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Seismic Fragility of Nuclear Power Plant Components (Phase II)

A Fragility Handbook on Eighteen Components

Prepared by
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Prepared for
U.S. Nuclear Regulatory Commission

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ABSTRACT

Fragility estimates of seven equipment classes were published in earlier reports. This report presents fragility analysis results for eleven additional equipment categories. The fragility levels are expressed in probabilistic terms. For users' convenience, this concluding report includes a summary of fragility results of all eighteen equipment classes. A set of conversion factors based on judgment is recommended for use of the information for early vintage equipment. The knowledge gained in conducting the Component Fragility Program and similar other programs is expected to provide a new direction for seismic verification and qualification of equipment.

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EXECUTIVE SUMMARY

This is the concluding report of a series published as part of the Component Fragility Program conducted at Brookhaven National Laboratory under the sponsorship of the Nuclear Regulatory Commission (NRC). The essential purpose of this program is to determine seismic fragilities of equipment by use of existing test data for application in addressing NRC licensing and research programs such as the Individual Plant Examination for External Events Program (IPEEE). The fragility analysis methodology in a probabilistic framework was developed and published in earlier reports. Fragility results of seven (7) classes of equipment (i.e., MCC, switchboard, panelboard, DC power supply, low voltage switchgear, medium voltage switchgear and NSSS I&C panels) were derived and also published in the earlier reports.

This report provides seismic fragilities of eleven (11) additional equipment categories (i.e., transmitters, indicators, switches, transformers, BOP I&C panels, miscellaneous control instruments, batteries on racks, battery chargers, inverters, electrical penetration assemblies and valve operators). A summary of all eighteen (18) categories of equipment is also included in this report for the users' convenience. As a minimum, all equipment pieces should be adequately anchored and all relays should be separately evaluated. In addition, since most of the data base equipment was manufactured as Class 1E or Seismic Category I after 1975, the use of the fragility results should be limited for similar equipment manufactured after 1975. However, for immediate needs, a set of conversion factors are recommended in the report to extrapolate the results to the early vintage (i.e., pre-1975) products. These factors are based on judgment and may be refined by further research.

The above fragility results have been obtained for each "generic" equipment class. However, due to their design complexities and variabilities, relays require model-specific evaluation. A test program was conducted on selected relay models and the test results were published in 1991. Further testing will be performed as part of a separate relay test program and the results will be published in FY 1992.

Since the fragility results are based on test data and extensive coordination with other similar programs (e.g., A-46), an application of these results in the IPEEE Program is expected to provide a reliable measure of the seismic capacities and vulnerabilities of equipment in nuclear plants. In conclusion, it is recommended that a systematic comparison between the test data and earthquake experience data be made for a reliable use of the latter and creation of a combined uniform data base. It is expected that the lessons learned from the Component Fragility Program and similar industry programs (e.g., A-46) will provide a new cost effective and reliable approach for seismic evaluation of equipment in existing nuclear plants, as well as advanced reactors.

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CHAPTER 1
INTRODUCTION

1.1 BACKGROUND

This report presents the results of the Component Fragility Program conducted at Brookhaven National Laboratory (BNL) under the sponsorship of the United States Nuclear Regulatory Commission (USNRC). Under this program, existing test data have been evaluated to determine the seismic fragility of equipment used in nuclear power plants.

As part of the Component Fragility Program, several other reports were published. NUREG/CR-0070[1] contains the proceedings of the component fragility workshop held at BNL in 1985. NUREG/CR-4659, Vol. 1[2] describes the methodology developed to determine the equipment fragility by use of existing test data. Volume 2 of the same NUREG[3] discusses a refinement of the fragility description methodology and presents a probabilistic framework for estimating the fragility level. The approach is consistent with and an improvement over the probabilistic methodology used by Lawrence Livermore National Laboratory in their Seismic Safety Margins Research Program[4]. The Volume 2[3] Report includes the fragility analysis of four equipment classes - motor control center, switchboard, panelboard and power supply. Subsequently, the test data for three additional equipment classes - low voltage switchgear, medium voltage switchgear and NSSS instrumentation and control (I&C) panels - were also analyzed and published in Volume 3[5]. The NSSS I&C panels include the following types of equipment:

1. Nuclear Instrumentation/Neutron Monitoring System Cabinets
2. Plant/Process Protection System Cabinets
3. Solid State Protection System Cabinets
4. Engineered Safeguards Test Cabinets.

A description of relay failure modes is also included in Volume 3. However, in order to gain more knowledge regarding relay model-specific failure modes and the corresponding vibration levels, a number of relay models were tested as part of the Component Fragility Program and the results are published in NUREG/CR-4867[6]. Amplification of seismic motion through cabinet structures is required for evaluation of electrical devices such as relays. Therefore, the dynamic amplification of electrical cabinets were also studied as part of the Component Fragility Program and the results are presented in NUREG/CR-5203[7].

