# Component Fragility Data Base for Reliability and Probability Studies

**K. Bandyopadhyay, C. Hofmayer, M. Kassir, S. Pepper**
*Brookhaven National Laboratory, Upton, NY USA*

## INTRODUCTION

Safety-related equipment in a nuclear plant plays a vital role in its proper operation and control, and failure of such equipment due to an earthquake may pose a risk to the safe operation of the plant. Therefore, in order to assess the overall reliability of a plant, the reliability of performance of the equipment should be studied first.

The success of a reliability or a probability study depends to a great extent on the data base. To meet this demand, Brookhaven National Laboratory (BNL), under a sponsorship of the United States Nuclear Regulatory Commission (USNRC), has formed a test data base relating the seismic capacity of equipment specimens to the earthquake levels. Subsequently, the test data have been analyzed for use in reliability and probability studies. This paper describes the data base and discusses the analysis methods. The final results that can be directly used in plant reliability and probability studies are also presented in this paper.

## DATA BASE

In the last fifteen years, numerous seismic tests were performed in the USA on various equipment for the purposes of qualification and development of these products. The results from these tests provide a spectrum of characteristics of the equipment classes manufactured in this time frame and supplied to the nuclear power plants. A large sample of these test data has been collected from various sources and constitutes the equipment data base at BNL. Typically, the data relating an equipment malfunction to the corresponding earthquake level are of special interest.

The equipment classes in the data base have been selected according to their importance in a nuclear plant. To date, the equipment classes included in the data base are as follows:

1. Motor Control Center
2. Switchboard
3. Panelboard
4. Power Supply
5. Switchgear
   a. Medium Voltage
   b. Low Voltage
6. NSSS Instrumentation Panels
7. Local Instruments
   a. Transmitter
   b. Switch
   c. Indicator
8. Relay
9. Other electrical devices

---

* This work was performed under the auspices of the U.S. Nuclear Regulatory Commission

The tests were performed since the mid-1970's on specimens representing the products manufactured by the major suppliers in the USA. Test data of representative specimens of a particular equipment class constitute the data base of that "generic" equipment class.

## DATA EVALUATION METHODOLOGY

The input vibration level used for testing is available in a typical test report, and also in the BNL data base, in terms of a test response spectrum (TRS). The TRS data were obtained from multifrequency test inputs and usually do not provide frequency dependent response values. Since in their current forms, reliability and probability studies do not accept the fragility levels in terms of these TRS data and instead require a median acceleration value associated with the coefficients of variation or a high confidence value, a data reduction becomes necessary. To this end, an acceleration value is selected to represent the TRS data set. Thus, for an equipment class, the fragility level is represented by a number of single acceleration values corresponding to all the fragility test runs. These acceleration values are then statistically analyzed for determination of the probabilistic fragility level. The selection of an appropriate acceleration value and the method used for the statistical analysis are discussed in the following subsections.

### Single-Valued Accelerations Representing TRS

In representing a TRS data set with a single parameter, i.e., an acceleration value, the objective is to select that parameter which has the most influence on the fragility phenomenon. The following parameters have been considered for this purpose (Bandyopadhyay, 1986):

a. Zero Period Acceleration (ZPA)
b. Spectral Acceleration
c. Equivalent ZPA

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

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

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

It appears from the above discussion that one parameter may not be adequate to represent the TRS. Therefore, in the BNL study two parameters have been used: ZPA and ASA (Average Spectral Acceleration).

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

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

## Statistical Methods

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

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

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

The above fragility parameters, i.e., the median value along with the coefficients of variation, are computed by employing both the method of moments and the method of maximum likelihood. In the former method, only the fragility data are used as input; whereas, in the latter method both the fragility and the highest qualification data are used. A discussion on formulation of both methods is included in Appendix A of NUREG/CR-4659, Vol. 2 (Bandyopadhyay, 1987).

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

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

The HCLPF value is the single acceleration value that has been sought to describe the generic fragility level of the equipment category and, in this paper, is referred to as the "fragility descriptor."

