - normally open and normally closed. Safety functions of an auxiliary relay could be one of the following:

- a) Closed contact when de-energized, should remain closed.
- b) Open contact when de-energized, should remain open.
- c) Closed contact when energized, should remain closed.
- d) Open contact when energized, should remain open.
- e) Any combination (of above four).
- f) Any combination with critical timing requirements, such as transition time or open before close.

4.3.2 Design

Sensitivity of a relay to seismic vibration depends to a great extent on its operating mechanism. But a precise classification of relays based on their operating mechanisms is difficult due to the variety and combinations of mechanism types. Relays can, however, be broadly categorized into two groups:

electro-mechanical and solid state. The fundamental action of an electro-mechanical relay is to mechanically change electrical flow paths on demand. Since it requires the relay to contain sensitive moving parts, an electro-mechanical relay is inherently susceptible to vibration. On the other hand, a solid state relay having few, if any, mechanical operating parts performs better in a seismic environment. However, a proper mounting needs to be assured regardless of the relay design.

The electro-mechanical relays again are of different types depending on the specific operating techniques. Some common forms are discussed in the following subsections.

A relay assembly may consist of one or more operating mechanisms for its contacts. For example, in a particular overcurrent protective relay model, the main contacts are driven by a rotary induction disk mechanism but the auxiliary contacts are operated by a hinged armature mechanism. Another relay model with hinged armature main and auxiliary contacts contains a solid state timer. Therefore, the overall performance of a relay depends on functionality of all the operating mechanisms it contains.

4.3.2.1 Hinged Armature

A hinged armature relay is composed of a moving armature which is electrically operated by a magnetic field, and contacts which are attached to the movable armature and physically move to change the electrical circuit. Figure 4-1 shows a schematic of a typical hinged armature relay. Since the armature is designed to move, it introduces a vulnerability to malfunction (e.g. contact bounce) which could be caused by a gross movement of the armature when subjected to vibration. Furthermore, the contacts are subjected to bounce as a result of local resonances of the structural elements of the relay. The slow armature movement is susceptible to the low frequency content of a seismic motion and the local structural elements typically resonate with the high frequency content. Therefore, a hinged armature relay is sensitive at both low and high frequencies, the low frequency input being more damaging.

The performance of a hinged armature relay when subjected to vibration is generally better when the relay is operated in the energized condition since the magnetic field of the coil tends to restrain motion of the armature more than the spring. The performance is also greatly affected by the direction of vibration. Dynamic motion in the direction of movement of the armature is potentially more damaging than motions in the other directions. A substantial increase in vibration resistance can be achieved by orienting the relay in its most resistant direction to the worst input directions. By adjusting tension in the spring, the flexibility of the armature movement can be altered and this changes the dynamic characteristics of the relay.

A variation of the self-reset hinged armature relay includes a latch which mechanically latches the relay in the operating condition allowing de-energization of the operate coil. The relay may be reset to the nonoperating condition either by hand or electrically with a reset coil on the relay, or both. Unlatching of such a relay due to seismic motion can cause its failure in the operating condition.

ISOMETRIC VIEW

SIDE VIEW

Fig. 4-1 A Typical Hinged Armature Relay

4.3.2.2 Rotary Induction Disk

In a rotary induction disk relay, the moving contact is attached to a disk mounted on a vertical shaft which is free to rotate on bearings as shown in Figure 4-2. By energizing or de-energizing a driving magnet, the disk and the attached moving contact can be made to rotate until the latter engages or disengages with the stationary contact, thereby changing the electrical circuit. Many protective relays are of this design. The location of the disk in the magnetic gap can be adjusted and the amount of vertical movement of the disk can be increased or decreased. Thus, such an adjustment, called an "end play adjustment," can change the dynamic characteristics of the relay.

