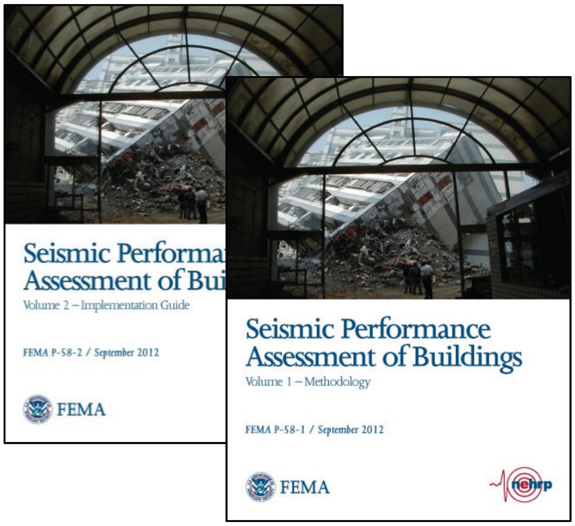


# Background Document

## FEMA P-58/BD-3.9.10

# Fragility of Mechanical, Electrical, and Plumbing Equipment Considering Installation Conditions

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## Background Documentation

FEMA P-58 Background Documents are a series of reports documenting the technical background and source information for key aspects of the FEMA P-58 methodology and its implementation. These reports were developed over the course of the 10-year ATC-58/ATC-58-1 Projects funded under FEMA Contracts EMW-2001-RP-0056 and HSFEHQ-06-D-1105.

Background Documents were developed by consultants, serving at various levels within the project hierarchy, reporting the results of: (1) decisions on technical development protocols; (2) focused studies on the development of key aspects of the methodology; (3) documentation of recommended procedures; and (4) collection of available data for the development of structural and nonstructural fragilities. They were initially intended to serve as a record of the technical state-of-knowledge at the time they were produced, and as resources for the development of the eventual project reports. As such, they represent a snapshot in time, and may, or may not, match the technical content, recommended procedures, or data incorporated into the final methodology and its implementation.

This Background Document is intended for the purpose of providing supplemental knowledge to users of the FEMA P-58 methodology. Information contained herein has not been independently verified for accuracy as a stand-alone document, and may have been superseded in its final implementation within the methodology. Specifically in the case of certain nonstructural component fragilities, the NISTIR fragility classification numbering scheme was modified over the course of the project, and the fragility classification number assigned in this document might be different from numbers assigned in the final fragility database. Users of information in this document assume all liability arising from such use.



Cover illustration – Primary resource documents for the FEMA P-58 *Seismic Performance Assessment of Buildings, Methodology and Implementation* series of products: FEMA P-58-1, *Volume 1 – Methodology*, and FEMA P-58-2, *Volume 2 – Implementation Guide*.

# Fragility of Mechanical, Electrical, and Plumbing Equipment Considering Installation Conditions

**Keith Porter**[a)]

Previous work offered earthquake experience data and seismic fragility functions for 15 classes of mechanical, electric, and plumbing equipment with average or unknown installation conditions. This work offers complementary data and fragility functions for most of the same classes, but considering installation conditions. The source data are post-earthquake observations of the installation conditions, excitation, and performance of approximately 1,500 pieces of equipment after 23 earthquakes at 123 sites. Unsurprisingly, observed installation conditions matter greatly, potentially reducing median capacities by 75% or more. There are several novelties to the present work. First, source data are offered along with the new MEP fragility functions. Fragilities are based in part on a large database of previously unpublished post-earthquake inspections at industrial facilities, and in part on shake-table tests. The resulting fragility functions are intended for use in 2nd-generation performance-based earthquake engineering evaluation of buildings, such as the procedures proposed by the ATC-58 project.

## INTRODUCTION

In 2nd-generation performance-based earthquake engineering (PBEE-2), the engineer seeks to analyze an existing or hypothetical building for its probabilistic seismic hazard, structural response, physical damage, and loss. In the version of PBEE-2 considered here (e.g., Porter 2000, 2003; Krawinkler 2005; ATC 2011), the building is modeled at a very detailed level: individual structural members and connections, individual architectural assemblies (a particular segment of wallboard partition on a particular floor), etc. This paper focuses on an aspect of the damage-analysis phase, in which one employs relationships called fragility functions that relate the excitation to which a component is subjected and the probability of its being damaged in specified ways. Fragility functions are required for all

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major component categories and must distinguish the effect of common design or installation alternatives.

Note that fragility functions are distinct from rated capacity. Designers of nuclear power plants, concerned with the seismic installation of MEP equipment, commonly check that the equipment and anchorage have a rated capacity that exceeds the calculated excitation. For example, Merz (1991) uses "past qualification test data to establish the generic seismic ruggedness of nuclear power plant safe shutdown equipment." That is, equipment subjected to excitation below the generic equipment ruggedness spectra (GERS) would probably not fail; they would be generically adequate. In fragility functions, by contrast, the objective is to calculate the probability of damage to the equipment at a given level of excitation, rather than check that the probability is sufficiently low.

In past work (e.g., Johnson et al. 1999), fragility functions were provided to reflect the probability that an equipment component would be damaged to the point of being rendered inoperative and requiring nontrivial repair (e.g., ignoring failures that require replacing a fuse or restarting the component). In Johnson et al. (1999), separate fragility functions were offered for each of several installation conditions: average conditions (or situations where installation conditions cannot be observed); observed to lack anchorage; observed to have isolator without seismic restraint; etc. These component fragility functions have proven to be useful for estimating the system failure probability of existing facilities, e.g., Porter (2006). They include anchorage failure, overturning of vibration isolators, damage to connections, and internal damage to the components—everything, one could say, from the plinth up. Let us refer to equipment fragility functions that include all these modes of damage as "plinth-up" fragility functions. This kind of fragility functions is *not* the subject of the present work.

PBEE-2 procedures currently in development for FEMA by the Applied Technology Council's ATC-58 project deal in part with new construction for which one cannot observe the equipment in its as-built conditions. One can however design the anchorage and thus calculate anchorage capacity. These developing procedures therefore require the analyst to calculate anchorage capacity separately from "internal" equipment damage, and apply a separate fragility function for internal equipment damage, i.e., exclusive of anchorage failure That is, under the ATC-58 approach, one must know the capacity of the anchorage and isolators, and apply these fragility functions separately. Let us refer to the fragility functions that exclude anchorage or isolator failure as internal-only fragility functions. The present manuscript deals with these internal-only fragility functions and briefly describes how ATC-58 is dealing with the anchorage fragility.

In Porter et al. (2007), the author and colleagues presented several methods for deriving fragility functions from a variety of data sources such as laboratory tests, post-earthquake observation, seismic qualification tests, etc. In Porter et al. (2010) the author and colleagues used these earlier procedures to offer plinth-up fragility functions for 15 classes of MEP equipment with average or unknown installation conditions. The challenge addressed here is to derive internal-only fragility functions for mechanical, electrical, and plumbing (MEP) equipment, based on a combination of post-earthquake observations and GERS test data, for a variety of installation conditions.

## AVAILABLE MEP FRAGILITY DATA AND OTHER PRIOR EFFORTS

***Johnson et al. (1999).*** In this work, the authors offer fragility functions based on earthquake experience data for a wide variety of common MEP components. The data came from first-hand post-earthquake observations and damage reports examined by engineers of EQE International and the Electric Power Research Institute (EPRI) at commercial and industrial facilities on the performance of MEP equipment during the period 1971-1993. The records are of individual MEP equipment components after 23 earthquakes between 1971 and 1993 at 123 sites—mostly industrial facilities—that had been shaken between approximately 0.12g and 0.85g peak ground acceleration. The authors estimated zero-period acceleration (ZPA) at each piece of equipment by amplifying PGAs by a factor that accounts for the elevation of equipment within buildings.

Johnson et al. (1999) offer fragility functions for a large number of MEP categories, 15 of which are relevant here. For each general category, the authors offer a fragility function for average or unknown installation conditions. For equipment with various installation deficiencies, they use a procedure called survival analysis that essentially fits a cumulative lognormal distribution function to the failure and survival data for all specimens in the equipment category. For many categories they also offer fragility functions for situations where installation deficiencies are known to exist that are believed to make an important difference to the seismic capacity of a specimen. The authors term these conditions performance modification factors (PMFs), which they identify in a series of worksheets that facility engineers can use for evaluating equipment system reliability. The fragility functions for equipment with installation deficiencies are based on the lowest estimated ZPA experienced by a specimen that had the relevant PMF and that failed (denoted here by $r_{HCLPF}$), using a high-confidence-of-low-probability-of-failure (HCLPF) methodology. In their approach, this ZPA value was associated with 95% confidence that the failure probability was no greater than 5%, and inferred a conservative median capacity of

$$\theta = r_{HCLPF} \exp\left(1.65\left(\beta_r + \beta_u\right)\right) \quad (1)$$

The values of the uncertainty parameters $\beta_r$ and $\beta_u$ were assigned based on the authors' knowledge of the population and the number of failures. Where the authors believed that a PMF may exist for a particular component class, but no failure observations were available (no observed value of $r_{HCLPG}$), the authors extrapolated from their detailed data from similar components that were expected to contain similar vulnerabilities.

***eSQUG database.*** Another source of earthquake experience data is found in EPRI's Seismic Qualification Utility Group's eSQUG database (EPRI 2007), which contains a large subset of the data compiled by EQE and EPRI, and reflects earthquakes between 1971 and 1993. (The effort of compiling these data has been suspended, so earthquakes and equipment performance since 1993 are not reflected in the database.) The eSQUG database excludes data from commercial facilities that were included in the Johnson et al. (1999) database. However, unlike the data available from Johnson et al. (1999), the eSQUG database also provides, for each specimen, its weight, manufacturer, model, installation conditions (if visible), and a detailed description of seismic performance. First-hand observations were made after a number of earthquakes by EQE International and by the Electric Power Research Institute (EPRI). The investigators also examined facility engineers' records or interviewed them. Observations were made with the intention of documenting failures *and* non-failures, with installation conditions, etc. The database contains photos of each component and often manufacturers' documents about the component. In approximately half of the observations, installation conditions were observed and recorded. For each site and earthquake, the authors estimated ground motion (PGA) either from onsite instruments or from nearby strong-motion instruments.

There is a possible but unknown selection bias in the EPRI (2007) and Johnson et al. (1999) data. In particular, engineers examined all equipment in each facility they examined—both failed and non-failed specimens—but it is possible that operators of facilities with greater-than-average damage refused to allow the inspectors on the premises, e.g., because they were too busy fixing their damage. The author is unaware of evidence that such selection bias exists, but neither is there obvious evidence to the contrary. In the face of such uncertainty, the empirical data are not altered in any way to deal with possible bias, but future researchers should perhaps record unsuccessful attempts to collect field data and the reason why they were unsuccessful.

***GERS Report.*** Merz (1991) provides insight into the performance of MEP equipment at much higher levels of excitation. The work, performed for the Electric Power Research Institute, proposes generic equipment ruggedness spectra (GERS). Merz compiled shake-table testing data on a variety of MEP equipment classes. He offers a range of horizontal and vertical resonant frequency observed for each equipment class, along with a smoothed (miltilinear) response spectrum for each test. In many cases the tests reflect several models by several equipment manufacturers. Some were qualification tests, i.e., the equipment did not fail during the test; and others were tested to failure. Testing in some cases was performed in excess of 4g zero-period acceleration (ZPA).

Failure was described in terms of failure to operate during seismic excitation, or failure to operate after earthquake excitation, or physical damage to the component, or some combination. The objective was to propose response spectra that a generic piece of equipment that had *not* been tested could be assumed survive in an actual earthquake. The specimen had to meet certain criteria listed for the equipment category in order to be judged likely to survive the seismic demand specified by the ruggedness spectrum. The criteria are identified in checklists, and generally reflect good installation conditions, but sometime are more limiting, such as age limits on batteries in racks.

***Kennedy, on the GERS study.*** Robert Kennedy served as the chairman of the Senior Seismic Review and Advisory Panel (SSRAP) for the GERS report (Merz 1991). He points out (pers. comm. 2009) that at the time of testing, actuator control was such that ZPAs were relatively high in comparison with spectral peaks, compared with natural ground motion. Consequently, a capacity based on the reported ZPA could overestimate the capacity in terms of $S_a(T_1)$. To deal with this issue, he recommends estimating an approximate average 5%-damped spectral acceleration response value near the equipment's natural period of vibration in horizontal excitation, denoted here by $S_a(\sim T_1)$, and dividing that value by 2.4 or 2.5 to arrive at a ZPA that would reflect the ratio of $S_a(T_1)$:ZPA that would occur in nature. He also advises addressing discrepancies between the criteria for Merz's (1991) inclusion of equipment in the generic class, and the sometimes broader class that would qualify here as equipment without installation deficiencies. He does not offer particular guidelines, other than to discount the GERS tests in some way where there are significant differences, and to ensure that the resulting medians for ZPA-based fragility functions look reasonable.

***Qualification certificates.*** There is a body of seismic qualification certificates that manufacturers of electrical equipment produce to certify that samples of particular products have been subjected to dynamic testing on shake tables and shown to remain operational afterwards. The certificates usually show the manufacturer and model number tested, the test protocol that was satisfied (e.g., ICC [2000] ES AC156), the level of excitation in terms of the ICC's (2006) design spectral response acceleration $S_{DS}$ and ASCE 7-05's (ASCE 2006) horizontal seismic design force normalized by component operating weight, $F_P/W_P$.

***Porter et al. (2010).*** More recently, the author and others reexamined the MEP fragility functions in Johnson et al. (1999), for the first time tabulating the data to support those fragility functions for average or unknown conditions, and applying the procedures for developing fragility functions proposed for ATC-58 by Porter et al. (2007). The present work seeks to supplement Porter et al. (2010) by performing similar analysis for equipment with and without known installation deficiencies using the EPRI (2007) data, Merz (1991), and qualification tests. The differences between these new fragility functions and those already offered by Johnson et al. (1999) are that (1) fragility functions are offered for specimens known to have no installation deficiencies; and (2) for each category and set of installation conditions the present work will use the ATC-58 procedures on all specimens, rather than the single-specimen HCLPF approach; and (3) it will use the Merz (1991) GERS data and other seismic qualification certificates to test that the resulting fragility functions do not appear to estimate medians that are too high.