1.2 CURRENT RESEARCH SCOPE

Subsequent to the fragility analysis of the seven equipment classes presented in Volumes 2 and 3[3,5], the test data for the following additional equipment classes were evaluated:

1. Transmitters
2. Indicators
3. Switches
4. Transformers
5. BOP I&C Panels

6. Miscellaneous Control Instruments (Bistables, Converters, Sensors and Signals Monitors)
7. Batteries on Racks
8. Battery Chargers
9. Inverters
10. Electrical Penetration Assemblies
11. Valve Operators (Motor and Solenoid)

The results from the above analyses are discussed in Chapter 2 of this report. For completeness of the data, the fragility levels of all equipment classes (i.e., the previous seven and the current eleven classes) are summarized in Chapter 3. The methodology used for the fragility analysis was discussed in depth in Volumes 1 and 2, a summary of which is presented in the following section.

1.3 FRAGILITY EVALUATION METHODOLOGY

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.

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 variation 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 to gain enough confidence.

CHAPTER 2
FRAGILITY ANALYSIS

2.1 INTRODUCTION

The data evaluation and fragility analysis methodology discussed in Chapter 1 was used to determine the fragility levels of eleven (11) additional equipment classes. The data base test results for each equipment is discussed and a summary of the test data is included. For many equipment models, the test reports provide only the qualification level. Subsequent to the study of these test reports, the results were discussed with the manufacturers and test engineers to gain more knowledge about the failure modes and the corresponding fragility levels. Since the test data included for each equipment class contain both qualification and fragility level results, a direct application of the statistical approach on these data will not provide realistic fragility values. Therefore, the fragility level of each specimen has been estimated from the available test data. The highest qualification level has been increased by 10%-30% to estimate the corresponding fragility level depending on performance of the specimen during the high level test runs. On the other hand, in some test programs, the specimens were modified as a result of failures observed earlier. However, the earlier test data were not available for this program. In addition, for some specimens, only the failure level data and not any qualification data were available. For the above two cases, the test data have been judgmentally reduced by 10%-20% to estimate fragility levels. Ultimately, a set of fragility level data have been estimated from the available test data and used as input for the statistical analysis which provides the median fragility level associated with the uncertainties. The coefficient of variation due to randomness, β_r, has been estimated as 0.1 based on past analyses [3,5] and that due to uncertainties, β_u, has been calculated from the total variation, β_c. The HCLPF value is computed from these fragility parameters as discussed in Chapter 1.

Unless otherwise mentioned, the above methodology has been used to obtain the fragility results for the eleven (11) equipment classes discussed in this chapter. More importance has been given to determining the ASA fragility values compared to the ZPA's. The coefficients of variation obtained for the ASA's have also been used in most cases to estimate those for the ZPA's, especially if the ZPA data have been considered insufficient for a statistical analysis. A description of the data base, the test data, the estimated fragility level input data and the fragility results are separately presented for each equipment class in the following sections.

2.2 TRANSMITTERS

Transmitters are used to monitor fluid pressure. The data base consists of results of twenty-four (24) test programs conducted on products of seven (7) manufacturers in the period 1971-1983. The BNL data base includes a wider variety of transmitters than what were considered in the EPRI/ANCO report [15]. The early vintage transmitters indicated accuracy problems during seismic testing and the diaphragm material was improved to correct the situation. Multiple specimens were tested under some of the test programs. The test data obtained from the data base test programs are listed in Table 2.1. The fragility level input data have been estimated from the test data as discussed in Section 2.1

Table 2-1
TRANSMITTERS

Test Data

ZPA	ASA @ 2% in "g"
3.2, 4.2, 8.0, 7.0, 6.0, 9.0, 5.0, 3.0, 3.0, 4.0	17.0, 11.0, 15.0, 13.0, 15.0, 15.0, 13.0, 15.0, 11.0, 11.0, 11.0, 11.0, 20.0, 11.0, 12.0, 14.0, 11.0, 11.0, 14.0, 15.0, 18.0, 16.0, 14.0, 18.0, 14.0, 13.0, 14.0

Estimated Fragility Level Input Data

ZPA	ASA @ 2% in "g"
3.5, 4.5, 9.0, 8.0, 6.5, 9.0, 4.5, 2.6, 2.7, 4.0	20.0, 13.0, 17.0, 15.0, 17.0, 17.0, 15.0, 17.0, 9.0, 13.0, 10.0, 9.0, 20.0, 13.0, 10.0, 15.0, 13.0, 13.0, 15.0, 17.0, 19.0, 18.0, 15.0, 15.0, 15.0, 15.0, 16.0

Fragility Results

	ZPA	ASA @ 2%
Median	4.9g	14.5g
β_u	0.30	0.20
β_r	0.10	0.10
HCLPF	2.5g	8.9g

above and are listed in Table 2.1. The fragility parameters have been computed from the estimated fragility level input data and are also shown in Table 2-1. The median and the HCLPF ASA values are 14.5g and 8.9g, respectively. For the ZPA input data, the computed uncertainty coefficient is very high due to presence of a few high level data. Therefore, the coefficient has been reduced to 0.30 to determine the HCLPF value of 2.5g.

2.3 INDICATORS

Indicators are panel-mounted instruments and provide a calibration check for accuracy. The data base consists of results of six (6) test programs for specimens supplied by four (4) electrical manufacturers. The test programs were conducted in the period 1975-1983 following the recommendations of IEEE Std 344-1975. The capacity levels obtained in the test programs are listed in Table 2-2. Indicators perform well up to a relatively high vibration level. At high levels, the specimens indicated shifts in accuracy. Accordingly, many indicators were redesigned, for example, to provide higher restoring torque. The set point problem was enhanced by modifying the coil.