4.3.2.3 Plunger

Plunger type mechanisms (sometimes called solenoid type mechanisms), are used in many styles of relays (Figure 4-3). One type is the very sensitive, fast-acting protective relay. It is usually vulnerable to vertical vibration inputs due to use of a gravity or very flexible spring for maintaining the normal contact state at the de-energized condition. Another type is equipped with heavier springs and is characterized as an industrial grade auxiliary relay. A third type is the pneumatic time delay relay which also uses a heavier spring and has a pneumatic diaphragm that delays contact action in one direction.

4.3.2.4 Induction Cup

The induction cup relay is similar to the induction disk relay except that the moving element is cylindrical and that it can be used for high speed response and for producing a more efficient torque (Figure 4-4).

4.4 DATA BASE TEST PROGRAMS

The data base test programs can be grouped into two types, depending on the testing methods and the available information as discussed in the following subsections.

4.4.1 Single Axis, Single Frequency Tests

Single axis, single frequency sine beat or sine dwell tests were performed on early vintage relays in the period 1973-75. The data base contains information on twenty five protective and auxiliary (including time delay) relay models. The relay specimens were tested at specific frequencies with increasing input level until they exhibited contact chatter of a pre-selected level (e.g. 1, 2 or 10 milliseconds) or until the capacity of the shake table was reached. The tests were repeated in different directions and for different electrical (i.e. energized and de-energized) and contact (i.e. normally open and normally closed) conditions. The vibration levels were measured in terms of the amplitude of the sine wave form and presented as a plot of input acceleration vs. frequency. The discrete points in the plot are connected to provide a continuous fragility (or test equipment capacity) curve in the frequency range 1-35Hz. Figure 4-5 shows a set of test results for a relay model. Curve A indicates the fragility chatter limit (2ms) for a normally closed contact of

Fig. 4-2 A Typical Rotary Induction Disk Relay

Fig. 4-3 A Typical Plunger Type Relay

Fig. 4-4 A Typical Induction Cup Type Relay

Fig. 4-5: Single Axis Sine Beat Test Amplitude
5A - Deenergized
5B - Energized

the sensing unit of the relay when de-energized and curve 5B corresponds to the shake table capacity which was reached for the energized condition with no chatter. For the data base relays, the contact chatter fragility level was as low as 0.1g and as high as 3.0g sine beat input motion.

Single frequency test results reveal the frequency sensitive nature of relays. However, it is often difficult to use the input acceleration values to determine whether the data set envelopes a required response spectrum, the common measure of the seismic demand in practice since the mid-1970's. Therefore, the use of the early test data is limited unless an appropriate conversion factor is developed.

4.4.2 Multiaxis, Multifrequency Tests

The data base contains multiaxis, multifrequency results from tests performed since the late 1970's. Most tests were performed with biaxial inputs either phase incoherent or phase coherent. Triaxial input motion was used for the rest. The fragility levels due to relay chatter were determined for various electrical modes and contact conditions and expressed in terms of the TRS. Some relay models did not exhibit chatter even at the shake table capacity vibration level. The multifrequency test data were of three different types and the nature of the data was also different as discussed in the following subsections.

4.4.2.1 Required Response Spectrum Tests

These tests were performed to meet a specific or a generic required response spectrum (RRS) and in the process the chatter fragility was reached. The corresponding vibration level was presented in terms of TRS data. These results are conservative in the sense that at some frequencies the relay may still withstand higher vibration levels. In Figure 4-6, curve 6A illustrates the fragility TRS of a time delay relay.

4.4.2.2 IEEE Std Tests

A large number of test programs were conducted following the generic procedure and the standard RRS shape recommended by IEEE Std C37.98-1978 [4]. Since the late 1970's, the manufacturers have used this approach for seismic rating of their products. Typically, the ZPA is used as a single-valued fragility level such that the 5% damped spectral level is two and a half times the ZPA at frequencies between 4 and 16Hz. This is a very convenient and concise way of expressing the capacity level and the seismic ratings (i.e. ZPA's) are readily available, sometimes even in manufacturers' catalogs and sales brochures. Also, the capacity levels of various relay models can be easily compared and the appropriate relay can be selected. However, the TRS data used for obtaining the seismic ratings are not easily available. Curve 6B in Figure 4-6 shows an example of the IEEE Std type capacity curve for an auxiliary relay with 0.5g ZPA seismic rating.