***Other data sources***. Numerous reconnaissance studies have mentioned nonstructural components, and there are in the literature several papers on laboratory tests of particular MEP components. Kao et al. (1999) present a database of nonstructural damage, which comprises a sort of enhanced bibliography in a tabular database format, showing keywords and short text excerpts about damage. The difficulty of using these sources for present purposes is that they tend to be nonrepresentative or otherwise insufficiently detailed with installation conditions, shaking, damage, or survival or equipment, for statistical use. The author is unaware of any organized effort or plans to collect future equipment damage data with the kind of detail and representativeness of the eSQUG database.

## METHODOLOGY

***Using the eSQUG and GERS data.*** Every instance in the eSQUG database (EPRI 2007) of a specimen whose installation conditions were observed and recorded was tabulated. For each eSQUG record of a specimen at particular facility and earthquake, the author and colleagues transcribed: the number of specimens; the inspectors' description of the installation conditions; the nature of the equipment fixity to the structure; the number of specimens with internal damage (as opposed to anchorage failure or isolator overturning); and the nature of the damage, in a few words. Specimens from eSQUG where the installation conditions were not recorded are ignored in this work. Three fixity conditions were considered, as listed in Table 1.

**Table 1. Anchorage condition categories**

| |
|---|
| 1. Unanchored equipment that is not vibration isolated; |
| 2. Vibration isolated equipment that is not snubbed or restrained; or |
| 3. Equipment that is either hard anchored or is vibration isolated with seismic restraints. |

The eSQUG database also includes an estimate of the peak ground acceleration at each site and each earthquake. (Which PGA is not always explicit—average of two components, geometric mean, etc.—but geometric mean seems reasonable and is assumed here.) As described in Porter et al. (2010), the zero-period acceleration to which each specimen is subjected is estimated as:

$$r = h \cdot PGA \qquad (2)$$

where *r* denotes the estimated demand on a particular specimen, *PGA* denotes the estimated geometric mean peak ground acceleration in the earthquake and site where the specimen was observed, and *h* is a height factor to account for building amplification of ground motion for the equipment class *in general*. It is calculated as

$$h = \frac{M_l + 1.5M_m + 2.0M_h}{M_l + M_m + M_h} \qquad (3)$$

where $M_l$, $M_m$, and $M_h$ denoted, respectively, the number of all specimens in all earthquakes in the equipment class in questions that were located in the lower, middle, and upper 1/3rd of the buildings in which they were they were located. See Porter et al. (2010) for the values of the height factors.

The eSQUG data were supplemented for several equipment categories using GERS data (Merz 1991). Note that damage for present purposes is a subset of failures considered by Merz, who was also concerned with relay chatter and damage requiring trivial repairs such as replacing fuses. Zero-period acceleration (ZPA, same as "peak floor acceleration") for the GERS specimens was estimated by averaging by eye the 5% damped spectral acceleration response recorded by Merz over a range of frequencies near the component's category's fundamental period of vibration, $T_1$, and then dividing by 2.5, as recommended by Kennedy (2009). The period $T_1$ varies between categories, typically in the range of 0.05 to 0.2 sec.

***Analysis methodology***. With these data in mind, let us now turn to how the data are analyzed to produce equipment fragility functions. In the following analyses, one of two procedures is used to create fragility functions. Both have been described earlier (Porter et al. 2007), but are recapped here for convenience. The first is a weighted-least-squares curve-fitting method applied to categories in which some specimens failed, others did not, and the estimated excitation to which each specimen was subjected is known[1].

In this method, referred to as type B in Porter et al. (2007), specimens are grouped into bins that have constant excitation within a bin, allowing a varying number of specimens per bin. Bins are weighted according to the number of specimens per bin. If the analyst believes the specimens or tests in one bin are more relevant to the general population of components than those in another bin, an additional weight can be applied, and bins are weighted by the product of the number of specimens and the analyst's assignment of subjective weight, though that wrinkle is not used here. Each bin is associated with a single value of demand and a single failure rate, and thus represents a single data point. Let

$N$ = number of bins
$i$ = index of bins, $i \in \{1, 2, \ldots N\}$
$M_i$ = number of specimens in bin $i$
$M$ = total number of specimens

[1] In cases where *all* of specimens failed, one can fake in imaginary undamaged specimens, subjected to very low demand, e.g., 0.10 g. The author recommends faking in one undamaged specimen for each damaged one.

$$M = \sum_i M_i \tag{1}$$

$m_i$ = number of failed specimens in bin $i$

$y_i$ = failure rate in bin $i$, i.e.,

$$y_i = \frac{m_i}{M_i} \tag{2}$$

$x_i$ = excitation in bin $i$

$w_i$ = subjective weight for bin $i$, i.e., the analyst's judgment of the degree to which the specimens or tests in bin $i$ represent the general population of specimens. Default = 1.

$W$ = total weight

$$W = \sum_i w_i M_i \tag{3}$$

One then finds the median capacity, denoted by $\theta$, and the logarithmic standard deviation implied by the data, denoted by $\beta_d$, to minimize $\varepsilon^2$ such that:

$$\begin{gathered} \varepsilon^2 = \frac{1}{W}\sum_{i=1}^{N} w_i M_i \left( y_i - \Phi\left( \frac{\ln\left(x_i/\theta\right)}{\beta_d} \right) \right)^2 \\ \theta > 0 \\ 0.2 \le \beta_d \le 0.6 \end{gathered} \tag{4}$$

Then one calculates $\beta$:

$$\begin{aligned} \beta &= \sqrt{\beta_d^2 + \beta_u^2} \\ &\le 0.6 \end{aligned} \tag{5}$$

where $\beta_u$ increases uncertainty to reflect potential difference between the sample set and the general population. It is taken as $\beta_u$ = 0.25 if any of the following is true, 0.10 otherwise:

All specimens were observed to be in the same configuration (if applicable)
All specimens were observed to have the same installation conditions
All specimens experienced the same loading history
Fewer than 5 specimens were observed

The second procedure is used where no specimens failed and the excitation to which each specimen was subjected is known (so-called Method C). The method was described in Porter et al. (2007), and is slightly enhanced here. (Note *a* in Table 1.) It assumes a logarithmic standard deviation of $\beta$ = 0.4, assigns a pseudo-failure probability to the level of excitation at or near that of the highest experienced by any specimens, and calculates the implied value of the median capacity $\theta$. Let

$r_i$ = excitation experienced by specimen $i$ ($i$ = 1, 2, ... $M$)

$r_{max} = max_i\{r_i\}$

$r_d$ = minimum excitation experienced by any specimen with distress

$r_a$ = the smaller of $r_d$ and $0.7 \cdot r_{max}$

$M_A$ = number of specimens without apparent distress and with $r_i \geq r_a$

$M_B$ = number of specimens at any $r_i$ with distress not suggestive of imminent failure

$M_C$ = number of specimens at any $r_i$ with distress suggestive of imminent failure

$r_m = r_{max}$ if $M_B + M_C = 0$

$= 0.5 \cdot (r_{max} + r_a)$ otherwise

$S$ = subjective failure probability at $r_m$

$$S = (0.5M_C + 0.1M_B)/(M_A + M_B + M_C) \tag{6}$$

One uses Table 2 to determine $F_{dm}(r_m)$ and Equation (7) to determine $\beta$ and $\theta$.

**Table 2.** Values of $\exp(-z\beta)$

| **Conditions** | $F_{dm}(r_m)$ | $Z$ | **exp(–zβ), β=0.4** | **Comments** |
|---|---|---|---|---|
| $M_A \geq 3$ and $S \leq 0.015$ | 0.01 | -2.326 | 2.54 | |
| $M_A \geq 3$ and $S \geq 0.015$ | $S$ | $\Phi^{-1}(S)$ | | a |
| $M_A < 3$ and $S \leq 0.075$ | 0.05 | -1.645 | 1.93 | |
| $M_A < 3$ and $0.075 < S \leq 0.15$ | 0.10 | -1.282 | 1.67 | |
| $M_A < 3$ and $0.15 < S \leq 0.3$ | 0.20 | -0.842 | 1.40 | |
| $M_A < 3$ and $S > 0.3$ | 0.40 | -0.253 | 1.11 | |

a. This row added for completeness. The condition did not appear in Porter et al. (2007)

$$\begin{aligned} \beta &= 0.4 \\ z &= \Phi^{-1}\left(F_{dm}\left(r_m\right)\right) \\ \theta &= r_m \exp\left(-z\beta\right) \end{aligned} \tag{7}$$

Note that in both procedures described above, the fragility functions are idealized using a cumulative lognormal distribution function (CDF). Other forms can be used, but there are several reasons why the author tends to use the lognormal, and does so here. Like the lognormal CDF, seismic capacity is positively valued with a median value (denoted here by $\theta$) and a logarithmic standard deviation ($\beta$). Information theory says that the lognormal is the minimum-information distribution constrained by positive value, fixed median and logarithmic standard deviation. The lognormal has strong precedent in probabilistic seismic risk analysis for the nuclear power industry. That is to say, most authors seem to have used the lognormal in similar work. The lognormal has a convenient, 2-parameter form. And finally, the lognormal often—though not always—fits the observed data.

**RESULTS**

The methodology proposed above is carried out for 13 equipment categories, and either 2 or all 3 anchorage condition categories listed in Table 1. The data include a total of 1,529 specimens, of which 118 were damaged to the point where significant repairs were required (e.g., more than replacing blown fuses). The results are summarized here. Detailed data on each equipment category are contained in an appendix.

In many cases, no specimens were recorded in the eSQUG database with category-1 or category-2 anchorage conditions. For example, electrical equipment without rotating parts generally has no need for vibration isolators, and thus the lack of category-2 specimens for battery chargers, battery racks, and so on is to be expected. Likewise, it is to be expected that equipment with rotating parts are unlikely to have specimens in category 1, with the exception of diesel generators and packaged air handling units, which may have internal vibration isolation. All specimens in the GERS database are assumed to be hard anchored.

Table 3 summarizes the frequency of various installation deficiencies interpreted from the eSQUG database, and the repairs that would seem to be required, based on the recorded seismic performance. The eSQUG database frequently does not include the repair efforts required for each specimen, so in many cases the repairs shown in the table are speculative.

Table 4 summarizes the resulting equipment fragility functions. These data are only somewhat comparable to the Johnson et al. (1999) fragility functions, since the latter are plinth-up fragility function and the present ones are for internal damage only. In the table, each row reflects one category of equipment. Columns show the number of specimens ("Spc") used to create the fragility functions, the number that were damaged ("Fail"), the Porter et al. (2007) method used to analyze the data ("Mtd"), and the median ($\theta$) and logarithmic standard deviation ($\beta$) of the geometric-mean zero-period acceleration associated with damage. The median $\theta$ is shown in units of gravity, and $\beta$ is rounded to the nearest 0.05. As noted above, the data are offered separately for each anchorage installation condition category of Table 1. The appendix contains site-by-site data and plots of the observations and fit curves. The data in the appendix tables all come from eSQUG unless labeled "GERS;" these come from Merz (1991). Each plot in the appendix indicates that the fragility function ought not to be used for values of peak floor acceleration greater than 1.5 times the maximum value in the data.

**Table 3. Summary of common installation deficiencies and repairs required**

| Component | Deficiencies | Repairs required |
|---|---|---|
| Air compressors | Isolators without snubbers (80%), welded to unanchored tank (20%) | Replace motor (67%) or repair cracked air line (33%) |
| Air handling units | Isolators without snubbers (90%), no lateral restraint (10%) | Repair piping or duct (100%) |
| Batteries in racks | No battery spacers (83%), no battery restraints (52%), no longitudinal bracing (29%), no anchorage (19%) | Replace batteries (100%), clean acid (~20%), replace rack (~20%) |
| Battery chargers | No anchorage or poor anchorage (100%) | Service for intermittent voltage output or for blown surge suppressor (50%), reinstall with new anchorage (50%) or replace (presumably required sometimes; not observed) |
| Chillers | Isloators without snubbers (94%), rigid piping support (18%) | Remount chiller with snubbed isolators (82%), repair rigidly attached piping (12%), repair anchorage (6%) |
| Control panels | No anchorage or poor anchorage (44%), inflexible attachments (44%), poor load path (28%), pounding or impact concerns (28%) | Rebuild rack and reinstall with proper anchorage (50%), replace relays (25%) or replace some boards (25%) |
| Cooling towers | Isolators without snubbers (50%), or no anchorage (50%) | Remount (100%) |
| Distribution panels | No anchorage (100%) | Replace shorted components (100%) |
| Engine generators | Differential displacement driver-generator (53%), no snubbers (29%), unanchored (18%) | Repair fractured pipes & damaged nozzles (70%), overhaul because of drive shaft misalignment (10%), minor electrical repair (10%), reconnect exhaust line (10%) |
| Fans | No snubbers (81%), fan-motor differential displacement (19%), rigid attachements (9%) | Remount fan on isolators, add snubbers |
| Low voltage switchgear | No anchorage (100%) | Replace insulator; possibly replace equipment |
| Motor control centers | No anchorage or poor anchorage (86%), interaction (14%; typ poorly connected together) | Upright and anchor or re-anchor |
| Motor generators | No anchorage (presumably 100%; none observed) | Replace equipment |
| Transformers | No anchorage or poor anchorage (100%) | Service and reinstall existing transformer |