Available test data, fragility level input data and the fragility analysis results are provided in Table 2.2. The median and the HCLPF ASA values are estimated as 16.3g and 9.0g, respectively. Since the ZPA input data base is insufficient for a statistical analysis, the ZPA fragility parameters have been estimated.

2.4 SWITCHES

Switches are usually panel-mounted electrical instruments and operate by changing state on demand. The data base consists of results from forty (40) seismic test programs on specimens supplied by fourteen (14) manufacturers. The test programs were conducted in the period 1975-1982 and the test data are listed in Table 2-3. Chatter is the usual mode of failure. For several models the springs were modified to avoid chatter at low vibration levels. Connection problems and pressure losses were also observed with liquid control switches. A change in the electrical circuit was sometimes used to avoid unacceptable chatter. Switches using mercury as a means of sensing and actuation were not included in the data base.

The test data, estimated fragility level input data and the fragility results are presented in Table 2-3. The median and the HCLPF ASA values are 10.7g and 4.7g, respectively. The ZPA fragility results are calculated by using the same β_u.

2.5 TRANSFORMERS

Transformers with 45-1500 KVA ratings are included in the data base. These transformers are housed in sheet metal enclosures and mounted directly on the ground or floor. Results of seven (7) test programs were reviewed to prepare the data base and are included in Table 2-4. The tests were conducted in the period 1975-83 and on specimens produced by seven (7) manufacturers. Structural failure of the transformer core/coil and the members supporting the coil was observed and, subsequently, the coil supports were redesigned for some specimens.

Table 2-2
INDICATORS

Test Data

ZPA in "g"	ASA @ 2% in "g"
4.5, 4.7, 5.5	12.0, 16.0, 14.0, 10.0, 20.0, 20.0

Estimated Fragility Level Input Data

ZPA in "g"	ASA @ 2% in "g"
5.0, 5.2, 6.2	13.2, 17.6, 15.4, 11.0, 22.0, 22.0

Fragility Results

	ZPA	ASA @ 2%
Median	5.4g	16.3g
β_u	0.26	0.26
β_r	0.10	0.10
HCLPF	3.0g	9.0g

Table 2-3
SWITCHES

Test Data

ZPA	ASA @ 2% in "g"
5.0, 5.0, 1.5, 4.0, 4.0, 5.0, 5.0, 5.0, 5.0, 5.0, 5.0, 5.0	14.0, 12.0, 9.0, 7.0, 9.0, 10.0, 11.0, 18.0, 12.0, 13.0, 5.0, 16.0, 14.0, 14.0, 14.0, 14.0, 7.0, 7.0, 7.0, 6.0, 20.0, 20.0, 11.0, 13.0, 10.0, 10.0, 10.0, 9.0, 8.0, 14.0, 14.0, 12.0, 12.0, 5.0, 5.0, 6.0, 6.0, 6.0, 6.0, 14.0, 12.0, 13.0, 5.0, 12.0

Estimated Fragility Level Input Data

ZPA in "g"	ASA @ 2% in "g"
5.5, 5.5, 2.5, 4.4, 4.4, 5.5, 5.5, 5.5, 5.5, 5.5, 5.5, 5.5	15.4, 13.2, 10.0, 5.6, 10.0, 11.0, 12.1, 19,0, 13.2, 14.3, 5.0, 17.6, 15.4, 15.4, 15.4, 15.4, 7.7, 7.7, 7.7, 5.0, 20.0, 20.0, 11.0, 13.0, 11.0, 11.0, 11.0, 10.0, 8.8, 15.4, 15.4, 13.2, 13.2, 6.0, 6.0, 7.0, 6.6, 6.6, 6.6, 15.4, 10.0, 14.3, 6.0, 13.2

Fragility Results

	ZPA	ASA @ 2%
Median	5.0g	10.7g
β_u	0.38	0.38
β_r	0.10	0.10
HCLPF	2.3g	4.7g

Table 2-4
TRANSFORMERS

Test Data

ZPA in "g"	ASA @ 2% in "g"
3.0, 3.2, 1.9, 2.0, 2.5, 3.2	10.0, 8.0, 3.0, 5.0, 6.0, 6.0, 6.0

Estimated Fragility Level Input Data

ZPA in "g"	ASA @ 2% in "g"
3.0, 3.2, 2.5, 2.4, 3.0, 3.8	10.0, 8.0, 4.0, 6.0, 7.2, 6.0, 7.2

Fragility Results

	ZPA	ASA @ 2%
Median	3.0g	6.8g
β_u	0.27	0.27
β_r	0.10	0.10
HCLPF	1.6g	3.7g

Electrical flashes and "burnout" due to contact between the bus bar/coil and the enclosure sheet metal were observed in early vintage transformers. Subsequent models maintain sufficient air gap (e.g., 2 inches) around the bus bar to avoid electrical burnout during vibration. Heavy transformers required special structural stiffening on top to avoid structural failure of the supports and enclosures.

The test data, estimated fragility level input data and the fragility results are presented in Table 2-4. Transformers with lower KVA ratings seem to have slightly larger seismic capabilities. The median and the HCLPF ASA values are 6.8g and 3.7g, respectively. The same β_u is used to compute the ZPA HCLPF.

