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# Appropriate Seismic Reliability for Critical Equipment Systems: Recommendations Based on Regional Analysis of Financial and Life Loss

by

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Technical Report MCEER-98-0016

November 10, 1998

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# Preface

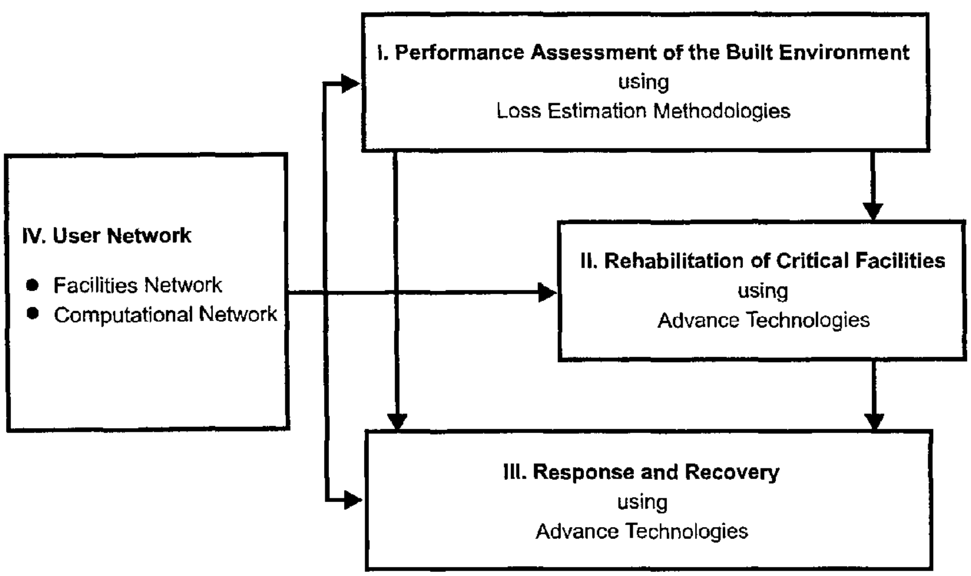
The Multidisciplinary Center for Earthquake Engineering Research (MCEER) is a national center of excellence in advanced technology applications that is dedicated to the reduction of earthquake losses nationwide. Headquartered at the University at Buffalo, State University of New York, the Center was originally established as the National Center for Earthquake Engineering Research (NCEER) by the National Science Foundation in 1986.

Comprising a consortium of researchers from a range of disciplines and over a dozen academic institutions and research organizations throughout the United States, the Center's mission is to reduce earthquake losses through research and the application of advanced technologies that improve engineering, pre-earthquake planning and post-earthquake recovery strategies. Toward this end, the Center coordinates a nationwide program of multidisciplinary team research, education and outreach activities.

MCEER's research is conducted under the sponsorship of two major federal agencies: the National Science Foundation (NSF) and the Federal Highway Administration (FHWA), and the State of New York. Significant support is derived from the Federal Emergency Management Agency (FEMA), other state governments, academic institutions, foreign governments and private industry.

The Center's NSF-sponsored research is focused around four major thrusts, as shown in the figure below:

- quantifying building and lifeline performance in future earthquake through the estimation of expected losses;
- developing cost-effective performance-based rehabilitation technologies for critical facilities;
- improving response and recovery through strategic planning and crisis management;
- establishing and operating two user networks, one in experimental facilities and computing environments and the other in computational and analytical resources.



*This study recommends a minimum seismic reliability level for critical equipment systems located in seismically vulnerable facilities. It describes a methodology to achieve cost-effective risk mitigation and applies that methodology to a test case involving an automatic sprinkler system in a high-rise building. The study builds on previously published works in this area that provide guidelines for identifying equipment systems that are important for either the normal operation of a facility or for life safety protection. By making it possible to calculate quantitative risk scores, the methodology provides a basis both for evaluating the seismic adequacy of equipment systems and for making cost-effective equipment retrofit decsions. The methodology is primarily for use in areas of high seismicity.*

*In addition to this report, an inventory of taxable high-rise buildings in San Francisco (as of January 1997) in spreadsheet format (Excel 97 and Lotus 1-2-3 version 3, leaf "Inventory" or "B", respectively) is located in the Publications section of MCEER's web site (http://mceer.buffalo.edu/pubs.html).*

## ABSTRACT

This study recommends minimum seismic reliability levels for critical equipment systems (CES) in critical facilities subject to seismic risk. *Seismic reliability* refers to the probability that an equipment system will perform its required function after an earthquake. For example, this study recommends that a fire detection and alarm system in a California office building should be expected to survive the 475-year earthquake and remain operational afterwards, with a probability of 99.9%, which is equivalent to a 0.1% probability of not operating after the 475-year earthquake.

Simple tools for identifying CES and evaluating their current reliability are provided in a companion study by Johnson, Sheppard, Quilici, and others (1998), entitled *Seismic Reliability Assessment of Critical Facilities: A Handbook.* The *Handbook* provides worksheets and computational tools to evaluate risk operational failure of an existing CES subjected to the design-basis earthquake (DBE). Using these tools, a facility operator evaluates a scalar risk score S, typically on the order of 0 to 6, for each existing CES. A higher score indicating a lower failure probability ($P_f \approx 10^{-S}$ given the DBE).

The score should be compared with institution reliability goals to determine adequacy. However, in cases where the institution has not set minimum performance goals, the minimum risk scores recommended here can be employed. If the operator calculates a risk score below the tolerable minimum, this indicates the advisability of seismic retrofit or further, more detailed analysis. If the calculated risk score is greater than the tolerable minimum, then the CES is estimated to meet or exceed comparable reliability standards for other building components. Minimum risk scores depend on facility type and CES life-safety role, and are summarized in the table below.

Appropriate levels of seismic reliability for CES were evaluated based on modeling in the highly seismic San Francisco Bay Area. The modeling involves computer simulation of CES in the inventory of high rise buildings for the region, and examination of potential life and financial losses under varying criteria.

The use of the combined methodology offers facility operators a rapid visual screening technique to evaluate the seismic adequacy of equipment, in a way similar to structural screening techniques such as ATC-21. It also provides insight into the main contributors to CES seismic risk, and thus to cost-effective remedies. It produces a comprehensible, quantitative measure of CES seismic risk – namely, probability of operational failure – that is comparable with other, more familiar risk sources. Finally, it offers decision-makers a basis for judging the tolerability of current CES seismic risk in light of current practice.

| Facility class | Life-safety CES | Operational CES |
|---|---|---|
| Essential (emergency response) | 4 | 3 |
| Ordinary | 3 | 2 |

* A score of 4 indicates $10^{-4}$ or 0.01% maximum tolerable probability of failure in the DBE; 3 indicates 0.1%; 2 indicates 1% failure probability.

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# SECTION 1
# INTRODUCTION

## 1.1 Background

Buildings in the United States are designed to resist a variety of extreme loading conditions: earthquake, severe windstorms, heavy snowfall accumulation, high live loads from occupants and furniture, unexpectedly high dead loads from permanent features of the building, and other situations. Structural design philosophy has long had as its main objective that these loading conditions could occur any time during the design life of the building, and, with a high degree of confidence, the structure would be strong and stiff enough to resist them and remain safe to occupy.

The advent of load and resistance factor design (LRFD) procedures introduced into design the notion that this confidence level could be quantified. Structural engineers design buildings using LRFD so that during the design life (typically taken as 50 years), with greater than some generally agreed-upon probability, the structural components of a building would remain life-safe, i.e., would not collapse, during any extreme-loading condition that might arise. The same cannot be said of critical equipment systems (CES), some of which are crucial to life safety. Examples include fire detection and suppression systems in ordinary buildings, switching equipment in telephone central offices that transmit 911 calls, operational equipment in hospitals, etc. Other CES may not be required for life safety, but their failure can cause extensive economic costs to the owner or to society in general. Examples include the computer equipment for a large regional bank, manufacturing equipment owned by a major electronics firm, etc.

## 1.2 Objectives

Addressing the issue of tolerable equipment risk for seismic loading was the primary focus of the present study, and of a companion study by Johnson and others (1998). This companion study, *Seismic Reliability Assessment of Critical Facilities*, developed simple tools to assess the seismic reliability of individual pieces of equipment subjected to design-basis earthquake (DBE, a 475-year event). The tools also provide a simplified version of fault-tree analysis to estimate the seismic reliability of entire equipment systems. For example, one estimates the probability that the battery racks of an uninterruptible power source (UPS) would remain operational after the DBE, then does so for the inverters, switchgear, and other UPS components. Then, using the tree analysis method, one develops an estimate of the probability that electric power will be available to computers in a large computer data center after the DBE.

It was the objective of our study to recommend a normative measure of this probability: that is, what the equipment system's reliability *should be*. Whatever its defects at the component level, if an equipment system achieves this target reliability, it may be considered adequately safe, and need not be strengthened. If it does not meet this objective, then various retrofit schemes can be considered, and the one that causes the target reliability to be met at the lowest cost can be chosen and implemented. The present report details our study of tolerable equipment risk both for life-safety equipment and operational equipment.

Combined with the tools of *Seismic Reliability Assessment* handbook , this study provides operators of important facilities with a yardstick to measure seismic risk of CES failure, along with guidelines for judging the tolerability of that risk. It offers the means to perform rapid visual screening of equipment for post-earthquake operational risk, in basically the same terms as ATC-21 (Applied Technology Council, 1988) produces for seismic risk of structural collapse.

The combined study employs the powerful tools of fault-tree analysis, draws upon an extensive database of equipment seismic performance, and presents them in a rapid, simple approach. The combined methodology can provide valuable insight into the main contributors to equipment risk, as well as helping facility operators identify cost-effective remedies. It employs a comprehensible quantitative measure of risk – namely, probability of operational failure – that is comparable with other, familiar risk sources. It gives the decision-maker a supplementary basis for judging the tolerability of current CES risk (supplementary to any internal organizational risk goals), in light of current practice. Finally, because tolerability guidelines are based on accepted practice in closely related fields, the combined methodology helps to secure buy-in from other participants in the risk-management decision process.

## 1.3 Technical approach

For life-safety equipment, we based our analysis on the assumption that risk of death from equipment failure should be no greater than that from structural failure, and then verified the practicality and cost-effectiveness of this assumption. We began by examining the literature forming the basis for seismic reliability of structures, and found a provisional target reliability for life-safety CES. We then examined the question of whether this target was achievable, through detailed fault-tree analysis of a seismically retrofitted CES.

Finally, we examined whether this target reliability was economically justified according to a variety of current standards, using regional assessment based on modeling economic and life-safety consequences in the highly seismic San Francisco Bay Area. We gauged risk against a variety of measures of tolerability and cost effectiveness, providing depth to the defense of the provisional guidelines.

For operational equipment, we based our recommendations on a review of current practice, and an attempt to reconcile that practice with some implications of developing building-code requirements for lesser, more frequent, earthquake events.

## 1.4 Organization of this report

This section introduced the objectives and methodology employed in the present study. Section 2 presents our review of life-safety risk metrics, and recommends a tolerable risk score, in the context of the *Seismic Reliability Assessment* guidelines. Section 3 presents the development of an inventory of highrise buildings in the San Francisco Bay area, and describes an analysis of life-safety and economic risk posed by the failure of automatic sprinklers (AS) in those buildings. Acceptable risk from operational equipment is assessed in Section 4. Section 5 presents conclusions and recommendations. References are provided in Section 6.

Five appendices provide supporting documentation. Appendix A details development of square-foot replacement costs (new) for the highrise building inventory. Occupant loads are detailed in Appendix B. Appendix C provides field definitions for the electronic database of highrise buildings accompanying this report. Appendix D contains a glossary of technical terms used throughout this report. Appendix E summarizes the seismic reliability assessment proposed by Johnson et al.

### 1.5 Acknowledgments

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# SECTION 2
# PERFORMANCE GOALS FOR LIFE-SAFETY EQUIPMENT

## 2.1 Code-tolerable risk of structural failure

**Relevant building codes.** The place to start looking for tolerable death risk from seismic structural failure is the building code. The dominant US codes are the *Uniform Building Code* (UBC, International Conference of Building Officials, 1997 etc.), the *Standard Building Code* (Southern Building Code Congress, various) and BOCA *National Building Code* (Building Officials and Code Administrators International, various). The UBC is the most advanced of the three in seismic issues, so we pursued its sources. The UBC's seismic design requirements draw on and aim for consistency with a number of more specialized codes. Its hazard definition and loading requirements are detailed in the *Blue Book* of the Structural Engineer's Association of California (Seismology Committee, 1996), NEHRP's *Recommended Provisions* (Building Seismic Safety Council, 1991), and ANSI/ASCE-7, a joint product of the American Society of Civil Engineers (1995) and the American National Standards Institute. In addition to these standards, a number of material-specific codes serve as authorities on specific construction materials, e.g., American Concrete Institute, American Institute of Steel Construction, etc.