**Table 4. Fragility functions**

| | Installation category 1 | | | | | Installation category 2 | | | | | Installation category 3 | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Component** | **Spc** | **Fail** | **Mtd** | **θ** | **β** | **Spc** | **Fail** | **Mtd** | **θ** | **β** | **Spc** | **Fail** | **Mtd** | **θ** | **β** |
| Battery charger | 16 | 0 | C | 1.07 | 0.40 | | | | | | 89 | 5 | B | 2.70 | 0.60 |
| Battery rack | 65 | 10 | B | 1.11 | 0.60 | | | | | | 83 | 8 | B | 2.32 | 0.20 |
| Chiller | | | | | | 18 | 10 | B | 0.43 | 0.60 | 27 | 1 | B | 0.72 | 0.20 |
| Compressor | 2 | 0 | E(2) | 0.25 | 0.45 | 9 | 1 | B | 0.47 | 0.20 | 99 | 2 | B | 1.84 | 0.60 |
| Control panel | 6 | 1 | C(1) | 0.69 | 0.40 | | | | | | 136 | 11 | B | 2.61 | 0.20 |
| Cooling tower | | | | | | 7 | 2 | B | 0.97 | 0.60 | 14 | 0 | C | 1.52 | 0.40 |
| Diesel generator | 8 | 1 | C(1) | 0.90 | 0.40 | 15 | 0 | C | 1.07 | 0.40 | 127 | 7 | B | 2.00 | 0.20 |
| Distribution panel | 3 | 0 | C | 2.16 | 0.45 | | | | | | 83 | 1 | B | 3.05 | 0.40 |
| HVAC fan | | | | | | 58 | 19 | B | 1.01 | 0.60 | 101 | 1 | B | 4.82 | 0.60 |
| Low voltage switchgear | 15 | 0 | C | 1.28 | 0.40 | | | | | | 35 | 1 | B | 2.40 | 0.40 |
| Motor control center | 30 | 2 | B | 0.73 | 0.45 | | | | | | 199 | 10 | C(1) | 2.50 | 0.40 |
| Packaged air handling unit | 6 | 6 | B(3) | 0.25 | 0.40 | | | | | | 103 | 14 | B | 1.54 | 0.60 |
| Transformer/primary service | 70 | 4 | B | 1.01 | 0.60 | | | | | | 105 | 1 | B | 3.05 | 0.60 |
| Total | 221 | 24 | | | | 107 | 32 | | | | 1201 | 62 | | | |

Notes:
(1) Method B did not converge. Method C was used, treating damaged components as "seriously damaged" under Porter et al. (2007).
(2) Insufficient data for method B
(3) Faked in 6 non-failures at 0.1g. No other established method seems to deal with the case where all specimens failed

## TREATING ANCHORAGE FAILURE

As noted earlier, ATC-58 will treat the failure of anchorage and seismic restraint separately from internal damage to components, since the capacity of anchorage and seismic snubbers can be calculated during the design phase. Anchorage and snubber capacity and the consequences of their failure will be treated using procedures specified in ASCE/SEI-43 (ASCE 2005). A consequence of the intention to treat anchorage and snubber failure with separate fragility functions is that cases of anchorage pullout are excluded from the failure data shown here; the present data include only so-called internal failures.

## A DISCUSSION ABOUT THE FIT OF THE CURVES TO THE DATA

As is apparent from the plots in the appendix, the lognormal cumulative distribution functions fit the failure data poorly, generally with very $R^2$ values. For the reader unfamiliar with regression analysis, $R^2$ refers to the fraction of the marginal variance in the data explained by the curve fit through the data. The interested reader is referred to any common statistics textbook for the equations needed to calculate $R^2$, such as Ang and Tang (1975).

One implication of a low $R^2$ value is that one cannot with confidence reject the null hypothesis that no trend exists, in this case between floor acceleration and failure probability. More generally it means that fragility functions for these component categories, in the range of accelerations in the data (generally less than 1.0g), with the form of a lognormal CDF, with β constrained between 0.2 and 0.6, and floor accelerations estimated on the basis of nearby PGAs and an h factor, do not predict failure rates well at all.

Should such a trend exist? It makes intuitive sense that failure rates should generally increase as floor acceleration increases, that they should be near zero at low accelerations, approach 1 at high accelerations, and ought to have some median and logarithmic standard deviation of capacity. That intuition argues for lognormal fragility functions with peak floor acceleration as the input excitation, as many previous authors have assumed.

So why are the $R^2$ values so low? Perhaps the problem is that the method of estimated peak floor acceleration imposes too much uncertainty, and better acceleration information would improve the fit. Perhaps because the mean failure rates are so low at these levels of acceleration—generally less than 10%—the signal of failure rate is being drowned out by the noise of variable installation conditions and poor acceleration estimates. Maybe more data at higher levels of excitation would better support the lognormal fragility functions. Maybe floor acceleration is just not the right excitation to use as the input to the fragility functions. Or maybe these component categories are by nature too diverse to justify estimating failure rate at all for the broad categories addressed here.

What can be done to deal with such low $R^2$ values? The previous paragraph suggests a few possibilities, none of which readily satisfies the demand for fragility functions for MEP equipment with known installation conditions:

(1) Instrument a lot of buildings with MEP equipment in them, wait for earthquakes to occur, and then inspect and record the equipment performance. Such has been the engineering community's approach to test and improve its methods for structural analysis; why not do the same for damage analysis? ANSS is slowly advancing down that route, though no program of which the author is aware is preparing to actually gather the equipment performance data. The EPRI effort is done—data are no longer being added to eSQUG—and ANSS has no post-earthquake equipment-inspection program. The necessary data-collection protocols for ANSS-instrumented buildings do not even exist.

(2) Perform shake-table tests of large numbers of specimens installed under a variety of conditions to high levels of acceleration. This approach is expensive: the components themselves can be expensive and the diversity of manufacturers and installation conditions multiplies the cost of thorough testing. Seismic qualification tests and tests to failure of some classes of MEP equipment are performed, but these are under fairly ideal conditions, never unanchored or with the various other deficiencies common in real buildings. Experimental programs such as NEES have shown little inclination to perform such mundane experiments as shaking a variety of potentially unanchored or poorly snubbed air handling units installed under a variety of conditions until they fail.

(3) See if different demand parameters such as peak floor velocity or a vector of demand parameters produce higher $R^2$ values. But how? The original observations reflected in this manuscript were in facilities that were generally not instrumented, and whose excitation had to be estimated using observations sometimes miles away. Perhaps

physics-based ground-motion models could produce better estimates of motions at the sites in the damage database, as these models become more commonly available.

(4) Rely on expert opinion or on fragility functions based on unpublished data, which may or may not be better than those offered here. This amounts to accepting an alternative largely because it is harder to check.

(5) Fall back on a HCLPF approach, i.e., base the fragility of the category on the highest excitation without specimen damage, or the lowest excitation with specimen damage. Such an approach seems likely to be conservative, and to reflect the fragility of the worst installation conditions rather than average or unknown ones. For instance, if some installation deficiency is rare but makes a big difference to fragility, a HCLPF approach could easily produce a fragility function reflecting that rare condition, significantly undervaluing the capacity of more-typical installation conditions.

(6) Give up, and do not try to estimate failure rates of equipment for which the analyst does not know installation conditions.

(7) Accept the fact that the fragility functions offered here meet some basic requirements, but not all one would want. They monotonically increase with floor acceleration, have a convenient and traditional form, and generally pass through the cloud of data, albeit for the most part no better than does a flat line through the average.

Finally, let us now consider some context related to ATC-58. The fragilities offered here draw primarily on the eSQUG database, which appears to be the only MEP seismic performance data from actual field installations containing all the necessary ingredients of a fragility function: an unbiased sample, quantities of both damaged and undamaged specimens, significant numbers of specimens in each category, and an estimate of the seismic excitation to which each specimen was subjected.

As more data become available, perhaps better statistical correlations can be achieved, or perhaps the engineering community will find demand parameters that better relate to MEP failure rates than does peak floor acceleration, together with sufficient observed performance data that can be related to that demand parameter.

If one has to estimate the performance of MEP equipment with known installation conditions, the choices seem to be: (1) use the fragility functions offered here with full knowledge of their limitations, (2) use unverifiable fragility functions based on expert opinion, or on unpublished data, or on first principles, or (3) make no estimates at all of MEP damage.

## A COMMENT ABOUT FUTURE FIELD DATA COLLECTION

It would be valuable for developing future fragility functions if a data-collection effort like EPRI's eSQUG database could be developed, in part using the input data required here as a guide. The data-collection instrument could be partly automated to avoid the labor-intensive copying and pasting of data that was required for the present effort. An example of such a data-collection instrument is the FEMA software Rapid Observation of Vulnerability and Estimation of Risk (ROVER), a mobile computing application that uses a client-server architecture. The client is a piece of software operating on a smartphone that is used to collect the field data (Porter et al. 2009). The field data include location, damage and survival data, digital photos, and sketches. The data are then uploaded via WiFi, wired connection, or a phone data plan to a secure, web-accessible database server that can reside anywhere in the world on an ordinary PC. ROVER is currently designed for pre- and post-earthquake field observation of seismic risk to buildings, but could be readily adapted to MEP and other nonstructural building component damage.

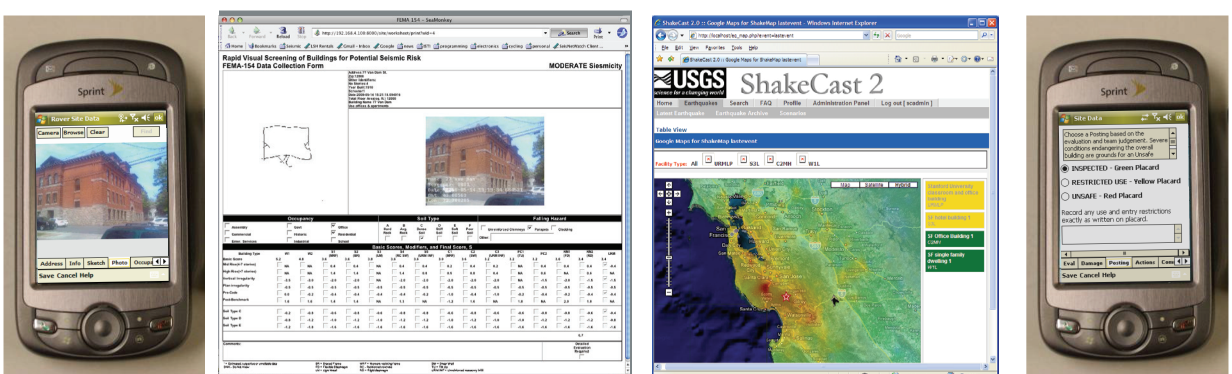


**Figure X. Future MEP equipment fragility data could be collected via a system like or adapted from FEMA's Rapid Observation of Vulnerability and Estimation of Risk (ROVER) software (Porter et al. 2009). ROVER is designed for collecting building safety risk information. In ROVER ver 1.0, building vulnerability data are collected in the field with ROVER on a smartphone (a), with its camera and sketch capability and geolocation captured via a Bluetooth GPS device. Data are sent wirelessly to a secure Internet-accessible server (b) located anywhere in the world. The data can be automatically imported to *ShakeCast* (c), which watches for relevant earthquakes and alerts the user when one has likely affected the buildings in the inventory, and lists the facilities in order of likely damage state. The user can then use *ROVER* on the same smartphone (d) to assist in safety tagging and post-earthquake data management.**

## CONCLUSIONS

Fragility functions were developed for 13 classes of mechanical, electrical, and plumbing (MEP) equipment, both well installed and under two categories of deficient installation conditions: unanchored, or with vibration isolation but lacking seismic snubbers or other restraint. The fragility functions were derived using EPRI's eSQUG database of MEP equipment damage and success in industrial facilities worldwide, in earthquakes between 1971 and 1993. These data are supplemented in several cases with laboratory tests recapped by Merz (1991) for EPRI's generic equipment ruggedness spectra (GERS). The earthquake experience is generally from shaking of up to 1.0g of zero-period acceleration. The laboratory testing in some cases exceeds 2.0g of zero-period acceleration. Median capacity of well installed equipment varies between 0.7g and 5g. Logarithmic standard deviations for equipment without observed failures are taken as 0.4. In performing the curve fitting for equipment with observed failures and non-failures, the logarithmic standard deviation was allowed to vary between 0.2 and 0.6.

Since the eSQUG data reflect equipment in operation between 1971 and 1993, and the GERS test data reflect testing no later than 1991, this work is not informative of any post-1993 equipment that is markedly different from pre-1993 equipment, e.g., computers in racks. Future MEP equipment performance data could be collected and adapted for use in PBEE-2 fragility functions more efficiently than was possible here if a mobile field data collection system and data-collection protocol were adopted as part of an ongoing effort to learn about component fragility from future earthquakes.