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

## FRAGILITY RESULTS

The test data have been evaluated following the methodology discussed above. For example, the test data for three different failure modes of MCC as shown in Table 1 have been analyzed and the corresponding fragility results are presented in Table 2. Fragility evaluation results of switchboard, panelboard, power supply, I&C panels (NSSS), low voltage switchgear and medium voltage switchgear are also included in Table 2 for various electrical malfunctions.

## CONCLUSIONS

Fragility evaluation of local instruments and other equipment test data are continuing. These results will be presented in future publications.

## ACKNOWLEDGEMENTS

The authors wish to thank Dr. J. O'Brien of the USNRC for his support of the Component Fragility Program at BNL. The cooperation of the data source organizations are gratefully acknowledged for sharing their test data with BNL. The consulting services of Professors M. Shinozuka, H. Hwang and W. Tsai were crucial for the data analysis and are sincerely appreciated.

## REFERENCES

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

Bandyopadhyay, K.K., Hofmayer, C.H., Kassir, M.K. and Pepper, S.E. (1987), Seismic Fragility of Nuclear Power Plant Components (Phase II), NUREG/CR-4659, Vol. 2.

TABLE 1 - MCC Test Data

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

TABLE 1 - MCC Test Data (continued)

| Failure Mode | ZPA in "g" |  | ASA in "g" @ 2% Damping |  |
|---|---|---|---|---|
|  | Qualification | Fragility | Qualification | Fragility |
| Change of state of starter main contact | 1.0, 1.1, 1.1<br>1.2, 1.5, 1.5<br>1.6, 1.6, 1.8<br>1.8, 2.1, 2.1<br>2.1, 2.1, 2.2<br>2.4, 2.5 | 1.2, 1.3, 1.3<br>2.2, 2.4 | 2.0, 2.3, 3.0<br>3.0, 3.0, 3.1<br>3.2, 3.7, 3.7<br>3.7, 4.0, 5.6<br>5.6, 5.6, 5.8<br>7.5, 7.9 | 2.5, 3.4, 3.7<br>4.6, 5.0 |

TABLE 2 - Fragility Analysis Results[1]

| Equipment | Failure Mode | Indicator | Method[2] | Median in "g" | $\beta_u$ | $\beta_r$ | HCLPF in "g" |
|---|---|---|---|---|---|---|---|
| Motor Control Center | Contact chatter | ZPA | 1 | 1.3 | 0.18 | 0.10 | 0.8 |
|  |  |  | 2 | 1.3 | 0.24 | 0.09 | 0.8 |
|  |  |  | 3 | 1.3 | 0.20 | 0.10 | 0.8 |
|  |  | ASA @ 2 % | 1 | 2.9 | 0.25 | 0.06 | 1.8 |
|  |  |  | 2 | 3.1 | 0.31 | 0.06 | 1.7 |
|  |  |  | 3 | 3.0 | 0.27 | 0.06 | 1.7 |
|  | Change of state of starter auxiliary contact | ZPA | 1 | 1.5 | 0.07 | 0.16 | 1.0 |
|  |  |  | 2 | 1.9 | 0.26 | 0.14 | 1.0 |
|  |  |  | 3 | 1.7 | 0.17 | 0.15 | 1.0 |
|  |  | ASA @ 2% | 1 | 3.5 | 0.04 | 0.19 | 2.4 |
|  |  |  | 2 | 4.5 | 0.34 | 0.18 | 2.0 |
|  |  |  | 3 | 4.0 | 0.20 | 0.18 | 2.1 |
|  | Change of state of starter main contact | ZPA | 1 | 1.6 | 0.32 | 0.07* | 0.9 |
|  |  |  | 2 | 2.7 | 0.44 | 0.09* | 1.1 |
|  |  |  | 3 | 2.1 | 0.33 | 0.07 | 1.1 |
|  |  | ASA @ 2% | 1 | 3.7 | 0.27 | 0.05* | 2.2 |
|  |  |  | 2 | 7.0 | 0.53 | 0.11* | 2.4 |
|  |  |  | 3 | 5.4 | 0.42 | 0.08 | 2.4 |
| Switchboard | Breaker Trip | ZPA | 3 | 3.5* | 0.30* | 0.10* | 1.8 |
|  |  | ASA @ 2% | 3 | 7.5* | 0.30* | 0.10* | 3.9 |
| Panelboard | Breaker Trip | ZPA | 1 | 1.7 | 0.49 | 0.10 | 0.6 |
|  |  |  | 2 | 3.2 | 0.54 | 0.11 | 1.1 |
|  |  |  | 3 | 2.5 | 0.45 | 0.10 | 1.0 |
|  |  | ASA @ 2% | 1 | 4.5 | 0.16 | 0.03 | 3.3 |
|  |  |  | 2 | 8.7 | 0.51 | 0.10 | 3.2 |
|  |  |  | 3 | 6.6 | 0.37 | 0.07 | 3.2 |
| Power Supply | Output level variiation less than ± 2% and output continuity satisfied when monitored by meter. | ZPA | 3 | 4.6* | 0.13* | 0.03* | 3.5 |
|  |  | ASA @ 2% | 3 | 10.7* | 0.13* | 0.03* | 8.2 |