**Design-basis earthquake.** The model codes handle seismic risk by specifying earthquake design loading conditions and then requiring strength levels adequate to resist those loads. The earthquake condition under which the UBC's design requirements apply is the design-level earthquake (DLE): a hypothetical, large event causing ground shaking estimated to have a 10% probability of exceedance in 50 years (0.21% annual probability, 475-year return period). SEAOC refers to this same event as the design-basis earthquake (DBE).

**Code performance objectives for buildings.** While the UBC and Blue Book quantify the probability of the DBE occurring, they do not explicitly quantify an acceptable level of risk for life safety under DBE conditions. The objectives are stated qualitatively. The 1994 UBC (section 101.2) aims "To provide minimum standards to safeguard life or limb, health, property and public welfare by regulating and controlling the design construction, quality of materials, use and occupancy, location and maintenance of all buildings and structures within this jurisdiction and certain equipment specifically regulated herein."

The Blue Book recognizes that no design standard can provide for 100% confidence of life safety. In, the commentary (C101.1) emphasizes "That the purpose of these recommended design procedures is to provide buildings that are *expected* to meet this life safety objective [original emphasis] .... The protection of life is reasonably provided, but not with complete assurance." It does not, however, quantify the probability of meeting this life-safety objective. Other code sources do address this probability explicitly.

MacGregor (1988) discusses the American Concrete Institute's (ACI) early philosophy toward failure probabilities in LRFD. Codewriters intended the load factor $\alpha$ to represent a 1/1000th chance of overload during the design life of the building (due to normal dead and live loads, not earthquake), and the resistance factor $\phi$ to represent a 1/100th chance of understrength. The union of the two events, overload and understrength, resulted in an assumed safety factor of $10^{-5}$.

Several investigators (notably Cornell, 1969, Hasofer and Lind, 1974, and Galambos et al. 1980) improved on the statistical methods used for early ACI codes. These authors examined the *safety margin,* Y, the difference between strength (capacity) and load (demand). The ratio of the mean value of Y to its standard deviation they called the *reliability index,* $\beta$ (the inverse of the coefficient of variation of Y). The probability that any particular element will be overstressed during its lifetime is thus a function of $\beta$ and the distribution of Y. The shape of that distribution is typically difficult to determine; consequently knowing $\beta$ alone is useful primarily as a relative measure of safety.

Galambos et al. found that the $\beta$ reflected in existing buildings for ordinary (non-seismic) loading conditions varies between 3.0 and 4.0, depending on the suddenness and consequences of element failure. If Y were normally distributed, these values would correspond to failure probabilities between $1.3*10^{-3}$ and $3.2*10^{-5}$ per structural element during the design life of 50 years. They recommended for seismic loading a $\beta$ of 1.75, equivalent (again assuming normal distribution) to a probability on the order of 0.04 that the element will be overstressed in the design-level earthquake (Galambos et al. pp. 61, 72). Their recommendation led to load combinations (p. 74) that were taken directly into ANSI A58.1 (p. 10) and then to various building codes, e.g., AISC's Manual of Steel Construction (1986).

Again, this reliability index $\beta$ refers to failure of one building component, where failure is typically defined in the context of seismic loading as fracture, rather than yielding. Overstress of a single component is considered life-threatening damage, but is not equivalent to the probability of casualties per se. It is possible to address more directly the risk of death, which after all is the point of true interest.

Before dealing with risk of death, it is worthwhile to examine the reason for the lower $\beta$ for seismic loading. It was considered necessary because of the high cost to design buildings to resist earthquake without damage. Through the use of ductile detailing, however, a much higher safety factor against structural collapse, as opposed to element overstress, is provided, and life safety is reasonably assured. As ASCE 7 puts it (American Society of Civil Engineers, 1995, commentary section 9.1),

> **The design limit state for resistance to an earthquake is unlike that for any other load within the scope of ASCE 7. The earthquake limit state is based on upon system performance, and considerable energy dissipation through repeated cycles of inelastic straining is anticipated. The reason is the large demand exerted by the earthquake and the high cost of providing enough strength to maintain linear elastic response in ordinary buildings.**

As an interesting aside, it is noteworthy that some consider the cost-effectiveness issue arguable. A case can be made for elastic design for earthquakes, that is, buildings designed to resist earthquake loads without the substantial damage allowed by current design standards. NEHRP's *Recommended Provisions Commentary* (Building Seismic Safety Council, 1991) suggests,

> **In highly seismic areas where moderate earthquakes occur frequently, any increase in building costs will be offset by reduced costs of damage. In less seismic areas, however, seismic design requirements can be justified only in terms of life safety since the expected savings in damage during very infrequent earthquakes are not great enough to justify an average 1 percent increase in building costs.**

Now with some understanding of the philosophy behind the $\beta$ factor for seismic loading, it is worthwhile attempting to estimate its consequences in terms of death risk. The NEHRP Building Seismic Safety Council elaborates on the physical significance of the seismic safety index: "If the design ground motion were to occur, there might be life-threatening damage in 1 to 2 percent of buildings designed according to the [NEHRP] *Provisions*. (In each building so damaged, on the average, about 1 percent of occupants might be major casualties.)"

NEHRP provides a graphic, copied to Figure 2-1 below, illustrating conditional probabilities of structural collapse and of life-threatening damage, as a function of the ratio between actual ground motion and design-level ground motion. The condition *(A)* referred to on the y-axis of Figure 2-1 is the occurrence of an earthquake causing the ground shaking quantified on the x-axis. The ground-shaking parameter EPA is *effective peak acceleration*, defined as 0.4 times the 5%-damped spectral acceleration $S_a$ of a design spectrum for the period range of 0.1 to 0.5 sec (NEHRP 1991, pg. 8).

The risk of serious casualty shown in Figure 2-1 is for a single building subjected to a single earthquake. The figure suggests that 10% of buildings with life-threatening damage would suffer collapse. To recap, the NEHRP Provisions appear to tolerate the following risk levels on a per-building basis, given the occurrence of the DBE:

- 1% probability of life-threatening damage.
- 0.1% probability of collapse
- 0.01% probability of any building occupant being killed from structural damage.

It is worthwhile examining the annualized risk of death from structural failure implied by these figures. The NEHRP Provisions provide an estimate of annual exceedance probability of various levels of ground shaking; see Figure 2-2. The annual risk of death from structural damage may be estimated using Figure 2-1 and Figure 2-2. If one accepts the NEHRP hazard estimates, annual earthquake death risk for one occupant in an engineered building would be:

$$\text{Annual risk} = \int P[\text{death} \mid \text{collapse}] * P[\text{collapse} \mid \text{EPA}] * f(\text{EPA})\, d\text{EPA}$$

where

$P[\text{death} \mid \text{collapse}] = 0.1$
$P[\text{collapse} \mid \text{EPA}]$ comes from the upper structural-collapse curve in Figure 2-1

f(EPA) is the negative first derivative of the 0.4-g contour of Figure 2-2.

The integral evaluates as approximately $1.0 * 10^{-6}$ probability of death per person per year from round-the-clock occupancy in an engineered building on NEHRP's 0.4-g EPA contour. For normal office occupancy, say 45 hours per week or 27% of the time, the risk is $0.28 * 10^{-6}$ per year. For a sense of magnitude, consider that this equates, for example, with two people out of New York City per year.

Remember that this is the risk associated with structural collapse. There are other deadly hazards in earthquakes: fire following earthquake, falls, etc., and it appears that death risk from structural failure is small compared with the sum from other earthquake hazards. Fatalities in hypothetical major California earthquakes have been estimated as high as 23,000 from all causes. Table 2-1 summarizes a few of these estimates. To compare the risk estimated above with the overall risk, we first assume that the annual probability of one of these earthquakes is on the order of 1/75 (two of these events have occurred in the past 150 years). Assume further that such an event occurring today would result in 5,000 deaths (somewhere in the middle of the figures quoted in Table 2-1). Consider only the 24 million San Francisco and LA-area residents exposed to these events. Annual death risk per person may then be estimated on the order of 1/75 * 5,000/24,000,000, or $3*10^{-6}$, approximately 10 times that of structural collapse alone. It is equivalent, for example, with 20 people out of New York City per year.

To put these risks in perspective, the risk of death from a single airplane flight during the 1990s was $0.125*10^{-6}$ (Federal Aviation Administration, 1997). The risk of death from motor vehicle accidents in 1995 was $159*10^{-6}$ (Rosenberg et al., 1996). Thus, the death risk from working in an engineered building for one year is approximately double the death risk from taking a single airplane trip. The death risk from being in an engineered building *during the DBE* ($100 * 10^{-6}$) is approximately 2/3rd the annual risk of being killed in a motor vehicle accident. (These comparisons are not intended to imply anything about the acceptability of earthquake risk, rather merely to provide reference points.)

***Table 2-1 – Estimated casualties from major California earthquakes***

| **Event** | **Estimated fatalities** | **Hospitalized injuries** | **Reference** |
|---|---|---|---|
| M 8+ Southern San Andreas | 3,000 - 13,000 | | FEMA, 1981 |
| M 7.5 Newport-Inglewood | 4,000 - 23,000 | | Same |
| M 8+ Northern San Andreas | 3,000 - 8,000 | 8,000 - 18,000 | RMS, 1995 |
| M 7.5 Hayward fault | 1,500 - 4,400 | 4,500 - 13,200 | Steinbrugge et al., 1987 |

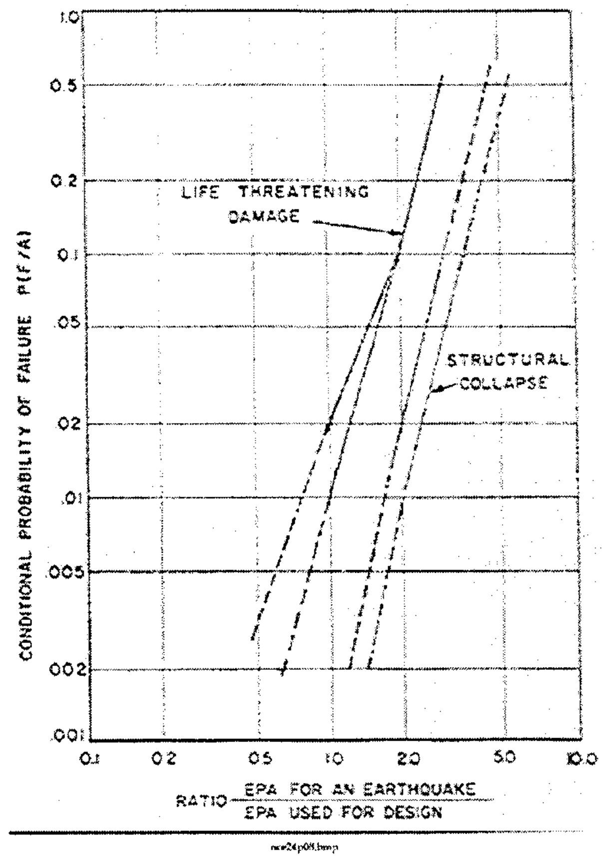


*Figure 2-1 – Per-building failure probability given an earthquake occurrence*

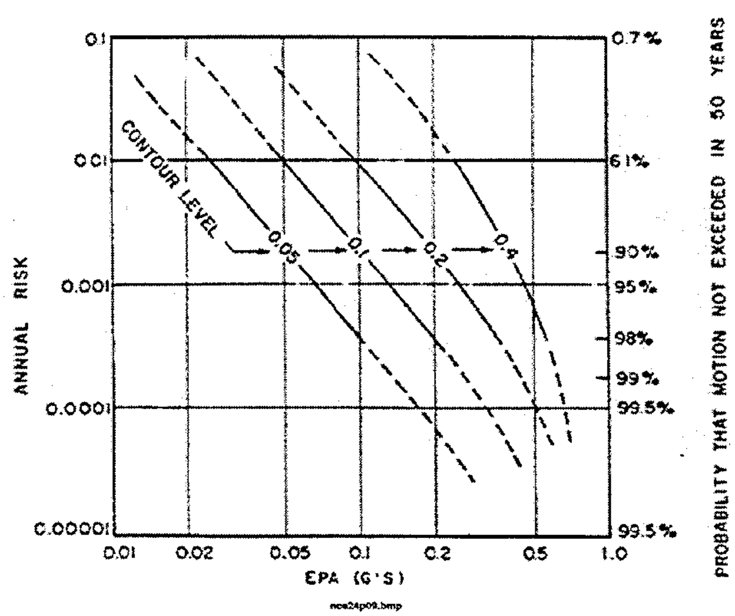


*Figure 2-2 – Annual probability of seismic shaking, by NEHRP hazard contour*

## 2.2 Provisional tolerable-risk levels for life-safety CES

There is a strong parallel between life-safety CES failure and structural collapse. Both represent the failure of entire life-safety systems. The risk tolerated for structural collapse, $10^{-3}$ in the DBE, would therefore be a reasonable tolerable-risk level for life-safety CES. Important buildings such as hospitals and other emergency-response facilities are designed to seismic loads 25% higher than ordinary buildings, according to UBC procedures, which leads to collapse probabilities almost an order of magnitude lower, according to Figure 2-2. For these facilities, a reasonable tolerable-risk level for life-safety CES would also be an order of magnitude lower. We therefore begin with the following provisional tolerable-risk levels for life-safety CES, given the DBE:

- $10^{-3}$ failure probability of life-safety CES for ordinary buildings, and
- $10^{-4}$ failure probability of life-safety CES for emergency-response facilities.