## ACKNOWLEDGMENTS

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# APPENDIX. FRAGILITY DATA AND PLOTS

## BATTERY CHARGERS

**Table 5. Battery chargers, installation category 1**

| PFA, g | M, units | m, failed | f = m/M | Comment |
|---|---|---|---|---|
| 0.20 | 2 | 0 | 0 | |
| 0.20 | 2 | 0 | 0 | |
| 0.20 | 2 | 0 | 0 | |
| 0.25 | 1 | 0 | 0 | |
| 0.25 | 2 | 0 | 0 | |
| 0.25 | 2 | 0 | 0 | |
| 0.25 | 2 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.42 | 2 | 0 | 0 | |

**Table 6. Battery chargers, installation category 3**

| PFA, g | M, units | m, failed | f = m/M | Comment |
|---|---|---|---|---|
| 0.20 | 2 | 0 | 0 | |
| 0.20 | 2 | 0 | 0 | |
| 0.20 | 2 | 0 | 0 | |
| 0.24 | 6 | 0 | 0 | |
| 0.25 | 6 | 0 | 0 | |
| 0.25 | 2 | 0 | 0 | |
| 0.25 | 1 | 0 | 0 | |
| 0.25 | 2 | 0 | 0 | |
| 0.26 | 1 | 0 | 0 | |
| 0.30 | 4 | 0 | 0 | |
| 0.32 | 3 | 0 | 0 | |
| 0.35 | 3 | 0 | 0 | |
| 0.35 | 1 | 0 | 0 | |
| 0.35 | 8 | 1 | 0.125 | |
| 0.40 | 4 | 0 | 0 | |
| 0.40 | 2 | 0 | 0 | |
| 0.40 | 2 | 0 | 0 | |
| 0.40 | 4 | 0 | 0 | |
| 0.40 | 2 | 1 | 0.5 | |
| 0.42 | 2 | 0 | 0 | |
| 0.50 | 3 | 0 | 0 | |
| 0.50 | 2 | 0 | 0 | |
| 0.50 | 3 | 0 | 0 | |
| 0.50 | 1 | 0 | 0 | |
| 0.56 | 2 | 0 | 0 | |
| 0.60 | 1 | 0 | 0 | GERS |
| 0.64 | 3 | 0 | 0 | GERS |
| 0.80 | 2 | 2 | 1 | GERS, blown surge suppressor |
| 0.85 | 3 | 0 | 0 | |
| 1.32 | 2 | 0 | 0 | GERS |
| 1.32 | 1 | 0 | 0 | GERS |
| 1.40 | 1 | 0 | 0 | GERS |
| 1.40 | 1 | 0 | 0 | GERS |

| PFA, g | M, units | m, failed | f = m/M | Comment |
|---|---|---|---|---|
| 1.44 | 1 | 1 | 1 | GERS failure intermittent voltage output |
| 1.48 | 3 | 0 | 0 | GERS |
| 1.60 | 1 | 0 | 0 | GERS |

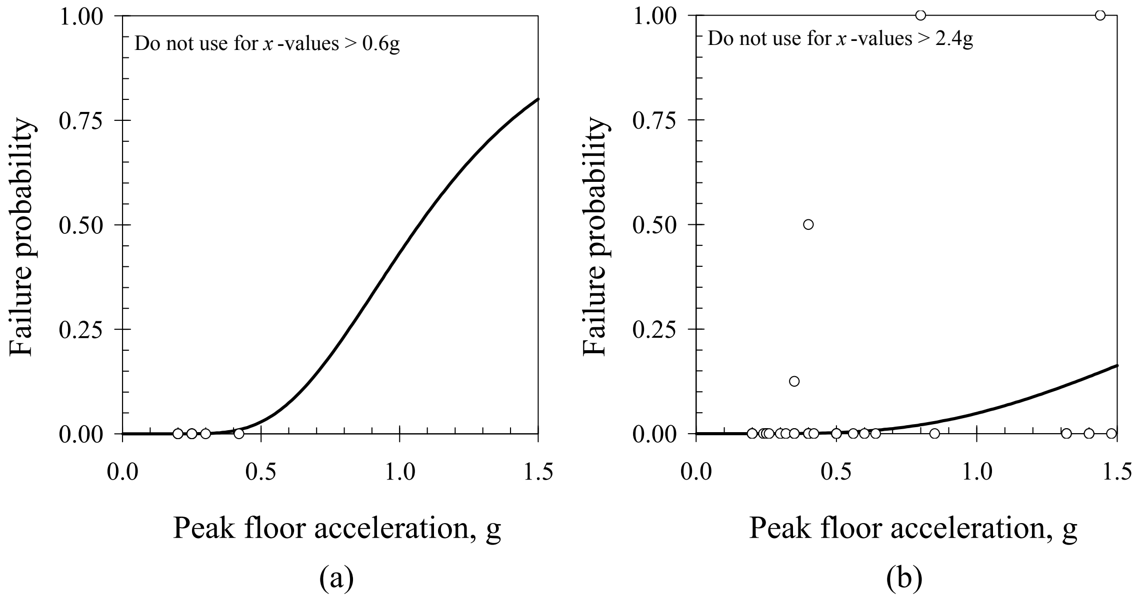



**Figure 1. Battery chargers (a) installation category 1 (b) installation category 3**

**BATTERIES IN RACKS**

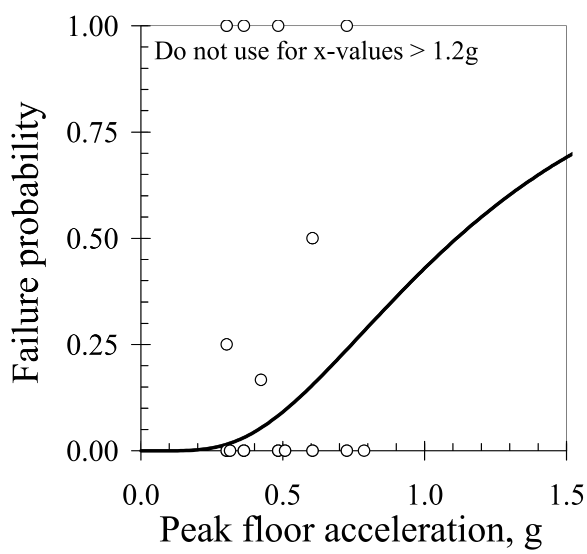
**Table 7. Batteries in racks, installation category 1**

| PFA, g | M, units | m, failed | f = m/M | Comment |
|---|---|---|---|---|
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 3 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 4 | 1 | 0.25 | Batteries fell from rack, jars cracked, spilled acid |
| 0.30 | 2 | 2 | 1 | Batteries fell from rack, jars cracked, spilled acid |
| 0.30 | 2 | 2 | 1 | Batteries fell from rack, jars cracked, spilled acid |
| 0.31 | 2 | 0 | 0 | |
| 0.31 | 2 | 0 | 0 | |
| 0.36 | 1 | 0 | 0 | |
| 0.36 | 2 | 0 | 0 | |
| 0.36 | 2 | 0 | 0 | |
| 0.36 | 2 | 0 | 0 | |
| 0.36 | 3 | 0 | 0 | |
| 0.36 | 1 | 1 | 1 | Dislodged plates in batteries |
| 0.42 | 6 | 1 | 0.17 | Batteries fell from rack, jars cracked, spilled acid |
| 0.48 | 1 | 0 | 0 | |
| 0.48 | 2 | 0 | 0 | |
| 0.48 | 1 | 0 | 0 | |
| 0.48 | 1 | 0 | 0 | |
| 0.48 | 1 | 0 | 0 | |
| 0.48 | 1 | 1 | 1 | Dislodged plates in batteries |
| 0.51 | 5 | 0 | 0 | |
| 0.51 | 2 | 0 | 0 | |
| 0.61 | 1 | 0 | 0 | |
| 0.61 | 5 | 0 | 0 | |
| 0.61 | 1 | 0 | 0 | |
| 0.61 | 2 | 1 | 0.5 | Batteries fell from rack, dislodged plates |
| 0.73 | 3 | 0 | 0 | |
| 0.73 | 1 | 0 | 0 | |
| 0.73 | 1 | 1 | 1 | Batteries fell from rack, damaged in unspecified way |
| 0.79 | 1 | 0 | 0 | |

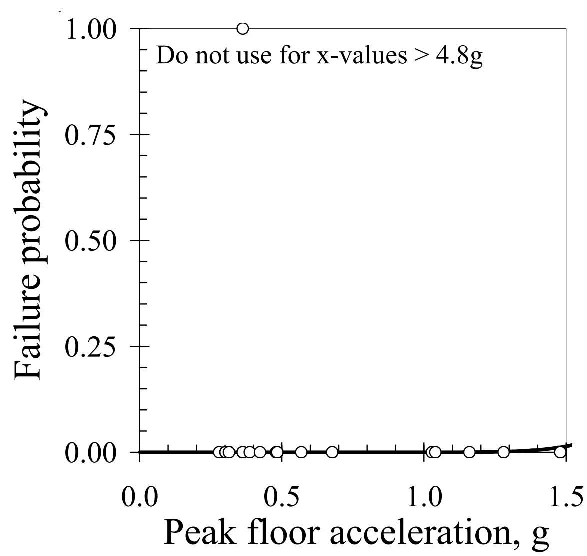
**Table 8. Batteries in racks, installation category 3**

| PFA, g | M, units | m, failed | f = m/M | Comment |
|---|---|---|---|---|
| 0.28 | 2 | 0 | 0 | GERS |
| 0.30 | 4 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 4 | 0 | 0 | |
| 0.30 | 2 | 0 | 0 | |
| 0.30 | 2 | 0 | 0 | |
| 0.31 | 1 | 0 | 0 | |
| 0.31 | 2 | 0 | 0 | |
| 0.36 | 1 | 0 | 0 | |
| 0.36 | 4 | 0 | 0 | |
| 0.36 | 1 | 0 | 0 | |
| 0.36 | 1 | 1 | 1 | Rack overturned, jars cracked, spilled acid |
| 0.39 | 1 | 0 | 0 | |

| PFA, g | M, units | m, failed | f = m/M | Comment |
|---|---|---|---|---|
| 0.42 | 4 | 0 | 0 | |
| 0.48 | 1 | 0 | 0 | GERS |
| 0.48 | 6 | 0 | 0 | |
| 0.48 | 1 | 0 | 0 | |
| 0.48 | 5 | 0 | 0 | |
| 0.57 | 2 | 0 | 0 | |
| 0.68 | 3 | 0 | 0 | |
| 0.68 | 1 | 0 | 0 | |
| 1.03 | 1 | 0 | 0 | |
| 1.03 | 1 | 0 | 0 | |
| 1.04 | 2 | 0 | 0 | GERS |
| 1.16 | 2 | 0 | 0 | GERS |
| 1.28 | 4 | 0 | 0 | GERS |
| 1.48 | 1 | 0 | 0 | GERS |
| 1.48 | 3 | 0 | 0 | GERS |
| 1.68 | 8 | 0 | 0 | GERS |
| 1.68 | 1 | 1 | 1 | GERS: jar cracked |
| 1.72 | 1 | 0 | 0 | GERS |
| 2.20 | 2 | 0 | 0 | GERS |
| 2.28 | 1 | 0 | 0 | GERS |
| 2.28 | 1 | 1 | 1 | GERS: spacers crushed |
| 2.56 | 1 | 1 | 1 | GERS: jar cracked |
| 2.80 | 1 | 1 | 1 | GERS: jar cracked |
| 2.80 | 1 | 1 | 1 | GERS: jar cracked |
| 3.08 | 1 | 1 | 1 | GERS: jar cracked |
| 3.20 | 1 | 1 | 1 | GERS: intermittent output |




(a)




(b)

**Figure 2. Batteries in racks (a) installation category 1 (b) installation category 3**

**CHILLERS**

**Table 9. Chillers, installation category 2**

| PFA, g | M, units | m, failed | f = m/M | Comment |
|---|---|---|---|---|
| 0.3 | 3 | 0 | 0 | |
| 0.5 | 9 | 8 | 0.89 | Dismounted from isolators; operable once remounted |
| 0.8 | 2 | 0 | 0 | |
| 0.8 | 2 | 1 | 0.50 | Dismounted, fractured attached water pipe |
| 0.84 | 2 | 1 | 0.50 | Dismounted from isolators; operable once remounted |

**Table 10. Chillers, installation category 3**

| PFA, g | M, units | m, failed | f = m/M | Comment |
|---|---|---|---|---|
| 0.20 | 4 | 0 | 0 | |
| 0.35 | 1 | 0 | 0 | |
| 0.35 | 4 | 0 | 0 | |
| 0.37 | 4 | 0 | 0 | |
| 0.40 | 2 | 0 | 0 | |
| 0.40 | 3 | 0 | 0 | |
| 0.42 | 4 | 0 | 0 | |
| 0.50 | 2 | 0 | 0 | |
| 0.60 | 2 | 0 | 0 | |
| 0.80 | 1 | 1 | 1 | Displacement broke an attached water tube |

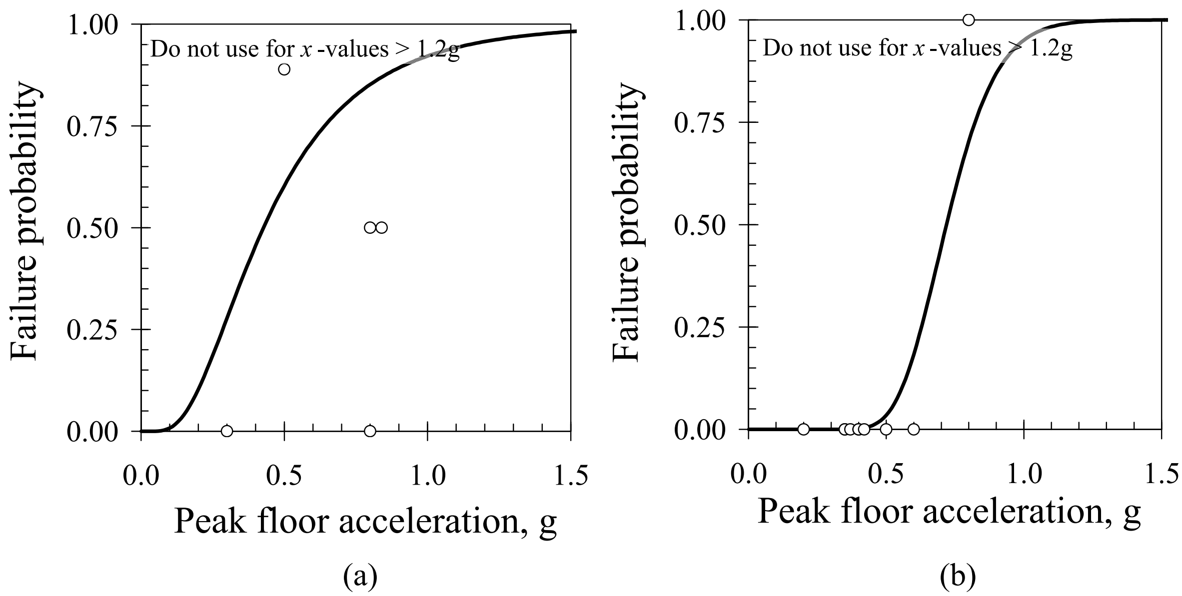



**Figure 3. Chillers (a) installation category 2 (b) installation category 3**

## AIR COMPRESSORS

**Table 11. Air compressors, installation category 2**

| PFA, g | M, units | m, failed | f = m/M | Comments |
|---|---|---|---|---|
| 0.20 | 3 | 0 | 0 | |
| 0.38 | 3 | 0 | 0 | |
| 0.41 | 2 | 0 | 0 | |
| 0.41 | 1 | 1 | 1 | Excessive rocking on isolators broke an attached tube |