2.6 BOP I&C PANELS

The BOP I&C panels are self-standing enclosures and contain numerous devices required for monitoring, control and operation of the plant. The data base consists of results of fifteen (15) test programs conducted on products of seven (7) manufacturers in the period 1978-1985. The vibration levels achieved during the test programs are listed in Table 2-5. Damage of the panel structure was observed for several specimens. Sliding of poorly mounted internal components was observed in early vintage panels.

The test data, estimated fragility level input data and the fragility results are presented in Table 2-5. The median and the HCLPF ASA values are 6.3g and 3.3g, respectively. The same variances are used to compute the ZPA HCLPF. For applicability of these results, the relays in the panels should be separately evaluated, as with other equipment classes. The NSSS I&C panels have been discussed in Volume 3 of this NUREG [5].

2.7 MISCELLANEOUS INSTRUMENTS

Miscellaneous instruments such as bistables, converters, sensors and signal monitors are usually mounted on instrumentation panels and racks. Results of eleven (11) test programs were reviewed to prepare the data base shown in Table 2-6. The test specimens were supplied by six (6) manufacturers and produced in the period 1976-1986.

The test data, estimated fragility level input data and the fragility results are presented in Table 2-6. The median fragility levels are estimated as 14.5g ASA and 4.5g ZPA. Since the instruments could be of various types and the data base is comparatively limited, the uncertainty factor is judged to be as high as 0.3. The resulting HCLPF values are calculated as 7.5g ASA and 2.3g ZPA.

2.8 BATTERIES ON RACKS

A large number of battery cells are grouped together to provide emergency power in case of loss of other power sources. The data base consists of test data for a large number of lead-calcium batteries mounted on racks manufactured by three leading companies. Among all nuclear plant components, probably the equipment that has been most extensively studied is batteries, especially because of aging concerns. Sandia National Laboratories [8-13] conducted an extensive

Table 2-5
BOP I&C Panels

Test Data

ZPA in "g"	ASA @ 2% in "g"
4.0, 5.5, 3.3, 4.6, 2.0, 1.2, 1.4, 3.8, 4.7, 1.3, 1.0, 2.8	9.0, 9.0, 6.0, 9.0, 5.0, 4.0, 4.0, 7.0, 7.0, 10.0, 3.0, 3.0, 4.0, 2.0*, 6.0

Estimated Fragility Level Input Data

ZPA in "g"	ASA @ 2% in "g"
4.0, 5.5, 3.3, 4.6, 2.4, 1.5, 1.6, 3.8, 4.7, 1.7, 1.3, 2.8	9.0, 9.0, 6.0, 9.0, 6.0, 5.0, 5.0, 7.0, 7.0, 10.0, 4.0, 4.0, 5.0, *, 6.0

* The test data of 2.0g ASA has been considered to be substantially lower than the fragility level and not used for estimation of the fragility results.

Fragility Results

	ZPA	ASA @ 2%
Median	2.4g	6.3g
β_u	0.30	0.30
β_r	0.10	0.10
HCLPF	1.3g	3.3g

Table 2-6
MISCELLANEOUS INSTRUMENTS
BISTABLES, CONVERTERS, SENSORS AND SIGNAL MONITORS

Test Data

ZPA in "g"	ASA @ 2% in "g"
3.0, 4.2, 3.4, 3.4, 3.4, 5.0, 5.0	11.0, 14.0, 15.0, 15.0, 15.0, 11.0, 10.0, 10.0, 10.0, 20.0, 14.0

Estimated Fragility Level Input Data

ZPA in "g"	ASA @ 2% in "g"
3.3, 4.6, 3.7, 3.7, 3.7, 5.0, 5.5	12.1, 14.4, 16.5, 16.5, 16.5, 12.1, 10.0, 11.0, 11.0, 21.0, 15.4

Fragility Results

	ZPA	ASA @ 2%
Median	4.5g	14.5g
β_u	0.30	0.30
β_r	0.10	0.10
HCLPF	2.3g	7.5g

test program with a large number of battery cells - new, naturally aged (for 10-25years) and artificially aged (for 12 years). Recently, Idaho National Engineering Laboratory has also tested naturally aged (for 13½ years) batteries from one manufacturer [14]. In addition, the data base consists of test results developed by the industry as part of their qualification programs.

The data base indicates that aging related degradation of the batteries can reduce their seismic capacities. However, the aging effects on different models in the data base test programs varied substantially. The observed failure modes are discharge to (or less than) an unacceptable level of 80% and cracking of cell jars. Sandia has arrived at the following conclusions regarding the aging effects:

1. Embrittlement and/or cracking of positive buses are aided by corrosion along large grain boundaries in all cell types tested. Fine grained material remains ductile.

2. Formation of brittle bus material is a significant aging effect which can lead to abrupt failure during a seismic event or reduced capacity after the event.

3. Excessive sulphation leading to plate hardening and expansion is also an aging effect of significance, but of less importance than the formation of brittle materials. Sulphation reduces post-seismic discharge capacity and increases self-discharge.

It appears that the aging effect on the seismic capacity of batteries depends to some extent on the maintenance program.