In terms of Johnson's CES risk scores, these probabilities correspond to 3 and 4, respectively. An important caveat, illustrated later, is that in some cases it may be impractical to reduce failure probability to these levels, particularly for distributed, inherently fragile systems such as automatic sprinklers. However, for these systems, practical means are available to reduce the risk substantially, and should be undertaken.

Another caveat relates to low-seismicity regions. Writers of building codes have begun to consider longer return intervals than the 475-year basis for the DBE. This period is too short to capture significant potential for casualties in regions of low to moderate seismicity but high catastrophic earthquake loss potential such as Memphis, Tennessee, or the Wasatch Front in Utah. See, for example, Taylor et al., 1992.

As a result, design criteria based on a 475-year DBE may be inappropriate to these regions of lower seismicity. However, present findings cannot address other return periods, since these findings are tied to Johnson's procedures, which were developed for the 475-year event.

We now address the question of how these recommendations compare with other sources on tolerable risk.

## 2.3 Comparison of provisional tolerable-risk levels with other sources

### 2.3.1 Vision 2000

The Vision 2000 standards, currently in development, provide insight into future code objectives for life-safety, post-earthquake functionality, and performance of building components and systems (Ref.: California Governor's Office of Emergency Services, 1995). The new standards provide these recommendations for four different earthquake scenarios ranging from frequent, small events to very rare, large-magnitude earthquakes. It is the rare 475-year event that is of interest for comparison purposes. Vision 2000 also accounts for the varying importance of different types of facilities, providing stricter standards for high-hazard and emergency-response facilities than for ordinary construction (Figure 2-3, after Appendix B-3 of the Blue Book).

Under the rare event, Vision 2000 allows light damage to fire-sprinkler piping in ordinary buildings: "Some pipes rupture at connections; many supports fail; few sprinkler heads fail." Under typical hydraulic design of automatic sprinklers, this would not cause AS failure. Wet sprinkler systems in light-hazard occupancies like homes and office buildings are designed to provide 500 to 750 gpm flow for 30 to 60 minutes, equivalent to 25 to 40 sprinklers open. For essential facilities, Vision 2000 requires a higher performance level: the building should remain operational in the DBE. Under its definition of operational, only minor damage and minor leaking are allowed for piping, and fire alarm systems must remain functional.

Vision 2000 does not quantify the degree to which its objectives should be assured. It does however support requiring the survival of life-safety equipment in ordinary buildings and operational equipment in essential facilities in the DBE. It also supports the notion that the telephone function of telephone central offices should be considered essential, and its equipment designed to be as reliable as that of hospitals, fire stations, and other emergency response facilities.

Thus it can be seen that, although Vision 2000 does not yet contain probability measures for its requirements that might be used as a check on our recommendations, it does support them in three respects:

- Vision 2000 agrees that life-safety CES should survive the DBE;
- The level of reliability should be substantially higher for essential facilities; and
- The survival of operational equipment in essential facilities is comparable to that of life-safety CES in ordinary facilities.

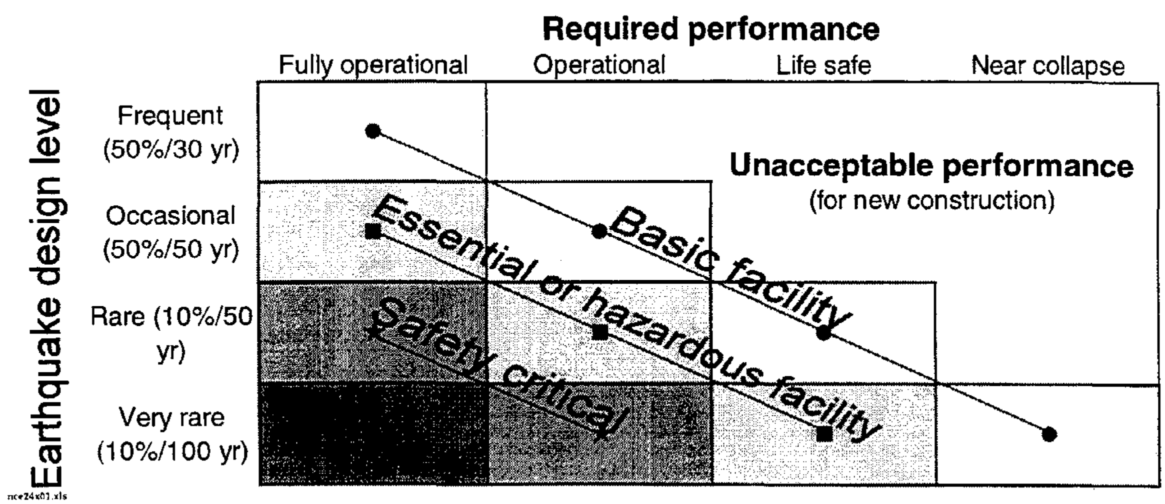


*Figure 2-3 – Vision 2000 recommended seismic performance objectives for buildings*

## 2.3.2 Optimal-cost approach to tolerable risk

The foregoing discussion dealt with measuring risk and tolerable risk in terms of death probability given the DBE. This is not the only way to measure life-safety risk. In fact, there is no general consensus on any metric for evaluating acceptable risk. Various other methods have been used, and several were reviewed for this study.

One interesting metric comes from John Wiggins (1978). In evaluating seismic building-code requirements, Wiggins found that two dimensions that essentially parallel each other are reduced damages and earthquake deaths per annum. He evaluated costs (construction plus earthquake damage and casualties) as a function of the desired risk level. Lower standards produce lower construction costs and higher earthquake damage; higher standards reduce eventual earthquake costs and casualties, but at a high construction cost. The optimal risk level for costs is the one with the lowest total costs. Wiggins found that the optimal annual risk level is $1 per $10,000 at risk (an annualized loss rate of 0.00001) and 1/1,000,000 people exposed. If one values life more highly, then these optimal or least-cost factors are lowered by a factor of two or three. Wiggins' findings supported UBC design levels based on an optimal-cost approach, and are therefore consistent with the provisional recommendations.

### 2.3.3 Considering severity

Ignored in the discussion so far is the event severity, that is, number of people killed. Figure 2-4 provides a recent perspective from Helm (1996) writing from New Zealand. Helm compares frequency and magnitude of deaths from industrial and other accidents. He uses the expression *tolerable risk* because literally speaking no fatalities are acceptable. Helm found an inverse linear relationship between severity and tolerability; 100 fatalities with an annual probability of $10^{-5}$ is equally tolerable as 1000 fatalities with an annual probability of $10^{-6}$. Helm divides risk into four regions:

1. Unacceptable. High frequency and severe consequences exceed local acceptability of deaths from industrial and other accidents. In this region, "risk cannot be justified except in extraordinary circumstances."

2. Possibly unjustifiable. Risk is "tolerable only if risk reduction is impractical or if its cost is grossly disproportionate to the improvement gained." This is the upper portion of the region Helm denotes ALARP (*as low as reasonably possible*), meaning the risk is tolerable as long as all reasonably practical steps are taken to reduce the risk further.

3. Lower ALARP. Risk is non-negligible, but is "tolerable if cost reduction would exceed the improvement gained."

4. Broadly acceptable. Below the negligibility line, frequency and severity are low enough to be considered negligible.

Charts like Figure 2-4 were anticipated by Chauncey Starr (1969, 1972), in his discussions of the revealed-preference method of determining acceptable risk. Starr found that the acceptable risk decreases with increasing number of exposed persons. Figure 2-5, based on Starr, summarizes an earlier version of acceptable risk charted as frequency versus severity versus voluntariness. Figure 2-6, from Starr (1979), illustrates risk versus benefit for involuntary exposure.

This inverse relationship is not universally recognized. The UBC does not require higher seismic design loading for highrises than for other buildings with ordinary occupancies. It classifies buildings with occupancy loads in excess of 5,000 as special-occupancy structures (UBC 93 Table 16-K), but assigns the same seismic load levels as for ordinary structures. Thus, the UBC implicitly accepts the same annual per-capita risk for both classes of structure. ASCE 7 does hold high-occupancy structures to a higher standard than ordinary buildings, with 20% to 40% lower allowable story drift, but similar design strength, that is, with the same unit importance factor.

Examination of equipment life-safety risk in Helm's terms helps anticipate public sentiment regarding severity, that is, number of people killed. It can be seen as a complement to estimation of risk purely on a per-person basis. For that reason, we have used the regions of Figure 2-4 to evaluate death risk from CES on a probabilistic basis for automatic sprinklers, as will be seen below.

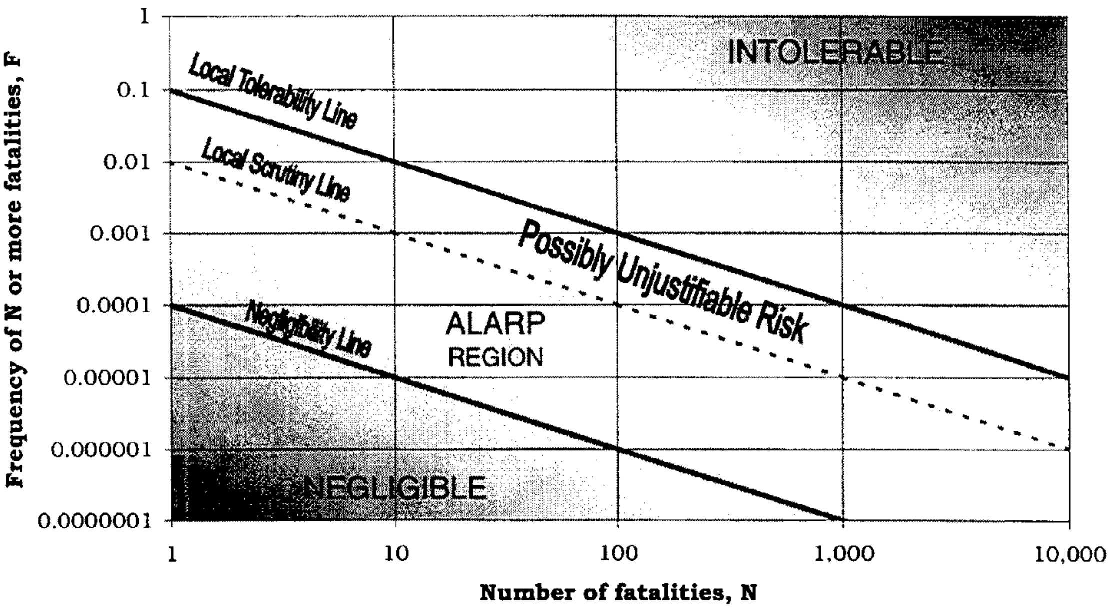


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*Figure 2-4 – Tolerable risk as a function of severity (after Helm, 1996)*