Fig. 4-6: Typical Multifrequency Relay TRS @ 5% Damping

6A - Shake Table Mounted Time Delay Relay
 6B - IEEE Std Capacity - Auxiliary Relay
 6C - Panel Mounted Auxiliary Relay

The data base indicates a wide range of seismic ratings - from as low as 0.5g ZPA to as high as 6.0g ZPA. For many relays, the seismic rating is controlled by the capacity of the test table rather than malfunction of the relays.

4.4.2.3 Panel Tests

A large number of electrical panels were tested with relays mounted in them. For a long time it has been known in the industry that relays are the typical weak links of electrical equipment. As a result, for selected relays, accelerometers have been used to measure the vibration level at the device locations and electrical channels have been used to monitor electrical performance. Such information is an important source of relay fragility data. The BNL data base contains relay information for equipment tested in the period 1977-80. The merit of the panel test data is that in application relays will be mounted in such panels and used in similar circuits. Therefore, the relay performance and the vibration level at locations recorded during panel testing are more direct, realistic and dependable, especially since the input vibration at the base of the equipment has been filtered through the cabinet structure. The limitation of the use of the panel test data is that the same relay located in another possible location in the same cabinet, or tested in another cabinet, may exhibit a different fragility level due to different characteristics of the filtering medium. Another limitation of the panel test data is that since the purpose of the test was not necessarily to determine the fragility threshold of a particular relay, the available information may indicate chatter duration either higher or lower than the threshold value, e.g. either 20ms chatter or no chatter for a 2ms chatter criterion. Figure 4-6, curve 6C shows the TRS at the location of an auxiliary relay mounted in an electrical panel when the device exhibited chatter.

4.4 FAILURE MODES

The most common malfunction of a relay is the temporary discontinuity of a contact commonly known as "contact chatter." In a vibratory environment, a normally closed contact becomes open for a short duration (on the order of milliseconds) and returns to its original closed condition. Similarly, a normally open contact closes for a short duration and comes back to the open position. For many electrical assemblies in the data base, relay chatter occurred prior to other malfunctions with increasing vibration levels. In the individual relay test programs, the fragility was controlled by contact chatter for most relays.

The moving contact has to traverse the contact gap for a normally open contact before it closes, whereas a normally closed contact becomes open immediately. Therefore, for electro-mechanical relays the normally closed contacts typically chatter at a lower vibration level compared to the normally open contacts. Sensitivity to vibration is especially pronounced on relay components performing mechanical functions and relying on springs, gravity and friction to operate correctly. For a hinged armature operating mechanism, the contact is more susceptible to vibration in the de-energized condition than when it is energized. In the energized condition the magnetic field of the coil tends to restrain motion of the armature.

Another type of relay malfunction in the data base is the change of state phenomenon which can be either a sustained change of state of a contact (also known as "trip") or a failure to change state on demand. A relay assembly containing the seal-in coil may change state as a result of contact chatter. Sensitivity for change of state also depends on the similar factors as described above for the contact chatter failure mode.

Although uncommon, there are examples in the data base of damaged and shorted coils causing a relay to become inoperable. In addition, there are examples of covers falling down and relay cases breaking at mounting locations. These failures were observed in the panel test programs at relatively high acceleration levels.

4.6 ACCEPTANCE CRITERIA

The malfunction types discussed above are not necessarily unacceptable and, if so, not necessarily in all situations. Whether a particular malfunction is recoverable or unrecoverable, and ultimately acceptable, depends on the sensitivity of the control function and the type of the system and circuit the relay is associated with. For a very sensitive control function (e.g. in a computer circuit), chattering of a fraction of a millisecond can cause failure while in some other operation (e.g. a power circuit breaker) chattering greater than 2ms can be acceptable. The electrical conditions of the device which the chattering relay will work with is also important. For example, the operating time required for changing state of a common auxiliary relay in the data base varies between 5ms and 54ms as shown in Table 4-1. The variation depends on whether the relay is de-energized or energized, AC or DC, or the contacts are normally open or closed. (The data presented in Table 4-1 are for a particular relay model and may not represent generic performance of other relays). On a generic basis, IEEE Std C37.98 [4] recommends a chatter duration of 2ms or greater as the failure criterion.