**Table 12. Air compressors, installation category 3**

| PFA, g | M, units | m, failed | f = m/M | Comment |
|---|---|---|---|---|
| 0.20 | 4 | 0 | 0 | |
| 0.20 | 2 | 0 | 0 | |
| 0.20 | 5 | 0 | 0 | |
| 0.23 | 8 | 0 | 0 | |
| 0.24 | 4 | 0 | 0 | |
| 0.26 | 6 | 0 | 0 | |
| 0.26 | 4 | 0 | 0 | |
| 0.26 | 4 | 0 | 0 | |
| 0.27 | 7 | 0 | 0 | |
| 0.27 | 4 | 0 | 0 | |
| 0.31 | 7 | 0 | 0 | |
| 0.31 | 2 | 0 | 0 | |
| 0.31 | 4 | 0 | 0 | |
| 0.31 | 4 | 0 | 0 | |
| 0.31 | 5 | 0 | 0 | |
| 0.31 | 2 | 2 | 1 | Burnt windings |
| 0.33 | 3 | 0 | 0 | |
| 0.36 | 2 | 0 | 0 | |
| 0.41 | 7 | 0 | 0 | |
| 0.43 | 7 | 0 | 0 | |
| 0.51 | 6 | 0 | 0 | |
| 0.57 | 2 | 0 | 0 | |

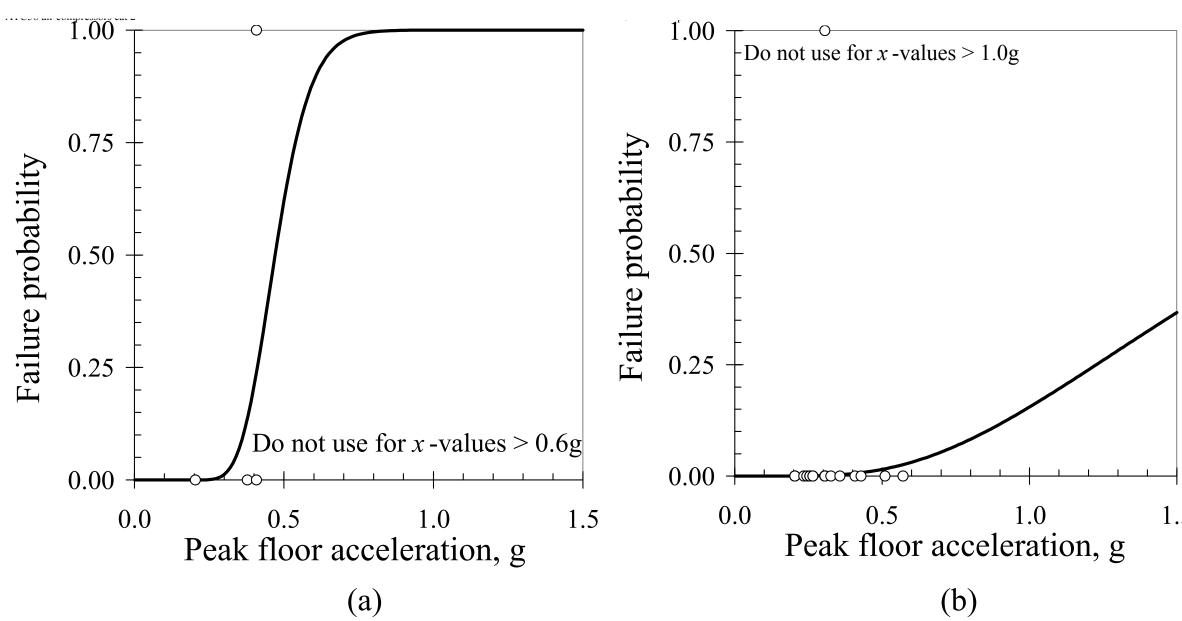



**Figure 4. Air compressors (a) installation category 2 (b) installation category 3**

## CONTROL PANELS

**Table 13. Control panels, installation category 1**

| PFA, g | M, units | m, failed | f = m/M | Comment |
|---|---|---|---|---|
| 0.24 | 1 | 0 | 0 | |
| 0.24 | 1 | 0 | 0 | |
| 0.30 | 1 | 1 | 1 | Relays, circuit boards & components dislodged |
| 0.36 | 1 | 0 | 0 | |
| 0.48 | 1 | 0 | 0 | |
| 0.57 | 1 | 0 | 0 | |

**Table 14. Control panels, installation category 3**

| PFA, g | M, units | m, failed | f = m/M | Comment |
|---|---|---|---|---|
| 0.17 | 1 | 0 | 0 | |
| 0.17 | 1 | 0 | 0 | |
| 0.17 | 1 | 0 | 0 | |
| 0.24 | 1 | 0 | 0 | |
| 0.24 | 1 | 0 | 0 | |
| 0.24 | 1 | 0 | 0 | |
| 0.24 | 1 | 0 | 0 | |
| 0.24 | 1 | 0 | 0 | |
| 0.24 | 2 | 0 | 0 | |
| 0.28 | 1 | 0 | 0 | |
| 0.28 | 1 | 1 | 1 | |
| 0.30 | 3 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 1 | 1 | 1 | Common rack for several items overturned from anchorage failure |
| 0.30 | 1 | 1 | 1 | Unrestrained relays, circuit boards and components dislodged or slid out of position |
| 0.31 | 1 | 0 | 0 | |
| 0.31 | 1 | 0 | 0 | |
| 0.31 | 1 | 0 | 0 | |
| 0.31 | 1 | 0 | 0 | |
| 0.31 | 1 | 0 | 0 | |
| 0.31 | 1 | 0 | 0 | |
| 0.36 | 1 | 0 | 0 | |
| 0.36 | 2 | 0 | 0 | |
| 0.36 | 1 | 0 | 0 | |

| PFA, g | M, units | m, failed | f = m/M | Comment |
|---|---|---|---|---|
| 0.36 | 1 | 0 | 0 | |
| 0.36 | 1 | 0 | 0 | |
| 0.36 | 1 | 0 | 0 | |
| 0.36 | 1 | 0 | 0 | |
| 0.36 | 1 | 0 | 0 | |
| 0.36 | 1 | 0 | 0 | |
| 0.36 | 1 | 0 | 0 | |
| 0.39 | 1 | 0 | 0 | |
| 0.42 | 1 | 0 | 0 | |
| 0.42 | 1 | 0 | 0 | |
| 0.42 | 1 | 0 | 0 | |
| 0.42 | 1 | 0 | 0 | |
| 0.45 | 1 | 0 | 0 | |
| 0.48 | 1 | 0 | 0 | |
| 0.48 | 1 | 0 | 0 | |
| 0.48 | 1 | 0 | 0 | |
| 0.48 | 12 | 0 | 0 | |
| 0.48 | 2 | 0 | 0 | |
| 0.48 | 1 | 0 | 0 | |
| 0.48 | 1 | 0 | 0 | |
| 0.48 | 7 | 0 | 0 | |
| 0.48 | 1 | 0 | 0 | |
| 0.48 | 1 | 0 | 0 | |
| 0.48 | 1 | 1 | 1 | Base sheet metal tearing caused overturning |
| 0.48 | 2 | 2 | 1 | Base sheet metal tearing caused overturning |
| 0.48 | 3 | 3 | 1 | Base sheet metal tearing caused overturning |
| 0.51 | 1 | 0 | 0 | |
| 0.51 | 1 | 0 | 0 | |
| 0.51 | 1 | 0 | 0 | |
| 0.51 | 1 | 0 | 0 | |
| 0.61 | 17 | 0 | 0 | |
| 0.61 | 2 | 0 | 0 | |
| 0.61 | 1 | 0 | 0 | |
| 0.67 | 1 | 1 | 1 | Porcelain circuit breaker base was fractured in main control panel |
| 0.68 | 1 | 0 | 0 | |
| 0.72 | 1 | 0 | 0 | GERS |
| 0.73 | 1 | 0 | 0 | |
| 0.73 | 1 | 0 | 0 | |
| 0.76 | 1 | 0 | 0 | GERS |
| 1.03 | 1 | 0 | 0 | |
| 1.03 | 1 | 0 | 0 | |
| 1.03 | 1 | 0 | 0 | |
| 1.03 | 1 | 0 | 0 | |
| 1.03 | 1 | 0 | 0 | |
| 1.03 | 1 | 0 | 0 | |
| 1.03 | 1 | 0 | 0 | |
| 1.03 | 1 | 0 | 0 | |
| 1.03 | 1 | 0 | 0 | |
| 1.28 | 1 | 1 | 1 | GERS: loose washer caused short circuit |
| 1.80 | 1 | 0 | 0 | GERS |
| 2.16 | 3 | 0 | 0 | GERS |
| 2.72 | 1 | 0 | 0 | GERS |

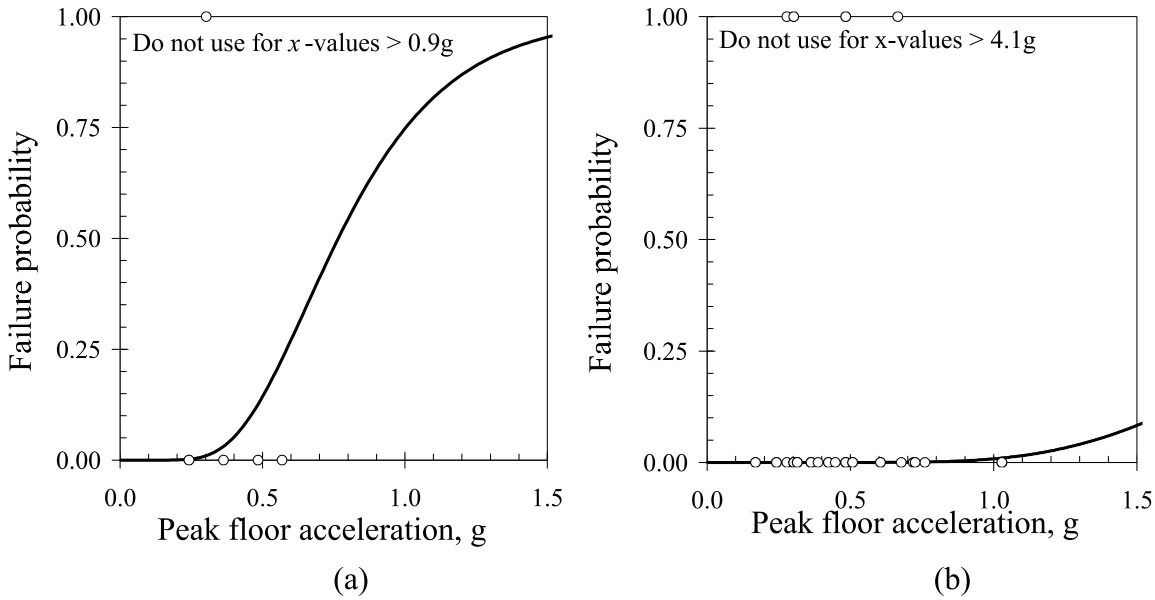



**Figure 5. Control panels (a) installation category 1 (b) installation category 3**

## COOLING TOWERS

**Table 15. Cooling towers, installation category 2**

| PFA, g | M, units | m, failed | f = m/M | Comment |
|---|---|---|---|---|
| 0.42 | 1 | 0 | 0 | |
| 0.60 | 2 | 0 | 0 | |
| 0.68 | 1 | 1 | 1 | The cooler rotated, dislodging from its isolation mounts. Operable once remounted. |
| 0.86 | 2 | 0 | 0 | |
| 0.86 | 1 | 1 | 1 | The cooling tower shifted off its isolation mounts, but otherwise remained operable. |

**Table 16. Cooling towers, installation category 3**

| PFA, g | M, units | m, failed | f = m/M | Comment |
|---|---|---|---|---|
| 0.12 | 4 | 0 | 0 | |
| 0.3 | 1 | 0 | 0 | |
| 0.4 | 2 | 0 | 0 | |
| 0.6 | 1 | 0 | 0 | |
| 0.6 | 2 | 0 | 0 | |
| 0.6 | 3 | 0 | 0 | |
| 0.6 | 1 | 0 | 0 | |