TABLE 2 - Fragility Analysis Results[1]
(continued)

| Equipment | Failure Mode | Indicator | Method[2] | Median in "g" | $\beta_u$ | $\beta_r$ | HCLPF in "g" |
|---|---|---|---|---|---|---|---|
|  | Output level variation less than ±10% and output continuity satisfied when monitored by meter | ZPA | 3 | 6.0* | 0.15* | 0.05* | 4.3 |
|  |  | ASA @ 2% | 3 | 13.1* | 0.15* | 0.05* | 9.4 |
|  | Output continuity monitored by oscillograph recorded and and duration of power loss not greater than 0.5ms | ZPA | 3 | 3.6* | 0.15* | 0.05* | 2.6 |
|  |  | ASA @ 2% | 3 | 9.0* | 0.15* | 0.05* | 6.5 |
| I&C Panels (NSSS) | Electrical discontinuity and trip | ASA @ 2% | 3 | 6.8* | 0.3* | 0.10* | 3.5 |
| Low Voltage Switchgear | Relay Chatter[3] | ZPA | 1 | 1.0 | 0.30* | 0.10* | 0.5 |
|  |  | ASA @ 2% | 1 | 1.9 | 0.30* | 0.10* | 1.0 |
|  | Breaker Malfunction[3] | ZPA | 1 | 1.5 | 0.30* | 0.10* | 0.8 |
|  |  | ASA @ 2% | 1 | 6.6 | 0.30* | 0.10* | 3.4 |
| Medium Voltage Switchgear | Relay Chatter[3] | ZPA | 1 | 0.6 | 0.44 | 0.10* | 0.2 |
|  |  | ASA @ 2% | 1 | 1.8 | 0.49 | 0.10* | 0.7 |
|  | Relay and Switch Change of State[3] | ZPA | 1 | 1.4 | 0.17 | 0.06 | 1.0 |
|  |  | ASA @ 2% | 1 | 3.9 | 0.11 | 0.08 | 2.9 |
|  | Internal Damage[4] | ASA @ 2% | 1 | 4.0* | 0.10* | 0.10* | 2.9 |
|  | Breaker Trip[5] | ZPA | 1 | 2.0 | 0.10* | 0.10* | 1.4 |
|  |  | ASA @ 2% | 1 | 6.3 | 0.10* | 0.10* | 4.5 |

---

1. The acceleration levels are measured at the base of the equipment.
2. Method:
   1. Method of Moments
   2. Method of Maximum Likelihood
   3. Recommended Values
3. Relay chatter and relay and switch change of state can cause breaker tripping. In the data base test program, these devices were not necessarily connected to the trip elements of the breaker to simulate inservice conditions.
4. Internal damage includes disconnection of a fuse holder and breaking of transformer support.
5. Consequences of malfunction of separately monitored controlling devices were not included (see item 3 above). One additional data point corresponding to breaker malfunction is being investigated and is currently not included in this analysis.

* Based on Judgment