The repeated occurrence of a shorter duration chatter can be as damaging as a single occurrence of a long duration chatter. For example, relays placed off the shake table have been observed to chatter for a duration of greater than 2ms due to the repeated occurrence of 1ms chatter of relays vibrated on the shake table.

The acceptability of relay test data should also be judged from the standpoint of electrical operating conditions used during testing. For example, a protective relay demonstrated a high fragility level on a breaker tripping output contact. The test was performed in a de-energized (zero amp) condition as well as in an overcurrent (seven amps) condition, but not in a normal current condition (four amps). The test data is incomplete since the usual operating

TABLE 4-1
Operating Time Required to Change State of a Common Auxiliary Relay

Conditions	Operating Time in Milliseconds	
	De-energized	Energized
DC - Normally open	54	17
DC - Normally closed	34	37
AC - Normally open	9	8
AC - Normally closed	5	16

condition was not tested. If the circuit breaker controlled by this relay has a safety function of staying closed except for overcurrent conditions, then the test information is not adequate to meet a reasonable acceptable criterion. IEEE Std C37.98 [4] requires testing for various electrical modes which are broadly categorized as follows:

- a) Nonoperating
- b) Operating
- c) Transition

In summary, the use of existing data to qualify relays to perform safety functions is highly dependent on the definition of acceptance criteria which relate directly to the system safety function. Test data might be sufficient for acceptance in one application and not another when using an identical relay in the same equipment, but with a somewhat different system function.

4.7 SENSITIVITY PARAMETERS

Some of the parameters controlling the fragility limits have been discussed in various places in the above sections. A complete list of them and their effects are discussed as follows. Single axis test results for contact chatter fragility modes are used for illustration.

4.7.1 Frequency of Vibration

Depending on the design and adjustment, most relays are capable of withstanding a higher vibration level at one frequency than another. The frequency range in which a particular relay is weak may be low (e.g. less than 10Hz), medium (e.g. 10-30Hz) or high (e.g. greater than 30Hz) as illustrated by the chatter fragility sine beat input vs frequency curves for two different relay models shown in Figure 4-7. One curve shows sensitivity at low frequencies and the other curve shows sensitivity at medium and high frequencies.

4.7.2 Chatter Duration

Depending on the chatter duration that can be accepted for a particular application, the fragility level may change. Single axis testing indicates that for most relays the vibration level is higher if a longer chatter can be accepted as demonstrated in Figure 4-8. ANCO [7] has reported similar observations for multifrequency test inputs.

4.7.3 Direction of Vibration Input

Depending on the design of the operating mechanism, relays exhibit varying capacity levels in different directions. Typically they are weak in the direction of the contact movement. Figure 4-9 shows single frequency capacity test data of an auxiliary relay model in three orthogonal directions, front-to-back (FB), side-to-side (SS), and vertical (V). The FB vibration controls the capacity level for the relay at frequencies greater than 12Hz.

Fig. 4-7 Single Axis Sine Beat Test Amplitude
Frequency Sensitivity

Fig. 4-8 Single Axis Sine Beat Test Amplitude
Chatter Duration Sensitivity

Fig. 4-9 Single Axis Sine Beat Amplitude
Input Motion Direction Sensitivity

4.7.4 Electrical Mode

Most two-state relays chatter in the de-energized electrical mode at a lower vibration level than the energized mode. This is true for mechanisms using a spring, since in the energized state the magnetic force of the coil is stronger than the spring force which maintains the de-energized state. Figure 4-10 shows single frequency capacity results of a popular auxiliary relay with a hinged armature mechanism for both the energized (E) and de-energized (DE) modes.