Some of the test results obtained from a study of the above test programs, as well as the EPRI/ANCO data base [15], are listed in Table 2-7. For some of the test runs, the horizontal input level is substantially lower than the vertical input level. For these cases, effective input levels have been judged to be closer to the vertical level and are listed in the test data table. Electrical discharge was observed for a small number of specimens in the data base. Discharge of a few batteries in a typical set up of a large number of such batteries may not be unacceptable for their intended use. The test data have been evaluated based on this judgment. Based on the test data, the fragility level input data have been estimated and fragility results have been calculated as shown in Table 2-7. The median values are 7.3g ASA and 3.7g ZPA. The corresponding HCLPF values are 4.4g and 2.2g. It is judged that the HCLPF values are reasonable but the median values are conservative and could be slightly higher.

2.9 BATTERY CHARGERS

Battery chargers are used to maintain the charge in the battery cells so that the batteries can provide power in case of emergency. The data base consists of results from four (4) test programs on products of three (3) manufacturers. The tests were performed in the period 1978-82. In addition to the above data base, the EPRI/ANCO data base was reviewed to estimate the fragility parameters.

Table 2-7
BATTERIES ON RACKS

Test Data

ZPA in "g"	ASA @ 2% in "g"
4.2, 2.0, 3.0, 2.2, 2.6, 2.8, 2.0, 2.0, 4.2, 2.2, 5.5, 5.2, 5.5, 2.7, 6.0, 5.0, 3.3, 3.0, 3.2, 5.2, 2.1, 4.0, 5.0, 5.0	7.5, 5.0, 7.5, 4.7, 4.7, 4.9, 3.9, 4.0, 7.2, 8.2, 9.2, 8.2, 9.0, 7.2, 10.2, 8.3, 5.5, 5.0, 7.5, 8.8, 5.3, 6.0, 11.0, 11.0

Estimated Fragility Level Input Data

ZPA in "g"	ASA @ 2% in "g"
4.2, 2.5, 3.5, 2.5, 3.0, 3.3, 2.5, 2.5, 4.2, 2.2, 6.0, 5.8, 5.0, 3.0, 6.6, 5.0, 3.3, 3.0, 3.7, 5.0, 2.8, 4.7, 4.0, 4.0	7.5, 6.0, 8.5, 5.5, 6.0, 6.2, 5.1, 5.2, 7.2, 8.2, 10.0, 9.0, 8.0, 8.0, 11.0, 8.3, 5.5, 5.0, 8.5, 8.5, 7.0, 7.0, 9.0, 9.0

Fragility Results

	ZPA	ASA @ 2%
Median	3.7g	7.3g
β_U	0.21	0.21
β_R	0.10	0.10
HCLPF	2.2g	4.4g

The test data, estimated fragility level input data and the fragility results are presented in Table 2-8. The median values are 5.0g ASA and 2.4g ZPA and the HCLPF values are 2.9g ASA and 1.4g ZPA.

2.10 INVERTERS

Inverters are used to convert direct current from batteries to alternating current for operation and control of the plant in the event of loss of other power sources. The data base consists of results of three (3) test programs conducted on products of three (3) manufacturers in the period 1975-1979. In two test programs, the specimens were supported only at the base; whereas, both horizontal and vertical supports were used in the third test program. Structural damage was observed requiring modification of the base.

In addition to the above data, the information presented in the ANCO report [15] was also evaluated to estimate the fragility levels. The test data, estimated fragility level input data and the fragility results are presented in Table 2-9. The median values are 5.6g ASA and 3.0g ZPA. The HCLPF values are 3.2g ASA and 1.7g ZPA.

2.11 ELECTRICAL PENETRATION ASSEMBLIES (EPA's)

EPA's are used to route electrical wiring through penetrations without losing leak tightness. The data base consists of results from four (4) test programs conducted on specimens from three (3) manufacturers. The EPRI/ANCO data base [15] was also studied. Usually, EPA's perform well at reasonable seismic levels. However, at higher levels, they exhibit loss of header pressure and structural damage. The junction boxes cantilevering from the header plate can also suffer structural damage. A substantial variation of the capacity levels was observed among various products.

A median fragility ASA value of 12.0g was estimated from a study of the test results. By use of an uncertainty coefficient of 0.3 and a randomness factor of 0.1, the corresponding HCLPF value is computed as 6.2g. The test data, estimated fragility levels and the fragility results are shown in Table 2-10.

2.12 VALVE OPERATORS

Active valves are automatically or remotely controlled (i.e., opened or closed) by use of operators. The operators included in the data base are motor and solenoid which are controlled by electrical power. Limit or positioning switches are used to control the stroke. The operator is typically mounted on top of the valve which it operates. The valve, in turn, is mounted on the pipe. The data base consists of results from six (6) test programs on motor operators and solenoid operators. Typically, the operators are seismically rigid and were tested with static load and sine dwell/beat motion, as well as random dynamic loads sometimes in integral assemblies including the valves and other appurtenances. The test programs were conducted on products from four (4) manufacturers in the period 1975-83. In addition, a qualitative description of the performance of other products was obtained through discussions with test/qualification engineers. The ANCO data base [15] was also evaluated.