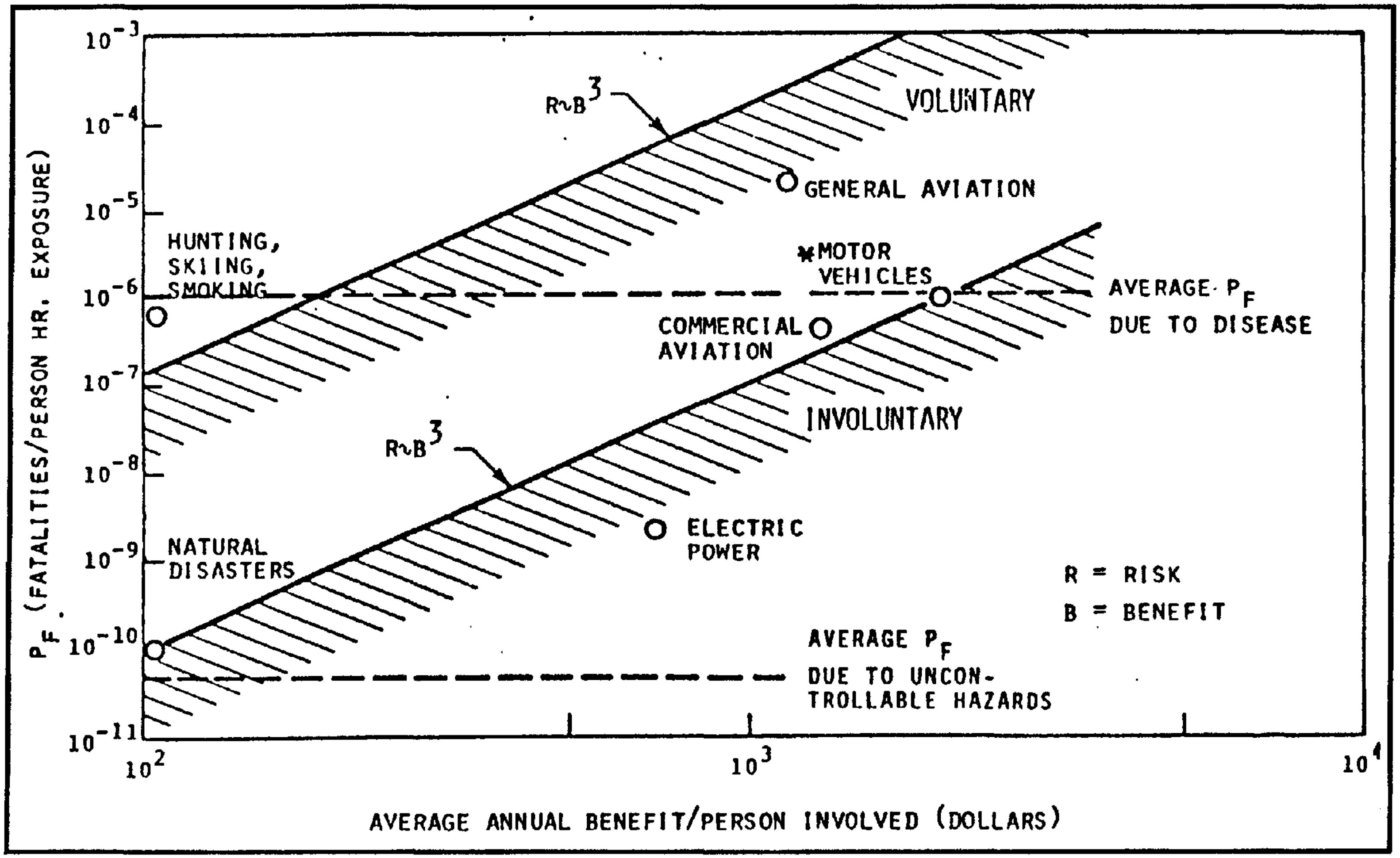


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*Figure 2-5 – Starr's risk-versus-benefit relationship*

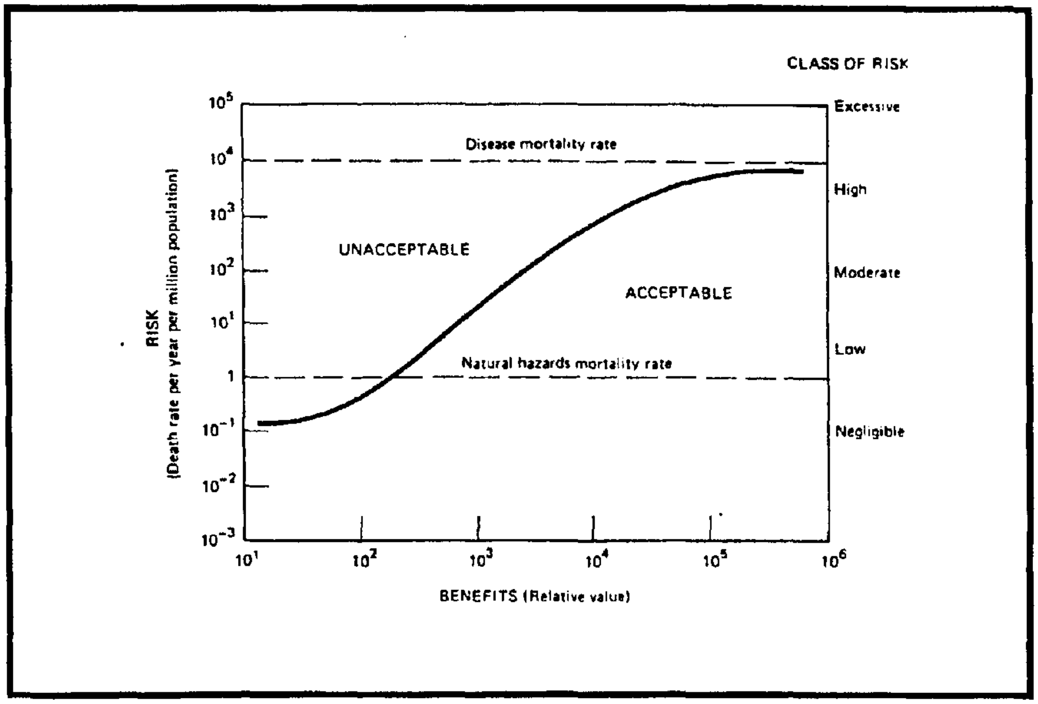


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*Figure 2-6 – Starr's risk-versus-benefit relationship for involuntary exposure*

## 2.3.4 Tolerable risk according to the US government

According to Lewis (1990) in his discussion of *de minimis* risk, "Some regulatory agencies appear to be drifting toward the position than an acceptable risk is one that imposes on the average person a threat of death of less than a chance in a million." Lewis illustrates and clarifies this statement as meaning one in a million per lifetime, when he writes:

> **EPA recently relaxed the standards on a number of environmental contaminants, including dioxins and lead, in an effort to bring the population risk to a uniform level of one in a million chance of untimely death per lifetime (seventy years). (This arbitrary choice of risk level is being increasingly used throughout government, presumably because it is a round number and is, for most people, synonymous with no risk at all.)**

It is shown later in this paper that, in the case of automatic sprinklers, the proposed tolerable-risk guidelines would provide for an annualized risk of less than 1 in 1,000,000 per building occupant. This equals Wiggins' optimal level, but is higher than the government's negligibility level of 1 in 1,000,000 per 70 years.

## 2.3.5 Revealed preference

We earlier alluded to Starr's discussions of the revealed-preference method of determining acceptable risk. The method assumes that current risks may be considered acceptable when evaluating new technologies. Fischhoff et al. (1981) refer to this method as *bootstrapping*, entailing the argument that "society achieves an acceptable tradeoff between risks and benefits ... through a protracted period of hands-on experience that allows for a trial-and-error learning."

Starr argued that revealed-preference analysis showed that public tolerance for voluntary risks allowed for 1000 times the risk associated with involuntary risks that offered the same dollar benefit per person. It is difficult to employ Starr's findings in the case of natural disasters, for which benefits are ill-defined, as is voluntariness (one could, after all, move somewhere without earthquakes). His method works better for hazards such as commercial aviation, motor vehicles, and electric power. However, the bootstrapping or revealed-preference approach is applicable here.

Revealed preference suffers from many philosophical shortcomings. It assumes that society has in some universal way consciously accepted longstanding risks. It assumes that society actually *can* have consistent preferences; that group preferences exist per se. Kenneth Arrow's (1963) impossibility theorem shows that such consistent group preferences may not be assumed to exist.

For public-safety issues, it would be more accurate to say that society has delegated judgment on tolerable risk to a variety of government agencies, who in turn delegated judgment to academics, who finally pled historic precedent; this at least is the case of LRFD and seismic design. Segments of the population frequently find fault with those judgments when confronted with the consequences. However, proper use of revealed preference can at least align related risks to reduce inconsistency. Then if societal judgment of tolerable risk from one hazard changes, other related risks can be mitigated accordingly.

In the present situation, seismic CES risk is closely related to seismic structural risk, both physically and psychologically, so the use of revealed preference seems to have some merit. It supports setting CES target reliability based on structural risk tolerated by current building code standards, as we have done. (Another argument for basing CES risk on structural risk is presented later.)

### 2.3.6 Valuing life

Several of the foregoing references mix dollars and lives. The optimal-cost approach to minimum risk requires an explicit value per life, and Helm's ALARP regions beg the question of what cost is "grossly disproportionate to the improvement gained," if improvement is measured in lives saved. There is no general agreement on how to value a life. It may be that no agreement is possible, since the value of a life is a largely subjective matter. Courts and various authors have made attempts, however. Fischhoff et al. (1981) report figures varying between $200,000 and $4 million, which in 1997 dollars equate with between $300,000 and $6 million.

Often this value is cast in terms of dollars spent to prevent fatalities. Fritzsche (1996) tabulated cost per statistical life saved from several sources; his figures are repeated in Table 2-2. He argues that items in the lower part of the table represent absurd waste of effort compared with the more efficient safety applications in the top of the table. This still leaves open the question of where the cutoff lies between reasonable and unreasonable expense.

Again, the US government has attempted to tackle this problem. As part of its 1990 debate over the Clean Air Act, the United States Congress created a commission (Commission on Risk Assessment and Risk Management, 1996) charged, among other tasks, with reviewing federal procedures to assess health risk. The commission reviewed a variety of federal programs that addressed cost per life saved. It found:

> **For agencies that explicitly value death risk reductions, the implied value of a statistical life ranges from $1 million to $10 million. For agencies that do not explicitly value death risk reductions, but instead base decisions on an "acceptable" cost per life-saved, the implicit value of a statistical life can be far higher. One study of EPA regulatory decisions that affected cancer risks found regulations promulgated that cost over $50 million per life saved. The Office of Management and Budget study of such behavior, involving a broader range of causes of death, found even higher costs per life saved, as did a recent Congressional Budget Office study of drinking-water standards.**

It will be shown later in this paper that retrofitting AS turns out to be economical by this measure -- as low as $700,000 per life saved.

Howard (1980) has presented an elegant alternative to attempting to value life. He proposes instead to value small probabilities of death, using a system he believes we all share. In his work on microrisks in medical decision analysis, Howard proposes two units to measure risk of death: the micromort (μmt), a $10^{-6}$ probability of death; and microhazard (μhz), a $10^{-6}$ probability of death per year from a continuing hazard. He argues that, for single-incident risks of death up to about 0.1%, the value we place on a unit risk of our own death is fairly constant. He illustrates the point with charts like Figure 2-7, which shows the payment a hypothetical person would require to accept risk of death $p$, as well as the payment we would be willing to make to avoid risk of death $p$.

Before proceeding, it would be worthwhile to explain these two curves in more detail. The former refers to payment an individual would require to accept addition risk above what he or she currently faces, for example, hazard pay to accept an unusually dangerous job. The latter refers to money an individual would be willing to pay to eliminate risk that is already integrated into his or her life. An example would be paying for optional airbags in a new car.

The curves in Figure 2-7 diverge above 1,000 to 10,000 μmt. Above this level, we lose the ability to pay more to avoid additional risk, and no amount of money paid to us can induce us to accept greater death risk. However, as long as death risk is below about 10,000 μmt, as is the case with building seismic safety, the curves coincide and are linear.

Howard points out that a individual's wealth state, risk attitude, time preference, and lifestyle as it relates to life expectancy drive his or her dollar value per μmt, but that on average, value can be estimated as a function of age, sex, and annual consumption in dollars. Howard (1989) proposes reasonable personal exchange rates per µmt and per µhz shown in Figure 2-8 and Figure 2-9, respectively. In the figures, annual consumption is defined as after-tax income above survival level. (More precisely, this is the constant level of consumption beyond bare survival over one's lifetime that would make one indifferent between this level and one's present prospects. The interested reader is referred to Howard, 1980, pg. 486.)

Howard's assessment of microrisks avoids the question of the value of a human life, and unambiguously answers the question of whose value system to use: that of the primary stakeholder, the person whose life is at risk. He points out that, as the stakeholder, we frequently consult our buying price for additional safety, e.g., when spending extra for a safer car, etc., and selling price for less safety, e.g., when taking on dangerous jobs in exchange for greater pay. Howard is *not* implying a price for human life, the "how-much-for-your-grandmother" question, but rather addressing the value we daily place on small changes in our own safety.

Recall the earlier estimate based on NEHRP that a person working in an engineered building faces an annual death risk of $0.28 * 10^{-6}$ from the earthquake-induced collapse of that structure. Using Howard's system, and referring to Figure 2-9, one could estimate that a 50-year-old woman with $45,000 constant annual consumption should be willing to pay a one-time sum of approximately $20 ($16.00/µhz/$10k * $45k * 0.28 µhz) permanently to avoid death from that particular ongoing hazard. This assumes that she understood and believed NEHRP's estimate of her degree of risk, and planned to remain in full-time work in a highrise building.

Looked at another way, she would be willing to pay approximately $1.60 per year to be protected from the risk for that one year (from Figure 2-8, $1.30/µmt/$10k * $45k * 0.28µhz). Howard's measure of microrisk value will be compared with amortized cost to reduce risk through AS retrofit. It turns out that AS retrofit reduces death risk in daytime occupancies at a per-occupant cost of $2.00 per µmt, basically equal to the 50-year-old woman's indifferent buying price of $1.60 per µmt.