4.7.5 Contact State

The moving contact of an electro-mechanical relay needs time to traverse the contact gap for a normally open contact before it closes by engaging the stationary contact. On the other hand, a normally closed contact becomes open immediately by disengaging the stationary contact. Therefore, for electro-mechanical relays, normally closed contacts typically chatter at a lower vibration level than normally open contacts. Figure 4-10 allows the comparison of the single frequency capacity levels of a normally closed (NC) contact and a normally open (NO) contact of an auxiliary relay in the de-energized mode.

4.7.6 Adjustment

In a hinged armature mechanism, the magnetic force experienced by the armature must overcome the tension of the balance spring for movement of the moving contact (Figure 4-1). An adequate spring tension is required for normal operation and engagement of the moving contact. A stronger tension value tends to press the moving contact tight against the stationary contact and thereby makes the moving contact less susceptible to vibration.

The vertical shaft of a rotary disk mechanism, on the other hand, is supported by two bearings and the disk tends to jump out of plane in a vibratory environment unless the play of the vertical shaft at the bearing is properly adjusted (Figure 4-2). One popular relay model was observed to exhibit such a phenomenon in a seismic test program resulting in malfunctioning of the relay. Subsequently, the manufacturer designed a bearing adjustment kit to control the end play.

Thus, for different operating mechanisms, adjustments can influence the seismic capacity of a relay.

4.8 MODEL NUMBER AND VINTAGE

The major manufacturers usually designate a relay type for a specific electrical function, e.g. an overcurrent relay type. Model numbers consisting of alphanumeric characters are used to uniquely identify a relay type associating it with several parameters, such as, mounting, case, cover, setting, reset mechanism, AC or DC, and quality control (e.g. Class 1E). Thus, a relay type may consist of several models and the seismic capacities of two different models of the same relay type from the same manufacturer are not necessarily the same. For example, the ZPA ratings of three different models of a popular auxiliary

Fig. 4-10 Single Axis Sine Beat Test Amplitude
Electrical Mode and Contact State Sensitivity

relay type are 0.5g, 1.7g and 3.0g. All three models are products of the same manufacturer. Therefore, unless conservatively enveloped by the capacity of the weakest model of a particular relay type, the seismic rating should be associated with the relay models rather than with the relay type. The models operated by DC coils typically exhibit lower seismic capacities than those operated by AC coils.

Available documents indicate that the design of certain relay types and models has been improved in the period 1968-76 in order to enhance their seismic ratings. The use of stronger springs, more efficient magnetic materials and greater ampere turns in the coil is part of the improvement. Spring guards have been introduced. Bearing screws have been redesigned for a popular rotary disk type overcurrent relay to limit the upward travel of the moving element during vibratory conditions. Auxiliary units¹ have been redesigned since earlier designs exhibited significantly lower capacities for the auxiliary units than the primary contacts. Some relay models used in earlier nuclear power plants either are obsolete or are not used any longer in safety-related systems due to their low seismic capabilities.

4.9 USE OF TEST DATA

It is clear from the above discussions, that the seismic capacity of a relay depends on numerous parameters and the fragility level may vary over a wide range, e.g. 0.5g-6.0g ZPA. Unlike other components discussed in this and previous reports, relays cannot be treated as a group for estimation of the fragility levels and, therefore, no attempt has been made in this report to present generic fragility estimates of these devices.

The relay fragility data should be used with specific information about the product and its application including the following:

- o Manufacturer
- o Complete model number
- o Vintage
- o Adjustments, if applicable
- o Acceptable chatter limit, if other than 2 ms

Since the mid-1970's the major manufacturers have supplied the seismic ratings of their products. Single frequency test data are available for some earlier models. However, it is difficult to correlate the single frequency test data with the IEEE Std C37.98 spectral shapes for seismic rating. A relay test program, as discussed in the following section, is being conducted by BNL to address this and other issues.

¹ See Section 4.2 for definition of auxiliary units.