Table 2-8
BATTERY CHARGERS

Test Data

ZPA in "g"	ASA @ 2% in "g"
1.5, 3.0, 3.0, 2.5, 1.5, 3.0, 1.9, 1.6, 1.9, 3.0, 1.4, 2.5, 1.5	4.0, 5.5, 6.0, 5.5, 3.0, 4.2, 5.5, 4.5, 5.5, 5.5, 2.8, 5.5, 3.0

Estimated Fragility Level Input Data

ZPA in "g"	ASA @ 2% in "g"
1.7, 3.3, 3.3, 2.7, 2.0, 3.0, 2.2, 2.0, 1.9, 3.0, 1.8, 2.8, 1.8	4.4, 6.0, 6.6, 6.0, 3.6, 4.2, 6.0, 6.0, 5.5, 5.5, 3.4, 6.0, 3.6

Fragility Results

	ZPA	ASA @ 2%
Median	2.4g	5.0g
β_u	0.23	0.23
β_r	0.10	0.10
HCLPF	1.4g	2.9g

Table 2-9
INVERTERS

Test Data

ZPA in "g"	ASA @ 2% in "g"
2.0, 1.5, 4.0	5.0, 5.0, 3.0, 7.0, 5.0, 6.0, 5.0, 6.0

Estimated Fragility Level Input Data

ZPA in "g"	ASA @ 2% in "g"
2.0, 2.0, 4.8	5.0, 6.0, 4.0, 8.4, 5.0, 6.0, 5.0, 6.0

Fragility Results

	ZPA	ASA @ 2%
Median	3.0g	5.6g
β_u	0.23	0.23
β_r	0.10	0.10
HCLPF	1.7g	3.2g

Table 2-10
ELECTRICAL PENETRATION ASSEMBLIES

Test Data ASA @ 2% in "g"	Estimated Fragility Levels ASA @ 2% in "g"
15.0	16.0
15.0	16.0
15.0	15.0
10.0	10.0
7.7	7.7

Fragility Results

	ASA @ 2%
Median	12.0g
β_u	0.30
β_r	0.10
HCLPF	6.2g

The products of a major motor operator supplier withstood a high seismic level provided certain modifications are made (e.g., installation of a seismic bracket). There was indication of extruding of gaskets and loosening of bolts at higher acceleration levels. One major user reported low seismic capacity levels for another product used in earlier plants (pre-1972).

As a result of evaluation of the available information, the HCLPF fragility level is estimated as 9.0g ASA provided seismic brackets or similar modifications recommended by the manufacturer are implemented. Assuming an uncertainty coefficient of 0.4 and a randomness factor of 0.1, the corresponding median is 20.5g which is judged to be a conservative but reasonable value. The above fragility levels are considered high and the overall failure of the valve assembly may occur at a lower level due to other reasons, such as, structural deformation of the yoke and/or the pipe lines supporting the valve. For smooth flow of the lubricant, the motor operators are recommended to be installed in the vertically upright or slightly slanted position.

CHAPTER 3
SUMMARY AND CONCLUSIONS

3.1 INTRODUCTION

A summary of the fragility results for all equipment classes studied as part of the Component Fragility Program is provided in this chapter for convenience. However, the users are directed to the specific sections of the reference reports for an understanding of the respective data bases, such as, anchorage, natural frequency and applicability of the results to a particular equipment item. The lessons learned in conducting this program and in interacting with other similar programs (e.g., USI A-46, IPEEE) are discussed in the conclusion section of this chapter.

3.2 SUMMARY OF FRAGILITY RESULTS

The fragility results of eighteen (18) equipment classes are summarized in Table 3-1. The corresponding failure modes are also identified. The following is a complete list of the equipment classes:

1. Motor Control Center (MCC)
2. Switchboard
3. Panelboard
4. DC Power Supply
5. Low Voltage Switchgear
6. Medium Voltage Switchgear
7. NSSS I&C Panels
8. Transmitters
9. Indicators
10. Switches
11. Transformers
12. BOP I&C Panels
13. Miscellaneous Control Instruments
    (Bistables, Converters, Sensors and Signal Monitors)
14. Batteries on Racks
15. Battery chargers
16. Inverters
17. Electrical Penetration Assemblies (EPA's)
18. Valve Operators (Motor and Solenoid)

3.2.1 Limitations

The fragility results presented above were based on evaluation of test data from selected test programs. Therefore, the applicability of these probabilistic results is limited to the equipment types and models that are represented by the data base. The limitations of the data base test specimens have been separately discussed for each equipment class. The users of the fragility results presented in this report should confirm that their equipment pieces belong to these so-called "generic" equipment classes (e.g., an MCC should be stiffly anchored).

Table 3-1
SUMMARY OF FRAGILITY RESULTS[1,2]