***Table 2-2 – Cost per life saved***

| **Safety measure** | **Cost ($US)** |
|---|---|
| Cure of child diseases in Cambodia | $10^2$ |
| Safety belts in automobiles | $25 - 112 \times 10^3$ |
| Air bags, driver protection | $130 - 400 \times 10^3$ |
| Grounding of DC 10 aircraft in 1979 | $30 \times 10^6$ |
| Removal of asbestos from public buildings | $75 - 1400 \times 10^6$ |
| Hydrogen recombiners in nuclear power plants | Over $3 \times 10^9$ |
| Evaporation of slightly radioactive waste water at TMI | $25 \times 10^9$ |
| Requested additional protection at low-level radioactive waste disposal facility | Many $10^{12}$ |

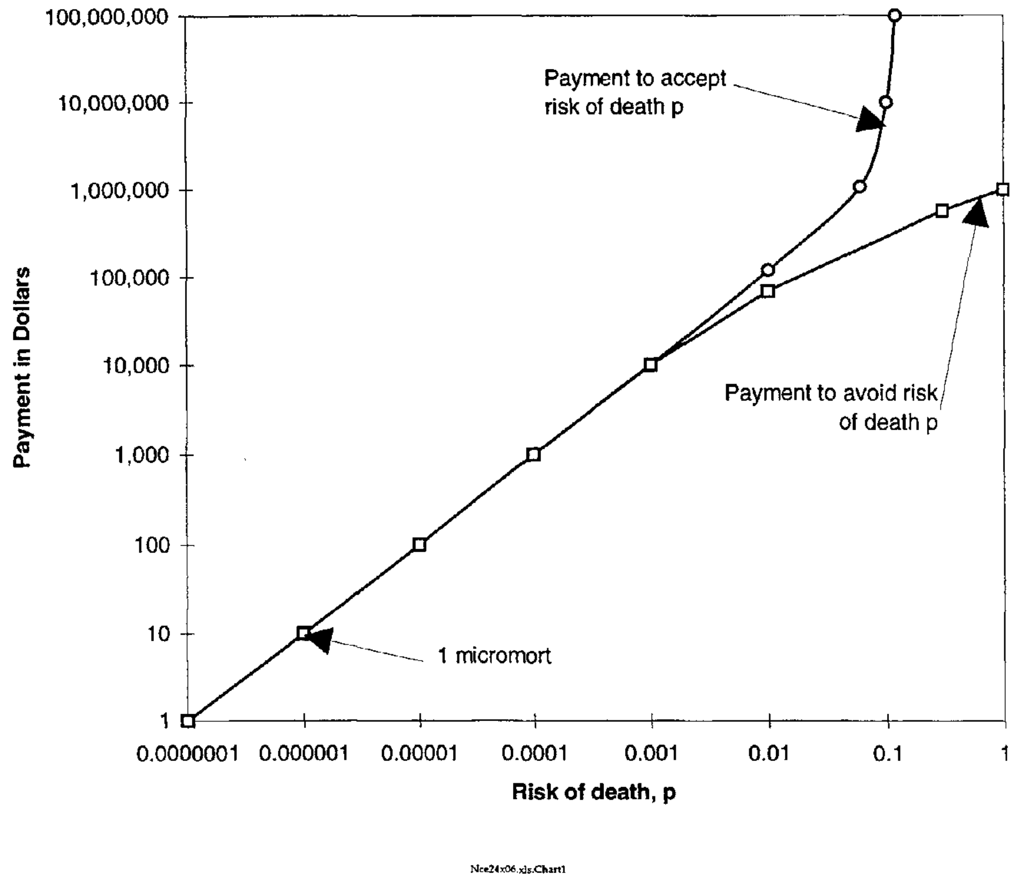


*Figure 2-7 – Payment to accept or avoid death risk p (after Howard, 1989)*

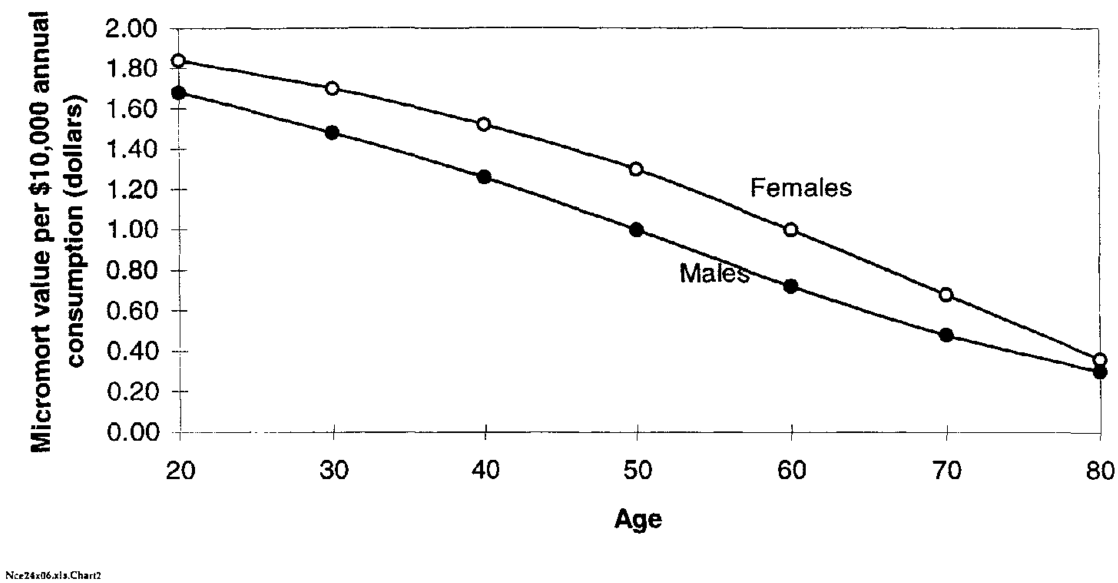


*Figure 2-8 – Micromort dollar value per $10,000 annual consumption as a function of age and sex (after Howard, 1989)*

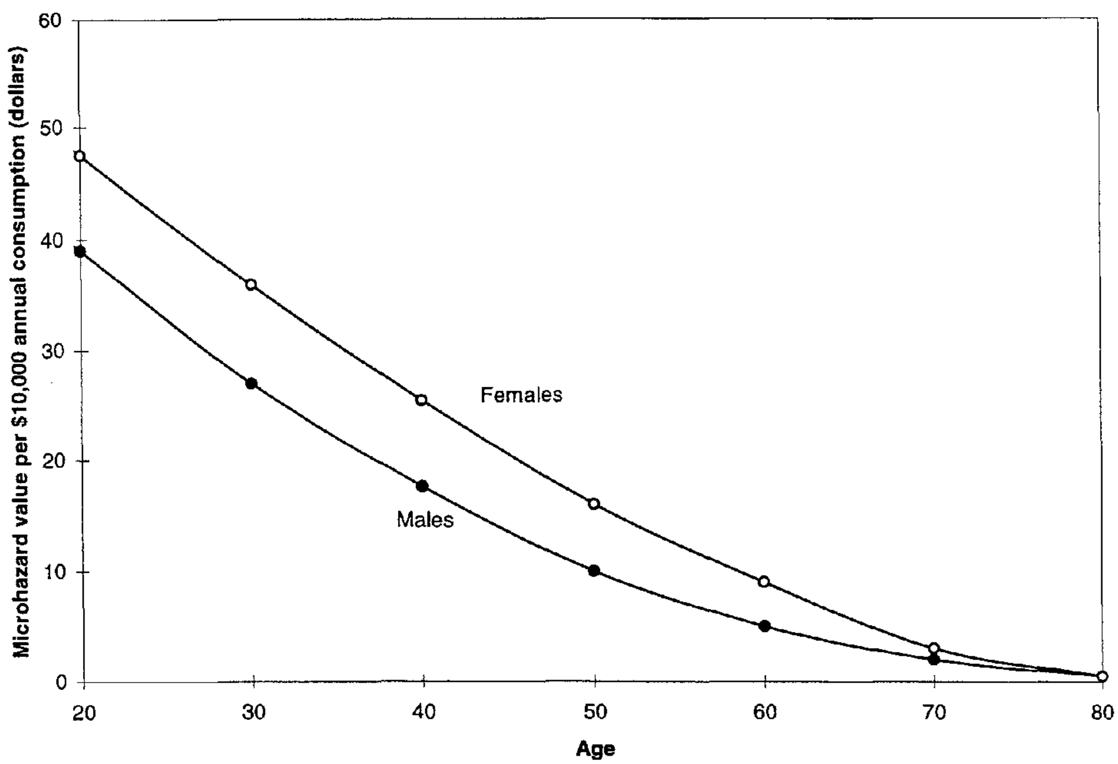


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*Figure 2-9 – Microhazard dollar value per $10,000 annual consumption as a function of age and sex (after Howard, 1989)*

## 2.3.7 Objection to tolerable risk as a concept

In reviewing efforts to attain uniform normative measures of acceptable risk, Pate (1983) despairs both of the prospects and desirability of such an achievement, and recommends instead that the emphasis of public-risk regulation should be placed on developing and employing an acceptable decision process. This process would be based on consistent laws and principles, rather than on uniform acceptable risk. She argues: "There are not ... good bases to infer from the acceptability of one form of risk the acceptability of another one...."

We counter that there may be exceptions to her argument. Consistent principles should lead to consistent tolerable risk where an individual is exposed to two closely related hazards. If I am willing to pay $2 per year to avoid death risk from structural failure in a building in an earthquake, it is reasonable for me to pay $2 a year to avoid the same quantity of risk from equipment failure in a building in an earthquake. Likewise, risk that is tolerable if it would cost $20 to avoid should be tolerable whether it is associated with either source, so close in nature are they.

The same people are exposed to life-safety risk from structural failure in earthquakes as are exposed to life-safety risk from building equipment failure in the same earthquakes. It seems reasonable to equate tolerable risk levels from these two sources of risk.

## 2.3.8 Objection to tolerable risk because of imprecise probabilities

We have related our recommended tolerable-risk scores to several other measures of tolerable failure probability. Minimal attention has been given to uncertainty in basic estimates of probability; none has been paid to possible disagreement among experts on basic probabilities.

The first point raises the issue of *ambiguity aversion*, the tendency of decision-makers to prefer certainty over uncertainty in epistemic (model) probabilities. This tendency can be measured as the premium one would pay to choose a lottery that had less epistemic uncertainty, despite equal expected value of utility. The second point deals with *conflict aversion*, the phenomenon whereby "people prefer consensual but ambiguous assessments to disagreeing but precise ones. Thus, people prefer ambiguity to conflict even when the one is informationally equivalent to the other...." (Smithson, 1996)

In the present context, policymakers' ambiguity and conflict aversions raise some interesting questions. Is there a pertinent difference between mitigation policy for which the casualty statistics are very reliable and a mitigation policy for which the casualty statistics are not very reliable? Is there a difference when experts disagree on probabilities of one policy but not the other? All other things being equal, is it preferable to pursue reliable or consensus-laden courses of action in preference to the unreliable or conflict-laden courses of action?

A decision-analysis approach would say that the answers depend on whether the decision-maker deals with ambiguity and conflict as an information issue (what you know) or as a preference issue (what you want). It may be that people adjust their notions of probability in the presence of ambiguity or conflict. If so, it is arguable whether disagreement or uncertainty in basic probabilities provides any information, and thus whether it is rational to acknowledge them in a decision analysis. On the other hand, if people deal with these conflicts as preference issues, it is arguable whether unambiguous or consistent estimates of probability provide any tangible value.

Methods to deal with these aversions exist using decision analysis. For example, Pate-Cornell (1991) describes a method for dealing with ambiguity aversion under the preference hypothesis, using what she terms a *secondary utility function* $\Phi$ that takes as its input the expected value of utility from purely aleatory variables, after separating them from epistemic uncertainties.

A decision-analysis approach to comparing equipment risk with other sources of risk would require developing decision-analysis models of both equipment risk and of any other source of risk with which we would compare equipment. For example, one would create a thorough probabilistic model of structure damage and consequent casualties, separating all sources of uncertainty into epistemic (modeling uncertainties) and aleatory (inherent randomness). It would then be necessary to create a value model that includes casualties, construction costs, repair costs, business interruption, and other secondary economic consequences. One would them frame the decision, for instance, as a choice between spending $1 billion in mitigating structure damage or in mitigating equipment damage.

This would probably result in valuable insights into seismic risk mitigation in buildings, and one of us (Porter) is currently pursuing research along these lines. However, the degree of complexity involved is beyond the resources of the present project. Furthermore, given the order-of-magnitude nature of the equipment risk scores under consideration, we suspect the effect on recommended minima would be of second order and therefore negligible.

In summary, although ambiguity aversion and conflict aversion could play a role in selecting minimum risk scores, we have not considered them. We justify the omission by pleading that they would likely make little material difference, and by noting that neither phenomenon is addressed in current structural design codes, and are unavailable for comparison in the present project.