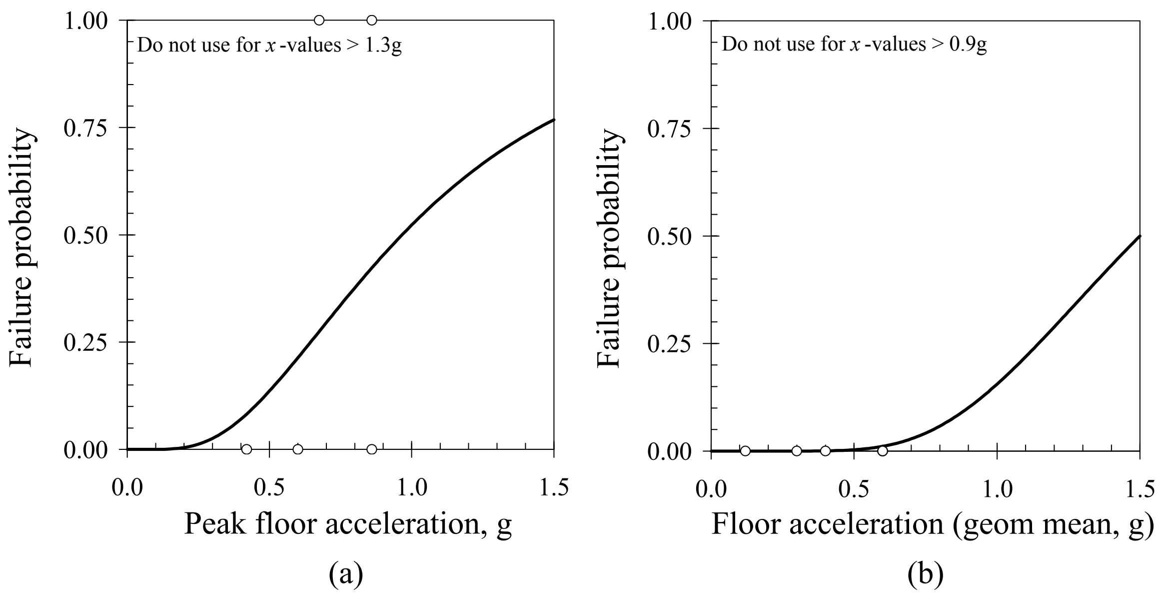



**Figure 6. Cooling towers (a) installation category 2 (b) installation category 3**

## DIESEL GENERATORS

**Table 17. Diesel towers, installation category 1**

| PGA, g | M, units | m, failed | f = m/M | Comment |
|---|---|---|---|---|
| 0.37 | 3 | 0 | 0 | |
| 0.42 | 2 | 0 | 0 | |
| 0.42 | 2 | 1 | 0.5 | Failed relay in control panel. |
| 0.55 | 1 | 0 | 0 | |

**Table 18. Diesel towers, installation category 2**

| PFA, g | M, units | m, failed | f = m/M | Comment |
|---|---|---|---|---|
| 0.23 | 4 | 0 | 0 | |
| 0.25 | 3 | 0 | 0 | |
| 0.40 | 6 | 0 | 0 | |
| 0.42 | 1 | 0 | 0 | |
| 0.42 | 1 | 0 | 0 | |

**Table 19. Diesel towers, installation category 3**

| PFA, g | M, units | m, failed | f = m/M | Comment |
|---|---|---|---|---|
| 0.12 | 1 | 1 | 1 | |
| 0.14 | 1 | 0 | 0 | |
| 0.20 | 3 | 0 | 0 | |
| 0.20 | 17 | 0 | 0 | |
| 0.20 | 4 | 0 | 0 | |
| 0.25 | 13 | 0 | 0 | |
| 0.25 | 15 | 0 | 0 | |
| 0.25 | 1 | 0 | 0 | |
| 0.25 | 1 | 0 | 0 | |
| 0.25 | 13 | 0 | 0 | |
| 0.25 | 1 | 1 | 1 | Burned outboard pillow block bearing because of differential settlement between bearing support and diesel generator. |
| 0.26 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 6 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 3 | 2 | 0.67 | Fuel lines serving the diesels pulled apart due to differential displacement imposed by ground failure beneath the concrete mats. |
| 0.30 | 5 | 3 | 0.60 | Differential settlement broke lube oil and cooling water pipes in 3 units, caused misalignment of drive shaft in 1. |
| 0.40 | 2 | 0 | 0 | |
| 0.40 | 2 | 0 | 0 | |
| 0.40 | 1 | 0 | 0 | |
| 0.40 | 6 | 0 | 0 | |
| 0.40 | 4 | 0 | 0 | |
| 0.50 | 1 | 0 | 0 | |
| 0.50 | 3 | 0 | 0 | |
| 0.50 | 1 | 0 | 0 | |
| 0.60 | 18 | 0 | 0 | |
| 0.85 | 1 | 0 | 0 | |

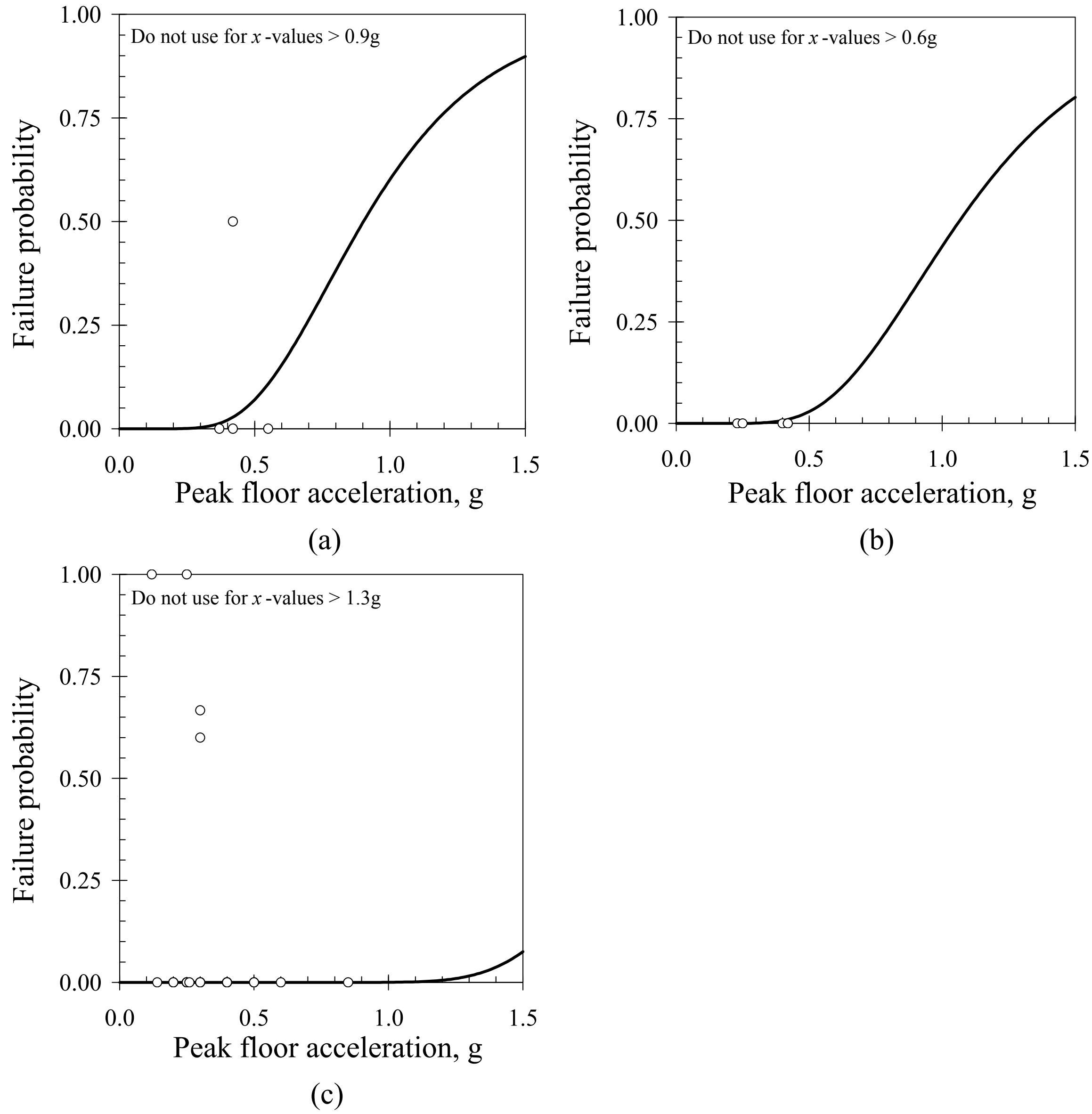



**Figure 7. Diesel generators (a) installation category 1 (b) installation category 2 (c) installation category 3**

## DISTRIBUTION PANELS

**Table 20. Distribution panels, installation category 1**

| PFA, g | M, units | m, failed | f = m/M | Comment |
|---|---|---|---|---|
| 0.42 | 2 | 0 | 0 | |
| 0.85 | 1 | 0 | 0 | |

**Table 21. Distribution panels, installation category 3**

| PFA, g | M, units | m, failed | f = m/M | Comment |
|---|---|---|---|---|
| 0.20 | 1 | 0 | 0 | |
| 0.20 | 1 | 0 | 0 | |
| 0.20 | 2 | 0 | 0 | |
| 0.20 | 1 | 0 | 0 | |
| 0.24 | 1 | 0 | 0 | |
| 0.24 | 2 | 0 | 0 | |
| 0.24 | 1 | 0 | 0 | |
| 0.25 | 1 | 0 | 0 | |
| 0.25 | 1 | 0 | 0 | |
| 0.25 | 1 | 0 | 0 | |
| 0.25 | 2 | 0 | 0 | |
| 0.26 | 1 | 0 | 0 | |
| 0.26 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 2 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.35 | 1 | 0 | 0 | |
| 0.35 | 3 | 0 | 0 | |
| 0.40 | 1 | 0 | 0 | |
| 0.40 | 1 | 0 | 0 | |
| 0.40 | 3 | 0 | 0 | |
| 0.40 | 1 | 0 | 0 | |
| 0.40 | 1 | 0 | 0 | |
| 0.40 | 8 | 0 | 0 | |
| 0.40 | 1 | 0 | 0 | |
| 0.40 | 2 | 0 | 0 | |
| 0.40 | 6 | 1 | 0.17 | Loose bus bars contacted and shorted the unit |
| 0.40 | 2 | 0 | 0 | |
| 0.40 | 1 | 0 | 0 | |
| 0.40 | 5 | 0 | 0 | |
| 0.42 | 1 | 0 | 0 | |
| 0.42 | 1 | 0 | 0 | |
| 0.50 | 2 | 0 | 0 | |
| 0.56 | 1 | 0 | 0 | |
| 0.56 | 1 | 0 | 0 | |
| 0.60 | 2 | 0 | 0 | GERS |
| 0.60 | 1 | 0 | 0 | |
| 0.85 | 2 | 0 | 0 | |
| 1.16 | 2 | 0 | 0 | GERS |
| 1.52 | 3 | 0 | 0 | GERS |
| 2.00 | 9 | 0 | 0 | GERS |

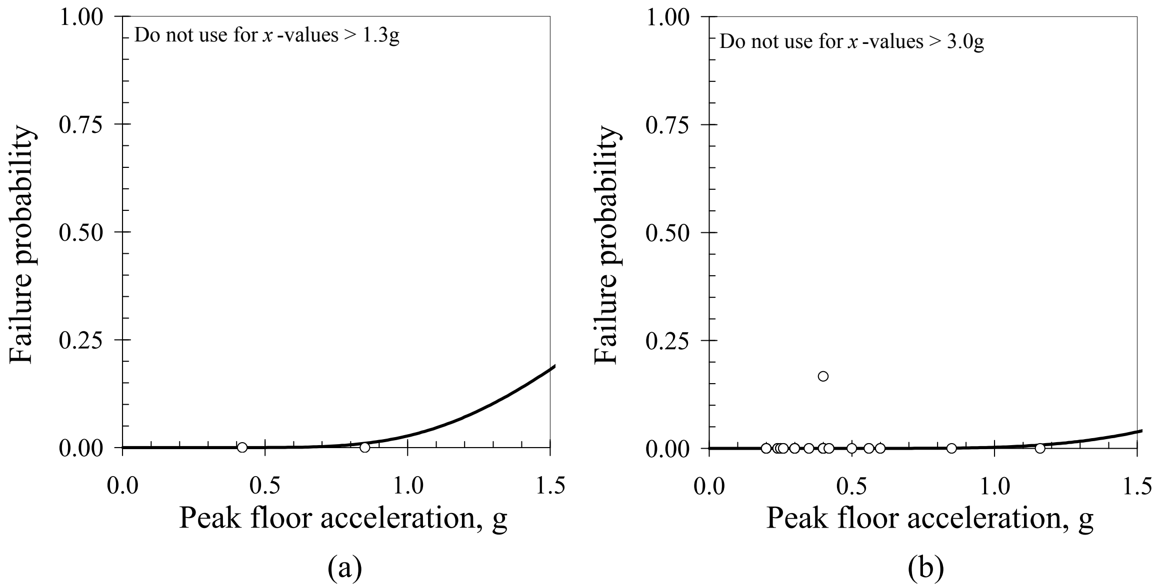



**Figure 8. Distribution panels (a) installation category 1 (b) installation category 3**

## HVAC FANS

**Table 22. HVAC fans, installation category 2**

| PFA, g | M, units | m, failed | f = m/M | Comment |
|---|---|---|---|---|
| 0.35 | 1 | 0 | 0 | |
| 0.44 | 1 | 1 | 1 | Dismounted from isolators, operative once remounted |
| 0.53 | 1 | 0 | 0 | |
| 0.61 | 1 | 0 | 0 | |
| 0.61 | 2 | 2 | 1 | Dismounted, 1 had damaged bellows and restraints; both operable once remounted & duct and supports repaired |
| 0.65 | 1 | 0 | 0 | |
| 0.70 | 2 | 0 | 0 | |
| 0.70 | 9 | 0 | 0 | |
| 0.70 | 6 | 0 | 0 | |
| 0.70 | 1 | 0 | 0 | |
| 0.70 | 2 | 2 | 1 | Dismounted from isolators; 1 operable after re-mounting, 1 required repairs |
| 0.70 | 6 | 6 | 1 | Dismounted from isolators; all operable after re-mounting |
| 0.70 | 7 | 7 | 1 | Dismounted from isolators; all operable after re-mounting except 1 |
| 0.88 | 3 | 0 | 0 | |
| 0.88 | 5 | 0 | 0 | |
| 0.88 | 6 | 0 | 0 | |
| 0.88 | 3 | 0 | 0 | |
| 0.88 | 1 | 1 | 1 | Broken cast iron isolators, dismounted; operable after re-mounting |