Equipment	Failure Mode	Acceleration	Median in "g"	β_u	β_r	HCLPF in "g"
MCC	Contact chatter	ZPA ASA	1.3 3.0	0.20 0.20[3]	0.10 0.06	0.8 2.0[3]
	Change of State	ZPA ASA	1.7 4.0	0.17 0.20	0.15 0.18	1.0 2.1
	Structural	ZPA ASA	2.5 5.0	0.20 0.20	0.06 0.06	1.6 3.2
Switchboard	Breaker	ZPA ASA	3.5 7.5	0.30 0.30	0.10 0.10	1.8 3.9
Panelboard	Breaker	ZPA ASA	2.5 6.6	0.45 0.37	0.10 0.07	1.0 3.2
DC Power Supply	Accuracy	ZPA ASA	3.6 9.0	0.15 0.15	0.05 0.05	2.6 6.5
Low Voltage Switchgear[4]	Breaker	ZPA ASA	1.5 6.6	0.30 0.30	0.10 0.10	0.8 3.4
	Structural	ZPA ASA	3.5 8.5	0.15 0.15	0.06 0.06	2.5 6.0
Medium Voltage Switchgear[4]	Internal Damage	ASA	4.0	0.10	0.10	2.9
	Breaker	ZPA ASA	2.0 6.3	0.10 0.10	0.10 0.10	1.4 4.5
	Structural	ZPA ASA	3.5 8.5	0.15 0.15	0.06 0.06	2.5 6.0
NSSS I&C Panels[5]	Electrical	ASA	6.8	0.30	0.10	3.5
	Structural	ASA	9.0	0.30	0.10	4.7
Transmitters[5]	Accuracy	ZPA ASA	4.9 14.5	0.30 0.20	0.10 0.10	2.5 8.9
Indicators	Accuracy	ZPA ASA	5.4 16.3	0.26 0.26	0.10 0.10	3.0 9.0
Switches[6]	Chatter	ZPA ASA	5.0 10.7	0.38 0.38	0.10 0.10	2.3 4.7
Transformers	Coil	ZPA ASA	3.0 6.8	0.27 0.27	0.10 0.10	1.6 3.7
BOP I&C Panels	Electrical	ZPA ASA	2.4 6.3	0.30 0.30	0.10 0.10	1.3 3.3
Misc. Instruments	Accuracy	ZPA ASA	4.5 14.5	0.30 0.30	0.10 0.10	2.3 7.5

Table 3-1 (continued)
SUMMARY OF FRAGILITY RESULTS[1,2]

Equipment	Failure Mode	Acceleration	Median in "g"	β_u	β_r	HCLPF in "g"
Batteries on Racks[7]	Discharge	ZPA ASA	3.7 7.3	0.21 0.21	0.10 0.10	2.2 4.4
Battery Chargers	Functional	ZPA ASA	2.4 5.0	0.23 0.23	0.10 0.10	1.4 2.9
Inverters	Functional	ZPA ASA	3.0 5.6	0.23 0.23	0.10 0.10	1.7 3.2
EPA's	Pressure Loss	ASA	12.0	0.30	0.10	6.2
Valve Operators[8]	Functional	ASA	20.5	0.40	0.10	9.0

[1] Acceleration levels are local i.e., they are measured at the base of the equipment. Legend: ZPA - zero period acceleration, ASA - average spectral acceleration at a damping value of 2% (averaged over 4-16Hz).

[2] The equipment type should be enveloped by the data base as described in the text for each equipment class. The most common limitations are as follows:

a) The equipment should be Class 1E or Seismic Category I and manufactured after 1975, unless otherwise mentioned.
b) All relays should be separately evaluated, i.e., the fragility levels presented in this table do not consider the effect of relay malfunction such as chatter.
c) All equipment should be adequately anchored.

[3] Since publication of the MCC Contact Chatter HCLPF value in Reference 3, the data have been further investigated and the results have been revised as shown in this table.

[4] The breakers should be restrained from relative motion and the switchgear should be in the operating (i.e., connected) position.

[5] The data base includes panels and transmitters manufactured after 1971.

[6] Switches operated by mercury are not included in the data base.

[7] The fragility results apply only to lead-calcium batteries not more than 10-12 years old. Electrical discharge of a small number of batteries in a large set up has been considered acceptable.

[8] Includes motor and solenoid operators modified with seismic brackets.

One of the important limitations for all equipment classes is the vintage of equipment. Most data base test programs were conducted on products manufactured in the period 1975-1985. Also, the data base test specimens were categorized as Class 1E or Seismic Category I. Therefore, the question is whether the fragility results can be applied to the "non-class 1E" or "non-Seismic Category I" equipment manufactured earlier. As discussed in earlier reports [3,5] with specific details, there are indications that many equipment types (mainly electrical) supplied to nuclear plants were modified in the late 1960's and early 1970's to achieve higher seismic resistance so that the capacities of earlier equipment are expected to be lower than that demonstrated by the data base equipment. For example, EPRI/ANCO reduced the capacity level of switchgear from 3.0g to 1.8g (spectral acceleration at a damping value of 5%) to accommodate earlier test data from one manufacturer [15]. In spite of the reduction, the equipment would require modifications even for the 1.8g level (e.g. side-to-side restraint for low voltage switchgear and potential transformer restraint were not apparently provided in earlier vintage switchgear).

Therefore, it is concluded that further research would be desired to determine the reduction of the fragility levels published in this report that will be necessary for application of the results to earlier vintage equipment (e.g., pre-1975 for most equipment classes). However, it is recognized that there may be an immediate need to estimate seismic fragility levels for the earlier equipment. Therefore, for interim purposes, the following steps are recommended for evaluation of earlier vintage equipment:

1. Confirm adequate anchorage.
2. Confirm relay functionality (by model number).
3. Apply a reduction factor to the median and HCLPF values presented in Table 3-1. Table 3-2 contains a list of suggested multiplication factors for different failure modes of each equipment*. These factors are based on knowledge gained from the review of an enormous amount of information gathered for conducting the Component Fragility Program (e.g., modification lists/drawings, early single axis test results, interviews with design/test engineers who were involved in equipment design/test through the early 1970's, description of damage of earlier equipment due to initial vibration tests). However, these numbers are results of judgment and may be refined with further research.