## SECTION 3
## TEST CASE: AUTOMATIC SPRINKLERS IN HIGHRISE BUILDINGS

### 3.1 Test-case objectives

We have shown that the proposed guidelines for tolerable risk are consistent with seismic safety levels in building codes. We have also hinted that these guidelines can be shown to be economical by government and personal standards. The remainder of this paper elaborates on the efficacy and cost-effectiveness of the proposed guidelines, by examining a test case: the seismic retrofit of automatic sprinklers. The purpose of the test is to answer several questions:

- **Necessity.** Are the provision guidelines necessary, in terms of mitigating risks that are currently unacceptable?
- **Practicality.** Is it possible to achieve the prescribed risk levels?
- **Efficacy.** Do they reduce risk to tolerable levels?
- **Efficiency.** Is retrofit to guideline levels economical in terms of cost per life saved or cost per microhazard avoided?
- **Equitability.** Are the costs and benefits fairly distributed among those involved?

To answer these questions, we modeled AS equipment and the system they comprise, with regard to seismic performance. We modeled their presence in all highrise buildings in the San Francisco Bay area, assessed the risk posed by failure of unbraced equipment in earthquakes, and reassessed the risk assuming the equipment were properly braced or anchored. For present purposes we define highrise buildings as those with seven stories or more above ground.

### 3.2 Modeling AS fragility

System fragility was estimated using fault-tree analysis. Figure 3-1 shows the fault tree for uncontrolled building fire in a highrise building, as developed in a previous phase of this study (Porter et al., 1993). Ovals indicate basic events whose fragility can be modeled using available data. Rectangles are upper events whose probability is determined from lower events, given shaking intensity. P-codes, e.g., $P_{21}$, are used to identify the event's probability distribution.

All basic-event fragilities except ignition ($P_{13}$ in Figure 3-1) were modeled as a compound lognormal distribution, as described by Kennedy et al. (1980). The parameters of the distributions were developed from statistics in EQE's database of historic equipment failure in 65 earthquakes.

In this methodology, component failure probability $P_f$ is estimated (as shown below) as a function of peak ground acceleration $a$, median failure acceleration $A_m$, and a randomness variable $\beta_r$. The parameter $H$ accounts for a component's location vertically within a building: H is 1 for ground level, 2 for roof level, and is taken as 1.5 for a component distributed vertically through a building. The parameter $A_m$ is itself modeled as a random variable with lognormal distribution, with median $A_{mm}$ and logarithmic standard deviation $\beta_u$.

Ignition probability ($P_{13}$) was modeled as a random variable dependent on pga, based on a recent study of fire following earthquake (EQE International, 1992).

$$P_f = \Phi\left(\frac{\ln\left(\frac{a \cdot H}{A_m}\right)}{\beta_r}\right)$$

Stochastic methods were used to evaluate the distribution of $P_{71}$, uncontrolled building fire. In particular, we used @RISK™ for Microsoft Excel, and developed a 3-dimensional fragility surface whose x axis is shaking intensity, y axis is probability of nonexceedance, and z is probability of uncontrolled building fire. Figure 3-2 illustrates the case of unbraced AS.

**AS Fragility Under Strengthened Conditions.** It is necessary to develop a similar surface for seismically retrofitted conditions. Unfortunately, inadequate empirical damage data exist from seismically retrofitted facilities to estimate a similar fragility surface directly. FEMA 74 (Federal Emergency Management Agency, 1994) and other published reports provide some direction, but rely on terms such as "negligible" and "low" to describe post-mitigation risk.

We therefore analyzed individual repair reports prepared by union Sprinkler Fitters UA Local 483 (1989) after the Loma Prieta earthquake. In addition, we reviewed the findings of a company that surveyed several hundred sprinklered sites affected by the Northridge earthquake. Of several dozen facilities that suffered sprinkler leakage, none were properly braced and anchored, although several dozen facilities existed that were subjected to strong shaking and had adequately braced sprinklers and ceilings. The EPRI *HCLPF* methodology (high confidence in low probability of failure) appears to be the best way to estimate the fragility parameters for retrofitted piping systems (Benjamin and Associates, 1994). It led to a median $A_m$ of 2.6g, as opposed to 0.72 without bracing.

Other in-building AS components such as motor control centers, switchgear, and generators, can be assumed to be rugged once properly anchored. These were assigned high $A_m$ values under retrofitted conditions. This caused AS system fragility to be driven primarily by AS piping. Again @RISK was used to estimate AS system fragility, this time under strengthened conditions. Figure 3-3 shows mean AS fragility curves (i.e., $P_{61}$ in Figure 3-1) with and without seismic retrofit.

**Practicality of Provisional Guidelines.** Figure 3-3 shows that even a retrofitted AS system is estimated to have a significant failure probability (1 to 2%) at DBE shaking of 0.4g. This means that the proposed tolerable failure probability for life-safety CES, $10^{-3}$ for ordinary buildings and $10^{-4}$ for essential facilities, may not be practical in cases of inherently fragile, distributed CES.

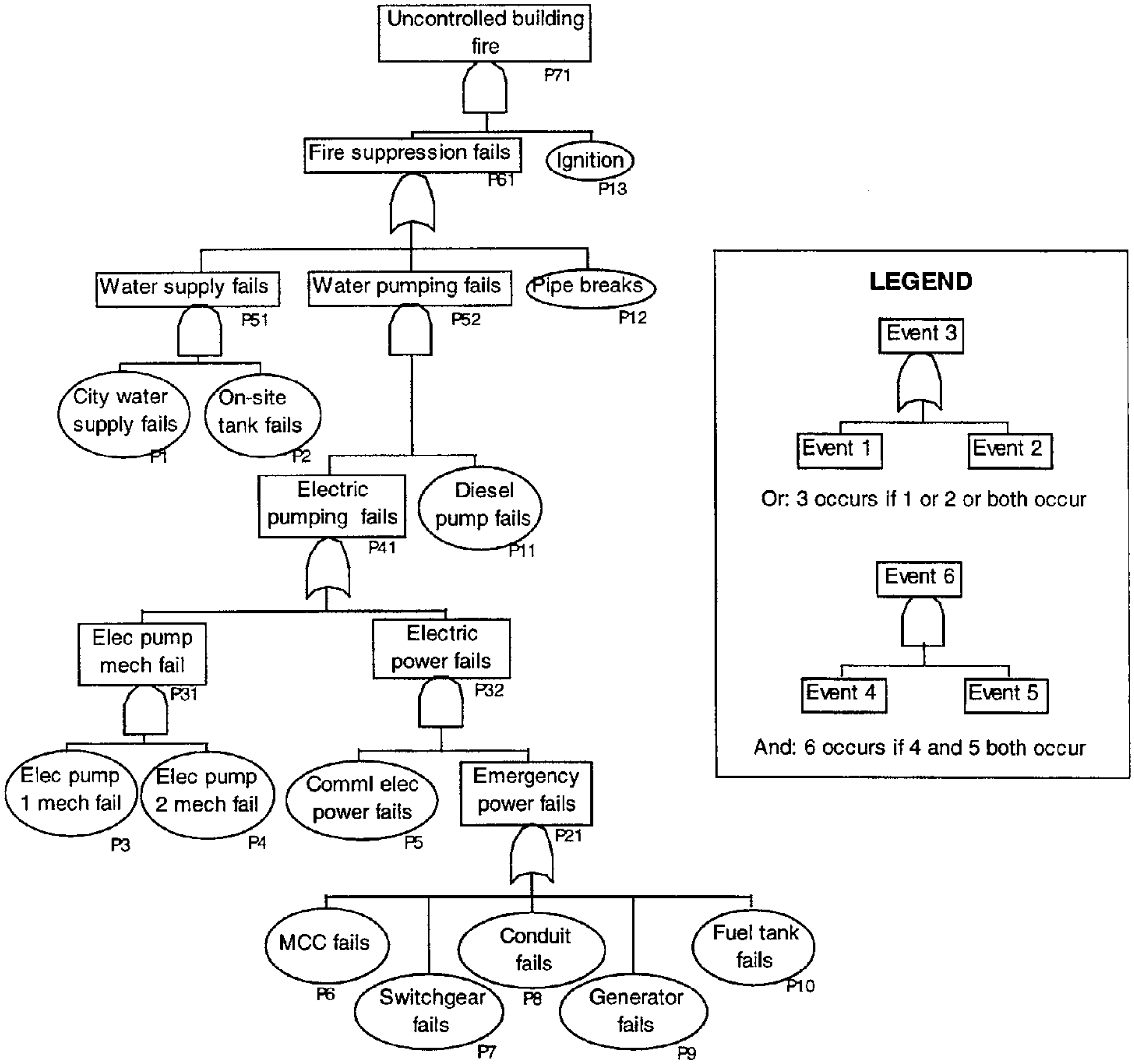


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*Figure 3-1 – Fault tree, uncontrolled building fire*

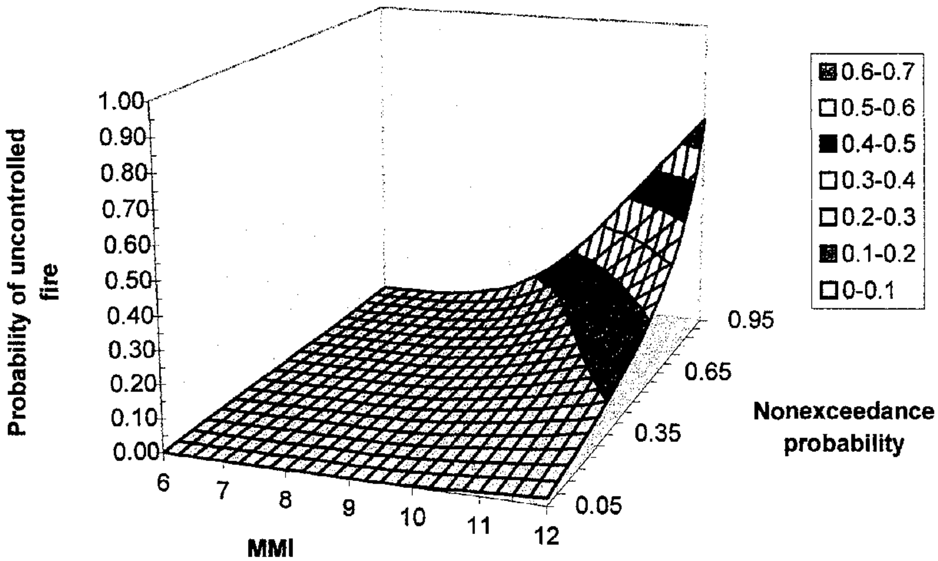


*Figure 3-2 – Probability of uncontrolled building fire, unbraced conditions*

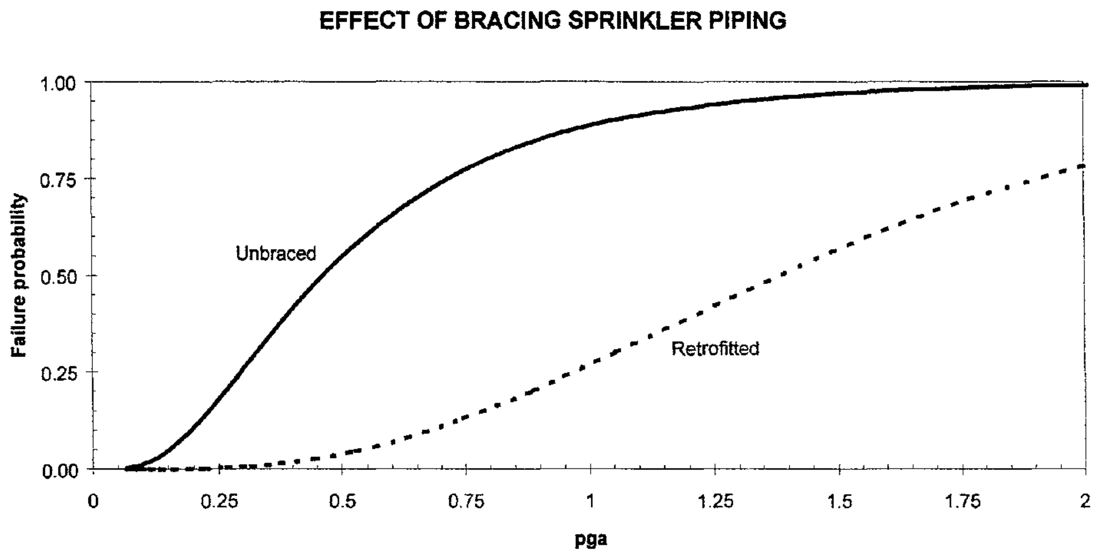


*Figure 3-3 – Comparison of mean AS system fragility, with and without bracing*

### 3.3 Seismic vulnerability functions

**Property vulnerability.** Given ignition probability, it is possible to estimate property damage vulnerability for highrise-building fire. It is worthwhile at this point to emphasize the distinction between fragility and vulnerability. By *fragility*, we refer to the probability that a component or system will fail to perform its function, expressed here as a function of seismic shaking intensity. Uncontrolled building fire can be described by a fragility function, because it represents an uncertain condition that either exists or does not exist.