4.10 CURRENT TEST PROGRAM AT BNL

Primarily, in order to further study the effect of parameters on relay fragility levels, BNL has initiated a relay test program. Establishing the correlation between single frequency fragility test inputs and multifrequency test response spectra, and confirming the similarity of relay models within a group are also objectives of the test program.

Single frequency sine dwell tests are performed to study the effect of vibration frequency on the fragility levels. Nineteen popular models from three manufacturers are tested. For ten models, more than one specimen are used to study the consistency of results.

Multifrequency tests are performed with separate single axis, biaxial and triaxial inputs on twelve relay models. For selected specimens, spectral shapes are matched with the respective single frequency fragility inputs so that the conversion factors relating the single frequency test inputs to the multifrequency test response spectra can be computed.

Four relay models from one manufacturer with three specimens for each are tested with biaxial multifrequency input motion following the IEEE Std C37.98 spectral shape. The test is intended to confirm the seismic rating for all four models as reported by the manufacturer.

All the above tests are performed on new (current vintage) relay models. The effect of spring tension and contact gap adjustments are studied by varying the respective parameters of two hinged armature relay models. The effect of end play adjustments are tested on two rotary disk relays. All adjustment tests are performed with single frequency inputs.

The initial single frequency tests are conducted in all three orthogonal directions for all three electrical modes (i.e. operating, nonoperating and transition) and two contact conditions (i.e. normally closed and normally open). All subsequent tests are performed only in the weakest direction for the weakest electrical modes and contact conditions. A chatter duration of 2ms or greater is used as the failure criterion to establish the fragility levels.

Phase I of the test program has been completed and the test data are being evaluated to draw conclusions regarding the effects of various parameters, the relation between single frequency and multifrequency results, and the similarity of relay models within the same seismic rating group. The results will be published in a separate report in 1990. Testing as part of Phase II of the program will be performed also in 1990.

4.11 CONCLUSIONS

The understanding of the performance of relays in seismic environments has evolved through the 1970's. Improvements have been made during this period, which have increased the seismic capacity. Most relay models currently available for Class 1E applications can withstand a strong motion, e.g. 6.0g ZPA and higher. A small portion of the current population is still seismically weak, e.g. 3.0g ZPA and lower. Manufacturers have substituted the weakest relays with stronger ones, avoided the use of some relays in certain applications and do not recommend the use of some models at all.

Due to lack of proper knowledge and defined acceptance criteria, many relays manufactured in the mid-1970's and earlier were very different from the seismic stand point. Some relays performed well in panel testing; some reduced the equipment capacity to a very low value (see the results presented for switch-gear in Chapter 2). Even the same relay model performed differently in two test programs. The vendors screened out the weak relays through panel testing.

In summary, the seismic capacity of the current generation of relays is uniformly defined and is easy to understand and apply. However, the performance of the earlier population as in the data base is nonuniform even within the same group. Therefore, extreme caution should be used to assign a seismic rating to an earlier product. As a minimum, it is recommended that the manufacturer, complete model number, vintage and adjustment, if applicable, should be known and used for establishing a seismic capacity level for an earlier relay. The current testing by BNL and ANCO will definitely shed more light in this regard.

CHAPTER 5

SUMMARY AND CONCLUSIONS

5.1 INTRODUCTION

This chapter provides a summary of the fragility results discussed in the previous chapters. A description of the current work at BNL under the scope of the Component Fragility Program is also included in this chapter. Recommendations for future research on related topics are provided with the concluding remarks.

5.2 SUMMARY

A summary of the data evaluation results are provided in Table 5-1 and is also briefly discussed for each equipment in the following subsections.