3.3 OTHER RELATED PROGRAMS

This report is the concluding one being published under the scope of the Component Fragility Research Program at BNL. The major component that has not been adequately addressed under this program is the relay which requires additional information for evaluation of its acceptability. A test program was conducted on relays in 1989 [6]; further testing will be performed in 1991 under the scope of a new relay test program. A major portion of the tests will be devoted to determine the effect of relay chatter on circuit breakers, lockout

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* The early vintage equipment has been considered in this study as a separate "statistical population."

Table 3-2
MULTIPLICATION FACTORS FOR EARLY VINTAGE EQUIPMENT[1,2]

Equipment	Failure Mode	Multiplication Factor	
		for Median	for HCLPF
MCC	Contact Chatter Change of State Structural	0.95 0.95 0.75	0.90 0.95 0.65
Switchboard	Breaker	0.75	0.70
Panelboard	Breaker	0.85	0.80
DC Power Supply	Accuracy	0.85	0.80
Low Voltage Switchgear	Breaker Structural	0.75 0.75	0.65 0.65
Medium Voltage Switchgear	Internal Damage Breaker Structural	0.75 0.75 0.75	0.65 0.65 0.65
NSSS I&C Panels	Electrical Structural	0.75 0.75	0.70 0.70
Transmitters	Accuracy	0.75	0.65
Indicators	Accuracy	0.75	0.65
Switches	Chatter	0.70	0.60
Transformers	Coil	0.75	0.60
BOP I&C Panels	Electrical	0.75	0.65
Misc. Instruments	Accuracy	0.70	0.60
Batteries on Racks	Discharge	0.90	0.90
Battery Chargers	Functional	0.80	0.75
Inverters	Functional	0.75	0.70
EPA's	Pressure Loss	0.75	0.65
Valve Operators	Functional	0.70	0.60

[1] The respective median and HCLPF values shown in Table 3-1 should be multiplied by these factors to obtain the fragility results for early vintage (i.e., pre-1975) equipment. β_r values are the same. The β_u values can be computed from the median, HCLPF and β_r values.

[2] The equipment type should be comparable to that in the data base as summarized by the footnotes for Table 3-1, except that the equipment can be manufactured prior to 1975 for application of the multiplication factors.

relays and other devices connected in an integral circuit. Electrical pulses will be generated to study the effect of chatter of various durations and combinations. Subsequently, vibration testing will be performed by use of the chatter tolerance characteristics that will be learned from the electrical pulse tests. The results will be published in FY 1992.

3.4 CONCLUSIONS

The seismic fragilities of equipment evaluated and expressed in probabilistic terms as part of the Component Fragility Program are based on test data. Sometimes judgments have been used in processing the data; but the basic information has always been derived from the test results. Therefore, the use of these fragility estimates in the IPEEE Program is expected to provide a meaningful, realistic and reliable measure of the seismic capacities and vulnerabilities of equipment in nuclear plants. It is expected that the users will exercise caution regarding the applicability of the results presented in this report to their equipment and supplement the results with plant-specific equipment fragility data, if available. The Component Fragility Program was initiated in FY 1985. During the period of conducting this program, the Seismic Qualification Utility Group and the Electric Power Research Institute also performed the basic technical work for the USI A-46 Program to determine generically the seismic capacities of various power plant components. Through cooperative agreements and other means there has been a great deal of interaction between these two programs (i.e., NRC/BNL and SQUG/EPRI) resulting in an increase in the confidence levels of the results for both programs.

Another aspect of the above SQUG/EPRI Program is the use of an earthquake experience data base which comprises a history of performance of many equipment pieces under several strong earthquake events in the last decade or so. Since these data are based on real earthquake histories, the resulting information is expected to depict more realistically the performance of equipment. However, the necessary technical information (e.g., response spectra and equipment performance) may not be as controlled as in a laboratory test. In addition, the nature of the vibratory motion experienced by an equipment in a real earthquake depends on the particular event, seismological and geological conditions and the stiffness of the supporting structure. In a typical laboratory test, effects of such parameters are enveloped by use of broad-band spectra or multiple narrow band spectra. Therefore, in order to reliably tap the enormous potential for the earthquake-based experience data, it is prudent (and therefore recommended) that research be undertaken to correlate some sample results of the earthquake experience data base with that from testing. This will increase the reliability of the earthquake data base. At the same time, both the earthquake experience data base and the test data base (e.g., EPRI/ANCO) can be combined to a uniform common data base (after applying a conversion factor for spectral levels) resulting in a much broader data base that can be used for seismic evaluation of equipment.

The knowledge gained through all these programs will increase our understanding in selecting the most appropriate and logical, cost effective and reliable approach for seismic verification and evaluation of equipment in existing power plants, as well as in future advanced reactors.

CHAPTER 4
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Fragility estimates of seven equipment classes were published in earlier reports. This report presents fragility analysis results for eleven additional equipment categories. The fragility levels are expressed in probabilistic terms. For users' convenience, the concluding report includes a summary of fragility results of all eighteen equipment classes. A set of conversion factors based on judgment is recommended for use of the information for early vintage equipment. The knowledge gained in conducting the Component Fragility Program and similar other programs is expected to provide a new direction for seismic verification and qualification of equipment.

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