By *vulnerability,* we mean the fraction of value lost, such as fraction of occupants killed or fraction of building value damaged by fire, as a function of seismic shaking intensity. Vulnerability can be seen as the product of fragility (e.g., probability of uncontrolled building fire) times the fraction of value lost given the fire. We now proceed to discuss the basis for estimating fraction of the various values lost given the occurrence of an uncontrolled building fire after an earthquake.

In the following discussion, it is necessary to understand how fire damage after an earthquake differs from damage due to building fires at other times. In ordinary conditions, the fire department would attack the fire and limit it to as small an area as possible within the origin building. By contrast, the heavy demands placed on the fire department after a large earthquake will require that the fire department's strategy be primarily defensive. That is, firefighters will concentrate on preventing fire spread to adjacent buildings, rather than on attacking a fire itself. Even with passive containment (closed fire partitions, etc.) the result is that uncontrolled highrise building fires after a large earthquake will most likely spread to the entire building above the floor of ignition.

Given an uncontrolled building fire, property damage within the building will depend on the vertical level where ignition occurs. We have modeled ignition floor as a random variable with ignition at the top floor twice as likely as ignition at the bottom floor, to account for increasing shaking severity higher in the building. Again we used @RISK to quantify property damage vulnerability. Figure 3-4 expresses fraction of building value lost (z axis) as a random variable (y axis) dependent on ground-shaking intensity (x axis). Figure 3-5 shows the same relationship under retrofitted conditions.

**Casualty vulnerability.** To estimate fraction of occupants killed and injured in highrise building fires, we analyzed data from 242 highrise fires that occurred in the United States between 1975 and 1995 (National Fire Protection Association, 1996). We found that casualty fraction is nearly lognormally distributed (passing Kolmogorov-Smirnov goodness-of-fit test at high significance), with a mean of 1.04% of occupants killed, and standard deviation (in the normal domain) of 2.3%. Expert judgment indicates that in post-earthquake conditions, because of debris and other hindrances to egress, casualties could be two to three times those under normal conditions (Blackburn, 1997). We used a median factor of 2.5, but to account for uncertainty, modeled this factor as a Gaussian variable with 0.6 coefficient of variation. Injuries were modeled as being 15 times the number of fatalities, based on statistics from nationwide fires in nonresidential buildings between 1977 and 1984 (National Fire Protection Association, 1986). Figure 3-6 shows the resulting probability distribution on fatalities for unbraced conditions; Figure 3-7, retrofitted.

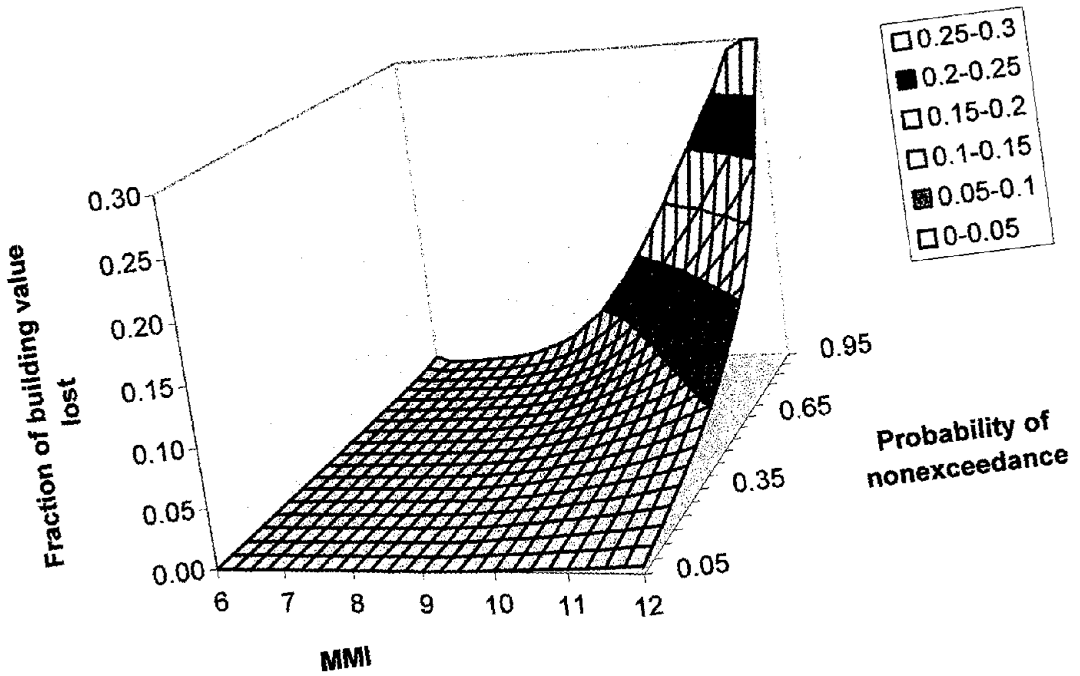


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*Figure 3-4 – Property vulnerability under unbraced conditions*

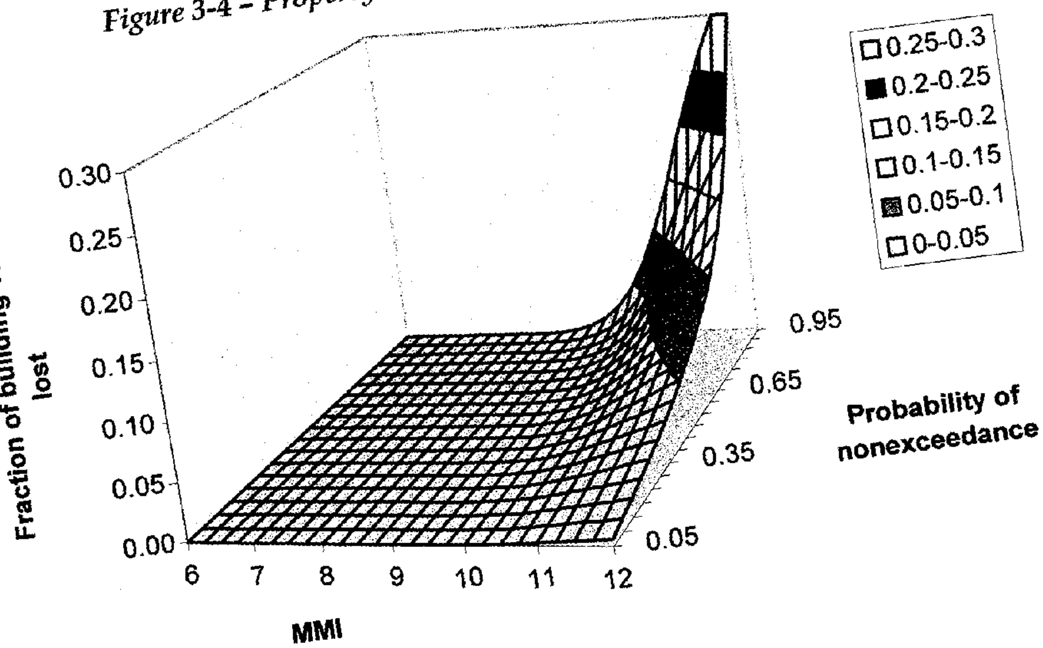


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*Figure 3-5 – Property vulnerability, retrofitted conditions*

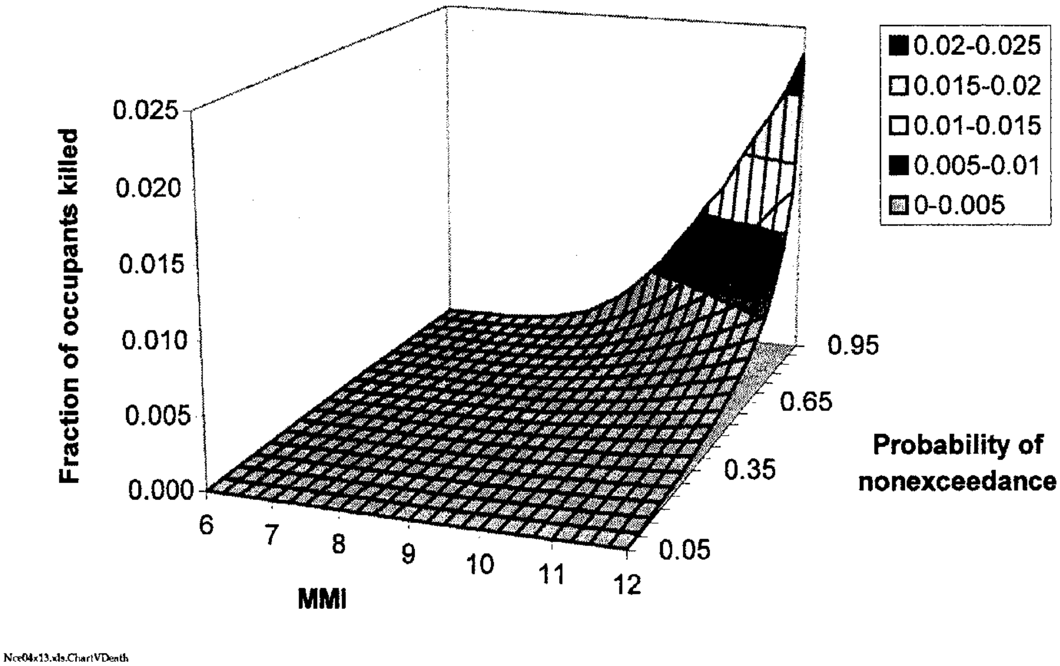


*Figure 3-6 – Highrise fire fatality vulnerability, unbraced conditions*

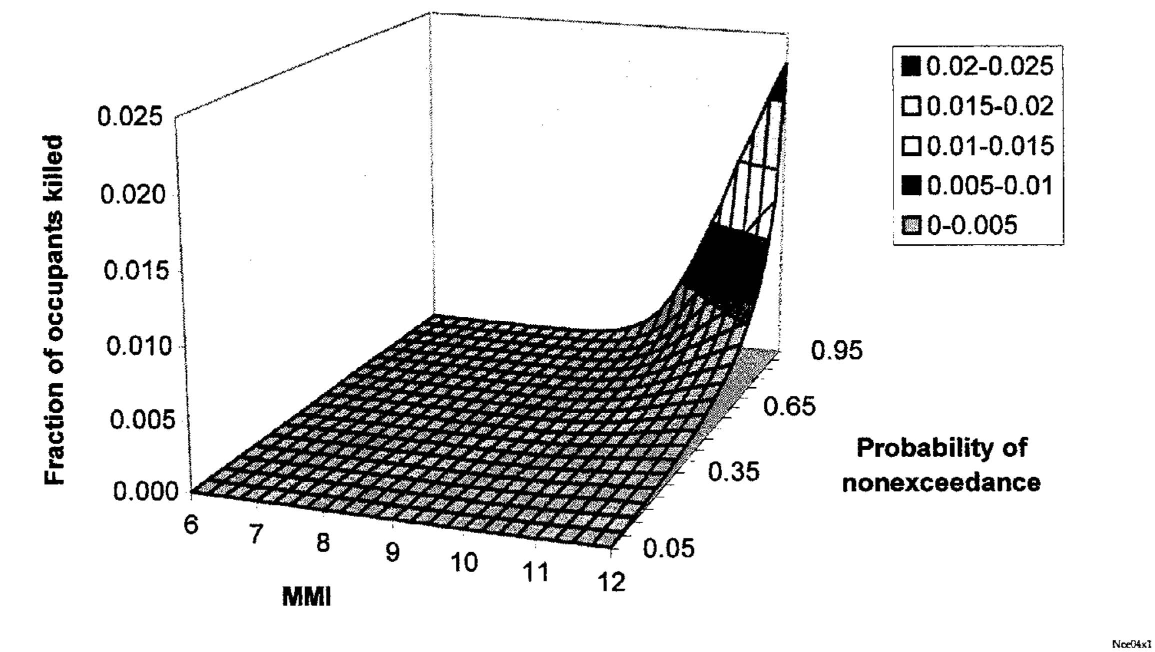


*Figure 3-7 – Highrise fire fatality vulnerability, retrofitted conditions*

## 3.4 Building inventory

**Purpose of assessing building inventory.** The foregoing sections detail the development of seismic vulnerability functions for AS in highrise buildings. To assess the average impact of AS fragility on people, it is necessary to model a particular set of people and buildings exposed. We have chosen to model all highrise buildings in the San Francisco Bay area. Thus the results of the case study will be applicable to that population, and by extension, highrise buildings in areas of similar seismic hazard.

**Highrise-building areas.** County tax-assessor data, while often incomplete or flawed with data-entry errors, are still the best basis for quantifying taxable property on a broad scale. We acquired these data for the nine San Francisco Bay area counties adjoining the Bay, plus Santa Cruz County, and created a single database of highrise buildings. Since each county assessor's office lays out and populates its database according to its own needs, some effort was required to combine these data into a consistent, useful form. This work is now described.

Four county assessors do not capture number of stories: Contra Costa, Marin, Napa, and Solano. For these counties, it was necessary to use other fields as proxies to identify highrise buildings. This was a multi-step process. First, we screened out parcels whose use was inconsistent with a highrise building, e.g., single-family dwelling, empty lot, etc. Next, footprint area was estimated based on lot area times percent improved.