**Table 23. HVAC fans, installation category 3**

| PFA, g | M, units | m, failed | f = m/M | Comment |
|---|---|---|---|---|
| 0.35 | 5 | 0 | 0 | |
| 0.35 | 2 | 0 | 0 | |
| 0.35 | 1 | 0 | 0 | |
| 0.35 | 12 | 0 | 0 | |
| 0.35 | 4 | 0 | 0 | |
| 0.42 | 2 | 0 | 0 | |
| 0.42 | 1 | 0 | 0 | |
| 0.42 | 1 | 0 | 0 | |
| 0.44 | 1 | 0 | 0 | |
| 0.44 | 5 | 0 | 0 | |
| 0.44 | 2 | 0 | 0 | |
| 0.44 | 1 | 0 | 0 | |
| 0.44 | 1 | 0 | 0 | |
| 0.44 | 3 | 1 | 0.33 | Ground settlement caused misalignment and contact between impeller and housing |
| 0.45 | 2 | 0 | 0 | |
| 0.45 | 2 | 0 | 0 | |
| 0.53 | 1 | 0 | 0 | |
| 0.53 | 1 | 0 | 0 | |
| 0.53 | 14 | 0 | 0 | |
| 0.53 | 20 | 0 | 0 | |
| 0.53 | 2 | 0 | 0 | |
| 0.56 | 3 | 0 | 0 | |

| PFA, g | M, units | m, failed | f = m/M | Comment |
|---|---|---|---|---|
| 0.56 | 1 | 0 | 0 | |
| 0.70 | 2 | 0 | 0 | |
| 0.70 | 2 | 0 | 0 | |
| 0.70 | 2 | 0 | 0 | |
| 0.73 | 2 | 0 | 0 | |
| 0.73 | 2 | 0 | 0 | |
| 0.82 | 3 | 0 | 0 | |
| 1.05 | 1 | 0 | 0 | |

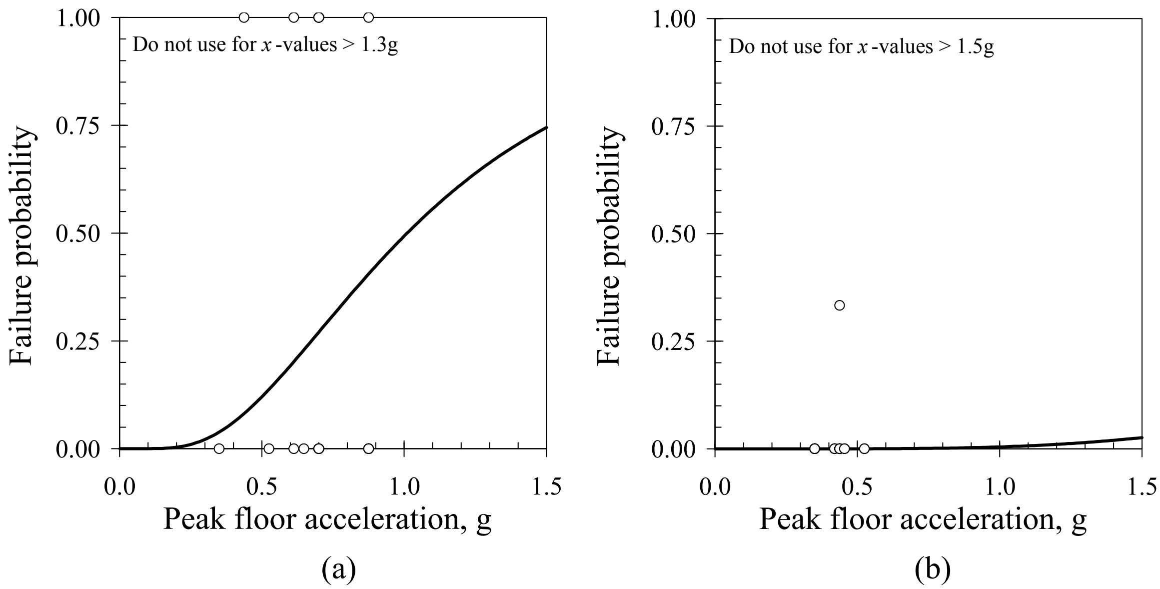



**Figure 9. HVAC fans (a) installation category 2 (b) installation category 3**

## LOW VOLTAGE SWITCHGEAR

**Table 24. Low voltage switchgear, installation category 1**

| PFA, g | M, units | m, failed | f = m/M | Comment |
|---|---|---|---|---|
| 0.25 | 1 | 0 | 0 | |
| 0.30 | 2 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.35 | 1 | 0 | 0 | |
| 0.35 | 1 | 0 | 0 | |
| 0.40 | 4 | 0 | 0 | |
| 0.40 | 1 | 0 | 0 | |
| 0.40 | 2 | 0 | 0 | |
| 0.51 | 2 | 0 | 0 | |

**Table 25. Low voltage switchgear, installation category 3**

| PFA, g | M, units | m, failed | f = m/M | Comment |
|---|---|---|---|---|
| 0.20 | 4 | 0 | 0 | |
| 0.20 | 4 | 0 | 0 | |
| 0.25 | 4 | 0 | 0 | |
| 0.25 | 1 | 0 | 0 | |
| 0.25 | 1 | 1 | 1 | Seismic deformation of the cabinet caused the fiberglass bus bar insulators to crack |
| 0.26 | 4 | 0 | 0 | |
| 0.30 | 5 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.40 | 2 | 0 | 0 | |
| 0.42 | 4 | 0 | 0 | |
| 0.56 | 1 | 0 | 0 | GERS |
| 0.72 | 1 | 0 | 0 | GERS |
| 0.80 | 1 | 0 | 0 | GERS |
| 1.32 | 1 | 0 | 0 | GERS |
| 1.84 | 1 | 0 | 0 | GERS |

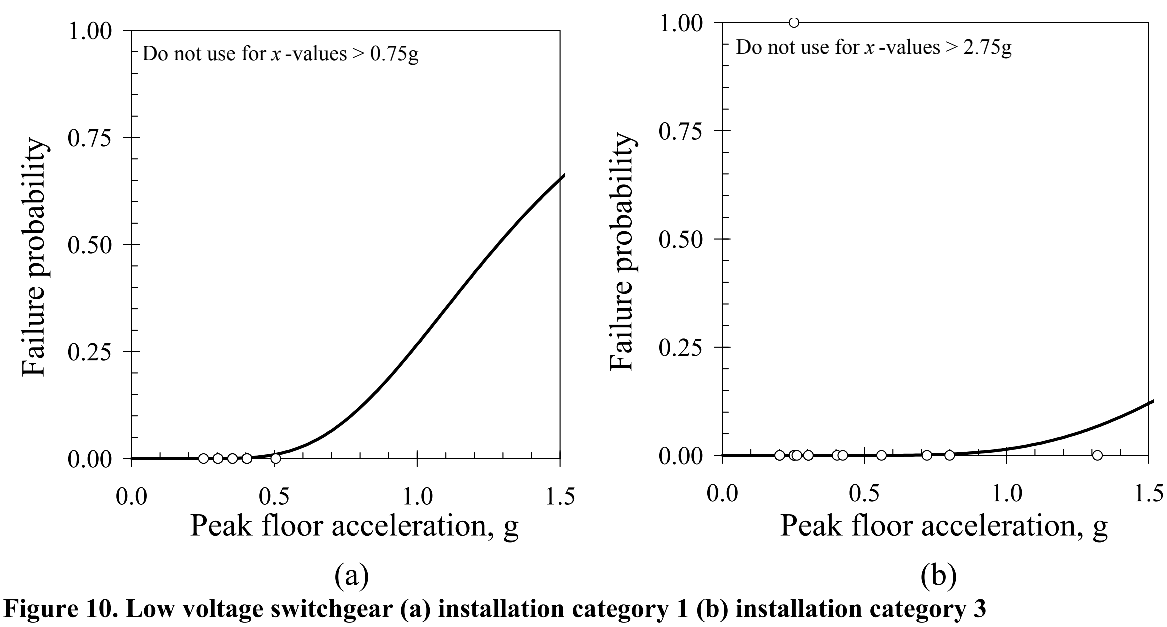



**Figure 10. Low voltage switchgear (a) installation category 1 (b) installation category 3**

**MOTOR CONTROL CENTERS**

**Table 26. Motor control centers, installation category 1**

| PFA, g | M, units | m, failed | f = m/M | Comment |
|---|---|---|---|---|
| 0.24 | 5 | 0 | 0 | |
| 0.30 | 5 | 0 | 0 | |
| 0.30 | 6 | 1 | 0.17 | Overturning of unanchored, bottom-fed MCC |
| 0.35 | 6 | 0 | 0 | |
| 0.35 | 2 | 0 | 0 | |
| 0.41 | 2 | 0 | 0 | |
| 0.41 | 1 | 0 | 0 | |
| 0.55 | 1 | 1 | 1 | Overturning of unanchored, bottom-fed MCC |
| 0.55 | 1 | 0 | 0 | |
| 0.59 | 1 | 0 | 0 | |

**Table 27. Motor control centers, installation category 3**

| PFA, g | M, units | m, failed | f = m/M | Comment |
|---|---|---|---|---|
| 0.24 | 2 | 0 | 0 | |
| 0.24 | 1 | 0 | 0 | |
| 0.24 | 1 | 0 | 0 | |
| 0.24 | 1 | 0 | 0 | |
| 0.24 | 1 | 0 | 0 | |
| 0.24 | 2 | 0 | 0 | |
| 0.24 | 1 | 0 | 0 | |
| 0.24 | 6 | 0 | 0 | |
| 0.24 | 1 | 0 | 0 | |
| 0.24 | 1 | 0 | 0 | |
| 0.24 | 1 | 0 | 0 | |
| 0.24 | 1 | 0 | 0 | |
| 0.24 | 1 | 0 | 0 | |
| 0.24 | 1 | 0 | 0 | |
| 0.24 | 1 | 0 | 0 | |
| 0.24 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 2 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 2 | 0 | 0 | |
| 0.30 | 4 | 0 | 0 | |
| 0.30 | 2 | 0 | 0 | |
| 0.30 | 2 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 2 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 12 | 9 | 0.75 | Sheared screws attaching the sheet metal panels to |

| PFA, g | M, units | m, failed | f = m/M | Comment |
|---|---|---|---|---|
| | | | | the rear of the MCC. Some buckled sheet-metal cubicles. Some cracked insulated casings of internal components. Cracking of internal components in 6 out of 12 MCCs. Some cracked fiberglass insulators hold vertical busbars in position. |
| 0.31 | 1 | 0 | 0 | |
| 0.31 | 1 | 0 | 0 | |
| 0.31 | 1 | 0 | 0 | |
| 0.31 | 1 | 0 | 0 | |
| 0.31 | 1 | 0 | 0 | |
| 0.31 | 1 | 0 | 0 | |
| 0.32 | 1 | 0 | 0 | GERS |
| 0.35 | 1 | 0 | 0 | |
| 0.35 | 1 | 0 | 0 | |
| 0.35 | 1 | 0 | 0 | |
| 0.35 | 1 | 0 | 0 | |
| 0.35 | 2 | 0 | 0 | |
| 0.35 | 2 | 0 | 0 | |
| 0.35 | 1 | 0 | 0 | |
| 0.35 | 1 | 0 | 0 | |
| 0.35 | 2 | 0 | 0 | |
| 0.38 | 4 | 0 | 0 | |
| 0.38 | 2 | 0 | 0 | |
| 0.41 | 5 | 0 | 0 | |
| 0.41 | 4 | 0 | 0 | |
| 0.41 | 12 | 0 | 0 | |
| 0.41 | 1 | 0 | 0 | |
| 0.41 | 1 | 0 | 0 | |
| 0.41 | 1 | 0 | 0 | |
| 0.41 | 1 | 0 | 0 | |
| 0.41 | 1 | 0 | 0 | |
| 0.44 | 1 | 0 | 0 | |
| 0.44 | 1 | 0 | 0 | |
| 0.47 | 1 | 0 | 0 | |
| 0.47 | 2 | 0 | 0 | |
| 0.47 | 2 | 0 | 0 | |
| 0.47 | 2 | 0 | 0 | |
| 0.47 | 4 | 0 | 0 | |
| 0.47 | 1 | 0 | 0 | |
| 0.47 | 1 | 0 | 0 | |
| 0.47 | 1 | 0 | 0 | |
| 0.47 | 1 | 0 | 0 | |
| 0.47 | 1 | 0 | 0 | |
| 0.47 | 1 | 0 | 0 | |
| 0.47 | 1 | 0 | 0 | |
| 0.47 | 1 | 0 | 0 | |
| 0.47 | 1 | 0 | 0 | |
| 0.47 | 1 | 0 | 0 | |
| 0.47 | 1 | 0 | 0 | |
| 0.47 | 2 | 0 | 0 | |
| 0.48 | 1 | 0 | 0 | GERS |
| 0.50 | 1 | 0 | 0 | |
| 0.50 | 1 | 0 | 0 | |
| 0.50 | 1 | 0 | 0 | |

| PFA, g | M, units | m, failed | f = m/M | Comment |
|---|---|---|---|---|
| 0.50 | 1 | 0 | 0 | |
| 0.50 | 1 | 0 | 0 | |
| 0.50 | 1 | 0 | 0 | |
| 0.50 | 1 | 0 | 0 | |
| 0.55 | 1 | 0 | 0 | |
| 0.55 | 4 | 0 | 0 | |
| 0.59 | 1 | 0 | 0 | |
| 0.59 | 1 | 0 | 0 | |
| 0.59 | 2 | 0 | 0 | |
| 0.59 | 6 | 0 | 0 | |
| 0.59 | 7 | 0 | 0 | |
| 0.59 | 5 | 0 | 0 | |
| 0.59 | 2 | 0 | 0 | |
| 0.59 | 1 | 0 | 0 | |
| 0.66 | 2 | 0 | 0 | |
| 0.66 | 2 | 0 | 0 | |
| 0.71 | 1 | 0 | 0 | |
| 0.71 | 1 | 0 | 0 | |
| 0.71 | 2 | 0 | 0 | |
| 0.72 | 1 | 0 | 0 | GERS |
| 0.72 | 1 | 0 | 0 | GERS |
| 0.72 | 1 | 0 | 0 | GERS |
| 0.88 | 1 | 1 | 1 | GERS: all 4 corners of the frame base broke away |
| 1.00 | 1 | 0 | 0 | GERS |
| 1.04 | 1 | 0 | 0 | GERS |
| 1.20 | 1 | 0 | 0 | GERS |
| 1.20 | 1 | 0 | 0 | GERS |
| 1.20 | 1 | 0 | 0 | GERS |
| 1.48 | 1 | 0 | 0 | GERS |
| 1.48 | 1 | 0 | 0 | GERS |
| 1.60 | 1 | 0 | 0 | GERS |
| 2.00 | 1 | 0 | 0 | GERS |