5.2.1 Switchgear

The resonant frequencies at various locations in the switchgear assemblies vary from 2Hz to 16Hz at a sine sweep rate of 0.2g. With increasing vibration levels, the first malfunction observed in switchgear is contact chatter of relays which occurred even at the lowest level of multifrequency tests available in the data base. The corresponding estimated HCLPF values are 1.0g ASA @ 2% damping for low voltage and 0.7g ASA @ 2% damping for medium voltage switchgear assemblies. The change of state of relays and switches have been observed at a higher vibration level for which the HCLPF is 2.9g ASA @ 2% damping for medium voltage switchgear. The breaker malfunction HCLPF values have been estimated as 3.4g and 4.5g ASA at 2% damping for low and medium voltage switchgear assemblies, respectively.

5.2.2 I&C Panels (NSSF)

The fundamental frequency of the data base I&C panels is in the range 4-12Hz at the 0.2g sine sweep level. The available documents indicate modifications of earlier equipment, and test data show a wide variation of the fragility levels. The lower bound fragility level related to disconnection of connectors is 4.1g ASA at 2% damping. The corresponding HCLPF level has been estimated as 3.5g. The structural fragility HCLPF value has been estimated as 4.7g ASA at 2% damping.

TABLE 5-1
Recommended Probabilistic Fragility Levels^{1,2,3}

Equipment	Failure Mode	Median in "g"		HCLPF	
		ZPA	ASA @ 2%	ZPA	ASA @ 2%
Low Voltage Switchgear	Relay Chatter ⁴	1.0	1.9	0.5	1.0
	Breaker Malfunction ⁷	1.5	6.6	0.8	3.4
	Major Structural Damage ⁸	3.5	8.5	2.5	6.0
Medium Voltage Switchgear	Relay Chatter ⁴	0.6	1.8	0.2	0.7
	Relay and Switch Change of State ⁴	1.4	3.9	1.0	2.9
	Internal Damage ⁵	-	4.0	-	2.9
	Breaker Trip ^{6,7}	2.0	6.3	1.4	4.5
	Major Structural Damage ⁸	3.5	8.5	2.5	6.0
I&C Panels (NSSS)	Electrical Discontinuity and Trip	-	6.8	-	3.5
	Structural Damage	-	9.0	-	4.7

1. The acceleration levels are measured at the base of the equipment.
2. The results are applicable only within the limitations discussed in Sections 2-7 and 3.5.
3. For evaluation methodology and authors' confidence in the results, see Section 1.3.
4. Relay chatter and relay and switch change of state can cause breaker tripping. In the data base test programs, these devices were not necessarily connected to the trip elements of the breaker to simulate inservice conditions (see Sections 2.5.2 and 2.5.3).
5. Internal damage includes disconnection of a fuse holder and breaking of a transformer support.
6. For use of these results, it should be assured that breaker relative movement and slipping out are inhibited by installation of racking and positioning mechanisms as recommended by the manufacturer.
7. For use of these results, the devices that directly or indirectly control the breaker operation should be qualified to the seismic demand at their respective locations. In the absence of detailed information about the seismic demand it is judged that these devices should be qualified as a minimum to a 3g ZPA capacity rating per ANSI/IEEE Std C37.98 (2ms chatter criterion) provided no seal-in or lockout relays are present in the breaker controlling circuit.
8. For definition of major structural damage, see Section 2.5.2 item h.

5.2.3 Relays

Relay chatter is a common phenomenon in a vibratory environment and, thus, governs the fragility of many electrical equipment types if the chatter is not acceptable for the particular system. Relays have been observed to chatter even at the lowest levels of vibration (e.g. 0.2g sine sweep and lower than OBE multifrequency tests) when mounted in a panel. But, not all relays are seismically weak. Some relay models do not exhibit any malfunction even at the capacity level of the shake table when tested separately. Thus, the relay fragility levels vary over a wide range (e.g. 0.5g-6.0g ZPA of IEEE Std C37.98 spectrum) depending on the manufacturers, model numbers, adjustments (if applicable) and acceptance criteria, among others. Design changes in relay models through the 1970's significantly improved their seismic ratings. Therefore, all these factors should be considered in assigning a seismic rating to a particular relay product.