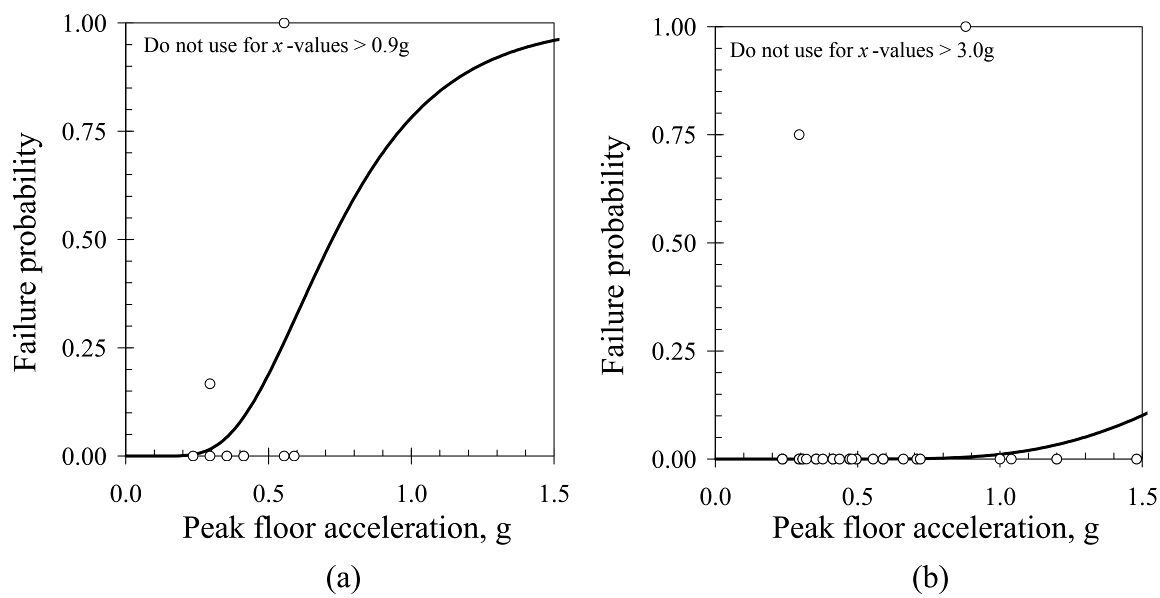



**Figure 11. Motor control centers (a) installation category 1 (b) installation category 3**

## PACKAGED AIR HANDLING UNITS

**Table 28. Packaged air handling units, installation category 1**

| PFA, g | M, units | m, failed | f = m/M | Comment |
|---|---|---|---|---|
| 0.10 | 6 | 0 | 0 | Faked-in data. No other established method seems to exist to deal with the case where all specimens failed |
| 0.62 | 6 | 6 | 1 | 4 units broke isolator springs and duct separated from displacement. 6 units shifted causing attachment damage |

**Table 29. Packaged air handling units, installation category 3**

| PFA, g | M, units | m, failed | f = m/M | Comment |
|---|---|---|---|---|
| 0.31 | 3 | 1 | 0.33 | Threaded line cracked at coil attachment (diff. displ.) |
| 0.39 | 4 | 0 | 0 | |
| 0.39 | 3 | 0 | 0 | |
| 0.47 | 1 | 0 | 0 | |
| 0.57 | 3 | 0 | 0 | |
| 0.62 | 1 | 0 | 0 | |
| 0.62 | 2 | 0 | 0 | |
| 0.62 | 2 | 0 | 0 | |
| 0.62 | 1 | 0 | 0 | |
| 0.62 | 4 | 1 | 0.25 | Rod hung PVC broke at attachment to unit |
| 0.62 | 9 | 1 | 0.11 | Rod hung units had leaks from attached lines |
| 0.62 | 4 | 4 | 1.00 | Ducting pulled apart at several seams. PVC water lines fractured in 4 locations. |
| 0.65 | 2 | 0 | 0 | |
| 0.65 | 2 | 2 | 1.00 | Swaying of rod hung unit broke attached piping |
| 0.78 | 54 | 5 | 0.09 | Units dismounted from isolators causing piping damage |
| 0.87 | 2 | 0 | 0 | |
| 0.93 | 6 | 0 | 0 | |

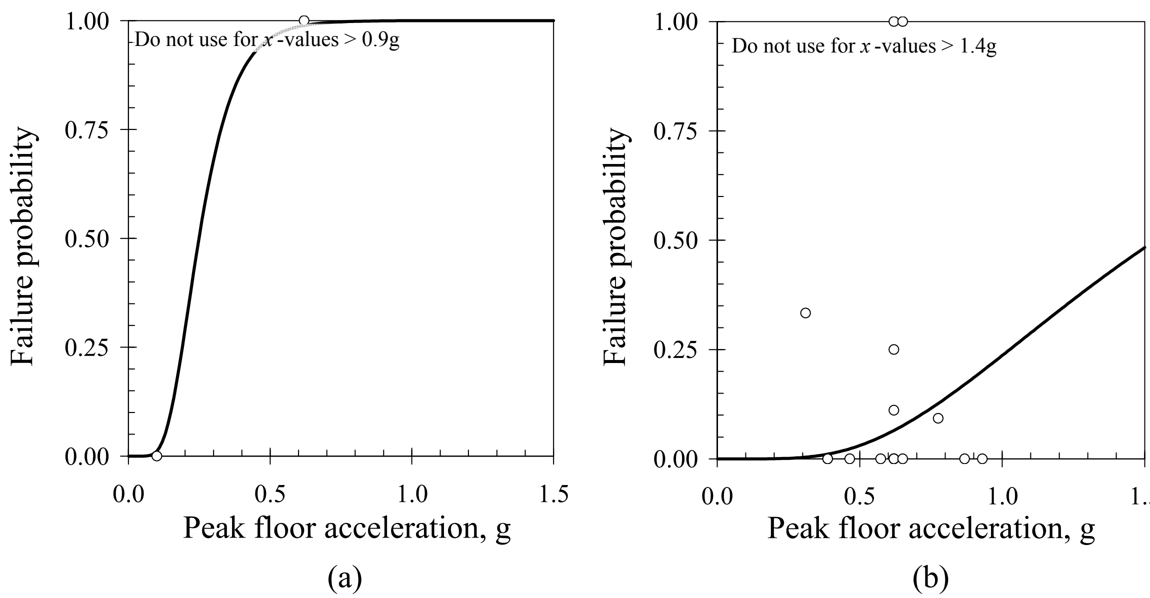



**Figure 12. Packaged air handling units (a) installation category 1 (b) installation category 3**

**TRANSFORMERS**

**Table 30. Transformers, installation category 1**

| PFA, g | M, units | m, failed | f = m/M | Comment |
|---|---|---|---|---|
| 0.25 | 3 | 0 | 0 | |
| 0.25 | 1 | 0 | 0 | |
| 0.25 | 1 | 0 | 0 | |
| 0.25 | 1 | 0 | 0 | |
| 0.25 | 1 | 0 | 0 | |
| 0.25 | 1 | 0 | 0 | |
| 0.25 | 2 | 1 | 0.5 | Unanchored transformer overturned |
| 0.25 | 20 | 1 | 0.05 | Internal ground fault in an internal bus connection |
| 0.26 | 2 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 2 | 0 | 0 | |
| 0.35 | 1 | 0 | 0 | |
| 0.40 | 3 | 0 | 0 | |
| 0.40 | 1 | 0 | 0 | |
| 0.40 | 1 | 0 | 0 | |
| 0.40 | 20 | 0 | 0 | |
| 0.40 | 1 | 0 | 0 | |
| 0.42 | 2 | 0 | 0 | |
| 0.47 | 3 | 2 | 0.67 | Shifted off platform, restrained from toppling by truss |
| 0.47 | 1 | 0 | 0 | |
| 0.60 | 1 | 0 | 0 | |
| 0.60 | 1 | 0 | 0 | |

**Table 31. Transformers, installation category 3**

| PFA, g | M, units | m, failed | f = m/M | Comment |
|---|---|---|---|---|
| 0.20 | 1 | 0 | 0 | |
| 0.20 | 2 | 0 | 0 | |
| 0.20 | 3 | 0 | 0 | |
| 0.20 | 3 | 0 | 0 | |
| 0.20 | 1 | 0 | 0 | |
| 0.20 | 1 | 0 | 0 | GERS |
| 0.20 | 1 | 0 | 0 | GERS |
| 0.20 | 1 | 0 | 0 | |
| 0.20 | 1 | 0 | 0 | |
| 0.20 | 2 | 0 | 0 | |
| 0.20 | 1 | 0 | 0 | |
| 0.24 | 1 | 0 | 0 | |
| 0.24 | 1 | 0 | 0 | |
| 0.24 | 1 | 0 | 0 | |
| 0.25 | 1 | 0 | 0 | |
| 0.25 | 1 | 0 | 0 | |
| 0.25 | 1 | 0 | 0 | |
| 0.25 | 1 | 0 | 0 | |
| 0.25 | 1 | 0 | 0 | |
| 0.25 | 20 | 0 | 0 | |
| 0.26 | 1 | 0 | 0 | |
| 0.26 | 2 | 0 | 0 | |
| 0.26 | 3 | 0 | 0 | |
| 0.26 | 2 | 0 | 0 | |
| 0.26 | 2 | 0 | 0 | |

| PFA, g | M, units | m, failed | f = m/M | Comment |
|---|---|---|---|---|
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 1 | 0 | 0 | |
| 0.30 | 2 | 0 | 0 | |
| 0.35 | 1 | 0 | 0 | |
| 0.37 | 1 | 0 | 0 | |
| 0.40 | 4 | 0 | 0 | |
| 0.40 | 1 | 0 | 0 | |
| 0.40 | 4 | 0 | 0 | |
| 0.40 | 1 | 0 | 0 | |
| 0.40 | 1 | 0 | 0 | |
| 0.40 | 1 | 0 | 0 | |
| 0.40 | 1 | 0 | 0 | |
| 0.40 | 2 | 0 | 0 | |
| 0.40 | 1 | 0 | 0 | |
| 0.40 | 1 | 0 | 0 | |
| 0.42 | 1 | 0 | 0 | |
| 0.42 | 1 | 0 | 0 | |
| 0.42 | 3 | 0 | 0 | |
| 0.42 | 2 | 0 | 0 | |
| 0.42 | 2 | 0 | 0 | |
| 0.42 | 1 | 0 | 0 | |
| 0.47 | 1 | 0 | 0 | |
| 0.47 | 2 | 0 | 0 | |
| 0.47 | 2 | 0 | 0 | |
| 0.50 | 1 | 0 | 0 | |
| 0.56 | 1 | 0 | 0 | |
| 0.56 | 1 | 0 | 0 | |
| 0.60 | 1 | 0 | 0 | |
| 0.60 | 1 | 0 | 0 | |
| 0.60 | 1 | 0 | 0 | |
| 0.80 | 1 | 0 | 0 | GERS |
| 1.28 | 1 | 0 | 0 | GERS |
| 1.44 | 1 | 1 | 1 | GERS |
| 2.60 | 1 | 0 | 0 | GERS |

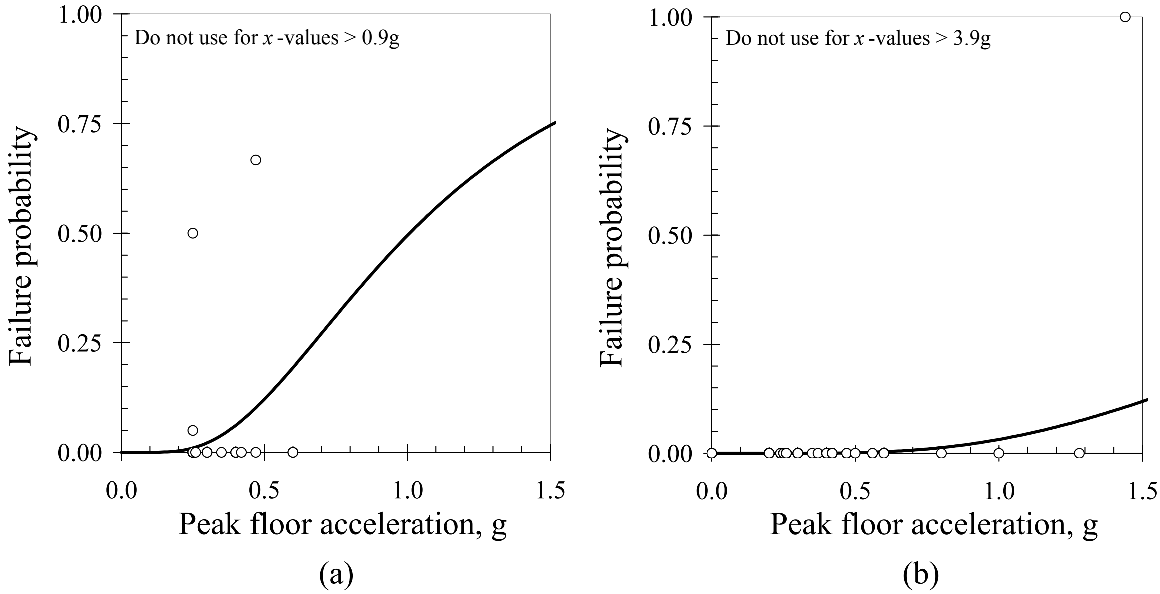



**Figure 13. Transformers (a) installation category 1 (b) installation category 3**