5.3 CURRENT PROGRAM

BNL is currently conducting a relay test program primarily to characterize the effects of various parameters on the seismic capacity of a relay. The first phase of testing under this program has been completed. The test results are being evaluated and will be published in 1990. The next phase of testing concentrating on certain issues identified in Phase I will be conducted also in 1990. BNL will also continue evaluating the seismic fragility of additional equipment classes, selecting from the following list:

1. Local Instruments
 - a) Transmitter
 - b) Indicator
 - c) Switch
2. Transformers
3. Inverters
4. Motors
5. BOP Instrumentation and Control Panels
6. Miscellaneous Control Instruments
 - a) Bistable
 - b) Recorder
 - c) Converter
 - d) Sensor
 - e) Signal Monitor
 - f) Square Root Extractor
 - g) Connector
 - h) Formette
7. Batteries and Battery Racks
8. Battery chargers
9. Small Valves
 - a) Spring Operated PRV
 - b) PORV
 - c) Pilot Operated Valve
10. Electrical Penetration Assemblies
11. CRD Equipment

Availability of resources and existing data will dictate the extent of the fragility evaluation.

5.4 RECOMMENDATIONS FOR FUTURE RESEARCH

As a result of the previous fragility and amplification studies performed, BNL provided several recommendations for future research [1,2,3]. Some of these recommendations have been implemented in subsequent phases of the Component Fragility Program. The ones which have not been implemented are not repeated in this report, except the vintage issue for which additional comments are provided. One additional recommendation is offered based on the observations made in the course of the fragility study of the equipment covered in this report.

5.4.1 Earthquake Experience vs Test Data

The latest version of IEEE Std 344 [5] accepted the use of earthquake experience data. In the resolution of USI A-46, the performance of equipment in industrial and nuclear plants under past earthquakes has been extensively studied and the experience data play a major role [6]. The current effort in the industry is to further enrich the experience data base for resolution of many present and future issues. Experience data are also being used by the NRC, directly or indirectly, to resolve important issues such as exceedance of OBE, high frequency content of earthquakes and severe accident issues. In summary, earthquake experience data are increasingly being used and will be used much more in making decisions for numerous applications - from equipment qualification to equipment modifications, from eastern seismicity issues to severe accident issues.

Earthquake experience data are a wealth of information; so are the existing test data. The obvious questions are: Do these two data sources support each other? Are they complementary? Is there any contradiction? These questions should be answered in order to reliably tap the great potential of the experience data.

Experience data demonstrate a "real" earthquake level that an equipment has been subjected to and has performed acceptably. But the data may be incomplete in the sense that the vibration level at the equipment location might not have been monitored. On the other hand, laboratory testing provides a controlled set of data, but the input motion may be unduly conservative at some frequencies and may not represent a true earthquake level.

In the course of the fragility study, BNL has studied a vast amount of fragility test data and also observed a great variation of performance. It appears from existing literature that some of these types of equipment probably performed better in an earthquake. However, it is not easy to compare directly due to a large number of variables that might have made the equipment perform differently.

Therefore, BNL considers that it is timely and expedient to correlate experience data with test data and recommends that research be initiated to study the correlation including the strengths and weaknesses of both. Limited testing may be required to address the issue.

5.4.2 Vintage

A detailed discussion on the possible effect of vintage of equipment on its seismic fragility was included in NUREG/CR-4659, Vol. 2 [2] and a recommendation was made for a study on vintage. Since then additional observations were made in the course of the current fragility study and some of them have been discussed in earlier chapters. These observations indicate that improvement of equipment design for upgrading its seismic capacity has occurred. Therefore, it appears that vintage has an effect on the seismic capacity of equipment and research on this subject is again recommended.

5.5 CONCLUSIONS

The Component Fragility Program at BNL has generated "generic" seismic fragility levels of equipment classes that can be directly used for screening purposes in margin studies and risk assessments. It has also characterized the performance of equipment in a simulated earthquake environment which can be useful in identifying the weak links of plant specific equipment and for subsequently modifying equipment to enhance the seismic capability. Combined together, the results are expected to be useful in individual plant examinations as well.

CHAPTER 6

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