Building area was then aggregated by street address (after parsing out floor or suite numbers, etc.), and each unique address was assumed to be one structure. Records in these four counties whose total building area or plate size was too low to be consistent with a highrise building were removed from the database. Remaining cases where total building area was at least seven times footprint size were likely candidates to be highrise buildings. These were reviewed individually for possible data-entry errors. In two cases, total square footage appeared to be inconsistent with use, and were eliminated. Personal knowledge eliminated another candidate.

Three counties appear from the data to have no highrise buildings: Solano, Santa Cruz, and Napa. Although San Mateo definitely has a few dozen highrise buildings along the Highway-101 corridor, the assessor database contains inadequately populated data fields to identify these buildings, so all San Mateo highrises were ignored for this analysis. (After completion of this research we learned that there is at least one highrise building in Santa Cruz, although the assessor data did not indicate it.)

The remaining six counties are estimated to contain 714 highrise buildings, of which 210 are residential; 504 commercial or industrial. These sites were all geocoded to street address. Table 3-1 shows estimated number of highrise buildings by county. The inventory of highrise buildings is dominated by office and apartment buildings (Figure 3-8), which together represent $3/4^{ths}$ of the total square footage. Hotels and mercantile and service space make up most nearly the remainder.

A site-by-site listing of the estimated highrise inventory, together with estimated value, is presented in a database detailed in Appendix C. Note that, while this assessor-based inventory is likely to be imperfect, owing to assessor data-entry errors and the necessary use of proxies in some cases, it nonetheless appears to reflect the geographic distribution of highrise buildings in the San Francisco Bay area. Development of estimated dollar values is summarized in the following section.

*Table 3-1 – Estimated count of highrise buildings by county*

| County | Count |
|---|---|
| San Francisco | 572 |
| Alameda | 65 |
| Santa Clara | 54 |
| Contra Costa | 21 |
| Sonoma | 1 |
| Marin | 1 |
| Napa | 0 |
| San Mateo | 0 |
| Santa Cruz | 0 |
| Solano | 0 |

**Construction costs, content value, time value, and occupant loads.** Building replacement costs (new) were estimated for each site using construction cost manuals such as RS Means (1995). Content values were estimated using ATC-13 (Applied Technology Council, 1985), except in cases where ATC-13 differed substantially from common insurance rules of thumb, where the latter was preferred. Time value was based on common insurance rules. Details of these value estimates are presented in Appendix A.

Occupant loads were based on several sources: for apartments and condominiums, data from the American Housing Survey (Bureau of the Census, 1995) were used to determine square footage per occupant. For workplaces and other occupancies besides residential, ATC-13 occupant loading were applied. We also considered occupancy loads discussed by NFPA (1986), but these appeared to be unreasonably low, as was confirmed by two field samples we performed. Occupant loading is detailed in Appendix B.

Total estimated values are as follows:

| | |
|---|---|
| Building value (replacement cost new): | $18.5 billion |
| Content value: | $17.6 billion |
| Time value per month: | $0.4 billion |
| Daytime occupants: | 365,000 |
| Nighttime occupants: | 98,000 |

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**Cost of sprinkler retrofit.** The square-foot cost to anchor or brace all components necessary for AS is estimated to be $2.80 per square foot, including the items listed in Table 3-2. The total cost is approximately $449 million. For each component, FEMA 74 and Means Construction Cost Data were used as the base cost guideline. Retrofit details took into account recommendations of the NFPA's Automatic Sprinkler Handbook (National Fire Protection Association, 1994). Costs were also checked for consistency against those detailed in Hazard Mitigation Grant Program applications (DR-1008 Northridge Earthquake Hazard Mitigation Grant Program), and an EQE study for the Contra Costa County Water District (EQE International, 1994).

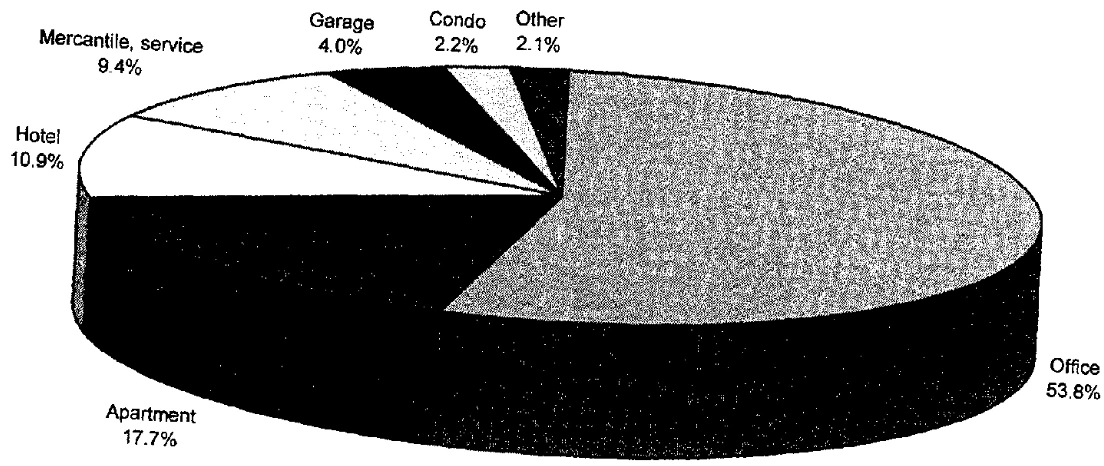


*Figure 3-8 - Highrise area by occupancy*

*Table 3-2 – Mitigation Costs and Measures for Various Non-Structural Components*

| Equipment or System being Mitigated | Mitigation Cost | Mitigation Measure |
|---|---|---|
| Motor Control Center (MCC) | $600 per MCC. Assume 2 units, plus 1 unit per every 60,000 SF. | Anchor unit to floor or wall. |
| Switchgear | $600 per switchgear. Assume 2 units per building. | Anchor unit to floor or wall. |
| Electrical Conduit | $500 per flex joint, and $350 per brace (every 40 feet) | Install flexible connections at seismic joints, and installation of transverse and longitudinal bracing located every 40 feet. |
| Generator (emergency)* | $3,500 per generator. Assume 2 per building. | Anchor restrain rails for battery set, anchor transfer switch, anchor engine generator (anchor or add snubbers and flex connectors), restrain muffler. |
| Diesel fuel Tank | $750 per tank. Assume 1 tank per building. | Anchor and brace fuel tank. Install flexible connections on fuel lines leading from tank. |
| Water Pumps** | $650 per pump Assume 4 potable water pumps per building. Assume pump per 200,000 sf. | Anchor and brace potable water and fire water pumps. Install flexible connectors on all lines into and out of pumps. |
| Fire Sprinkler Piping and Sprinkler Heads | $0.50 per total square foot of structure. | Installation of flexible joints on risers at each floor and at all building expansion joints. Install additional transverse and longitudinal bracing on distribution lines, and install branch line restraints. Ensure adequate clearance between structural members and piping |
| Suspended Ceilings*** | $1.20/SF | Provide 4 way diagonal bracing and compression strut approximately every 12 feet each way. |
| Suspended Light Fixtures*** | $50 per unit; typically 1/100 sf | Install 12 gauge wire at each corner anchored to structure above. |

*** Generator assumes a generator set consisting of a diesel engine generator, battery, charger, muffler, transfer switch.**
****Note: For the mitigation program, it was assumed that a fire pump was required only in buildings of 6 or more stories. Since this project assumes only high rise (8 stories or greater), there will be a minimum of 1 pump in each building.**
*****It has been shown that ceiling & lighting mitigation is required to reduce damage to sprinkler heads due to differential motion. This is supported by conversations with sprinkler system contractors, reports by pipe fitters after earthquakes, and other EQE studies.**

### 3.5 Risk analysis

**Hazards.** The portfolio of highrise buildings was analyzed with the earthquake-risk software USQUAKE™ (EQECAT, Inc., 1997) using the vulnerability functions discussed above. The analysis produced damage and casualty estimates for the hazard of post-earthquake fire. We analyzed these losses for specific earthquake scenarios, as well as estimating probabilistic losses on an annualized basis, considering all local faults, possible magnitudes, return periods, etc. In the scenario analyses, nine significant seismic sources in the San Francisco Bay area were identified (Table 3-3, Figure 3-9), and portfolio damage and casualties assessed for the rare (475-year, DBE) event on each fault.

In the scenario analysis, an earthquake of the given magnitude is assumed to occur somewhere along the fault. The rupturing portion is modeled at one end of the fault, and a series of simulations is run for that faulting location to estimate the probability distribution of damage and casualties. The location of the rupture is then moved incrementally along the fault, and the loss probability distribution again simulated. Results for the location with the highest mean damage are then reported (the so-called *limiting-case* event). Typically the limiting case is approximately equal to the average case, since a 475-year event ruptures most or all the fault segment of interest.

In the probabilistic analyses, earthquakes are simulated on all local faults in 0.1 magnitude increments, from a threshold magnitude of 5.0 to the maximum magnitude of which the fault is believed capable. The rupture location is also simulated incrementally from one end of the fault to the other. All other major relevant sources of randomness and uncertainty are accounted for in the analysis, and the full probability distributions of economic and casualty losses are accumulated. In addition to the major seismic sources shown in Figure 3-9, the probabilistic analysis accounts for less significant sources, shown in Figure 3-10.

*Table 3-3 – Seismic sources used in scenario analyses*

| Source | 475-year magnitude |
|---|---|
| Calaveras: Southern and Northern | 7.39 |
| Coast Range Thrust-Sierran Block Boundary Zone | 7.00 |
| Concord | 6.50 |
| Hayward: entire segment | 7.09 |
| Maacama | 7.25 |
| Rodgers Creek | 7.00 |
| San Gregorio – Hosgri | 7.50 |
| San Andreas Fault: SF Peninsula and north coast | 7.65 |
| San Francisco Bay area background zone | 6.25 |

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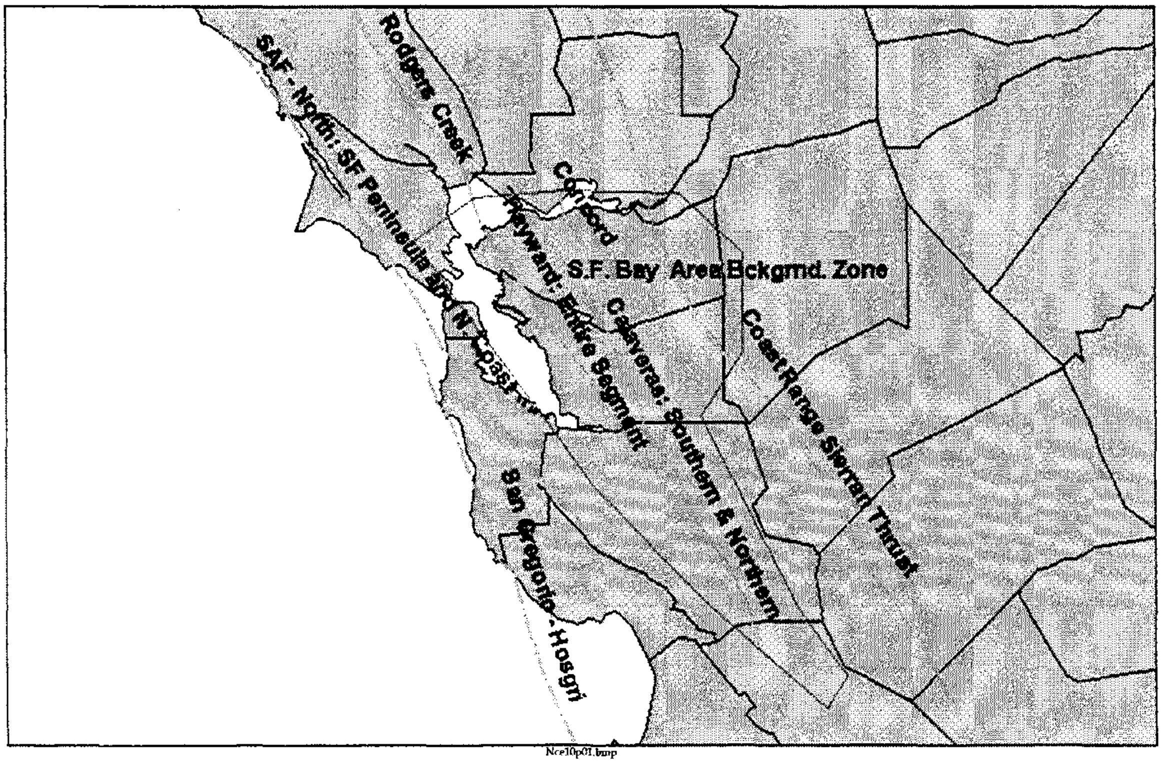


*Figure 3-9 – Seismic sources used in scenario analyses*

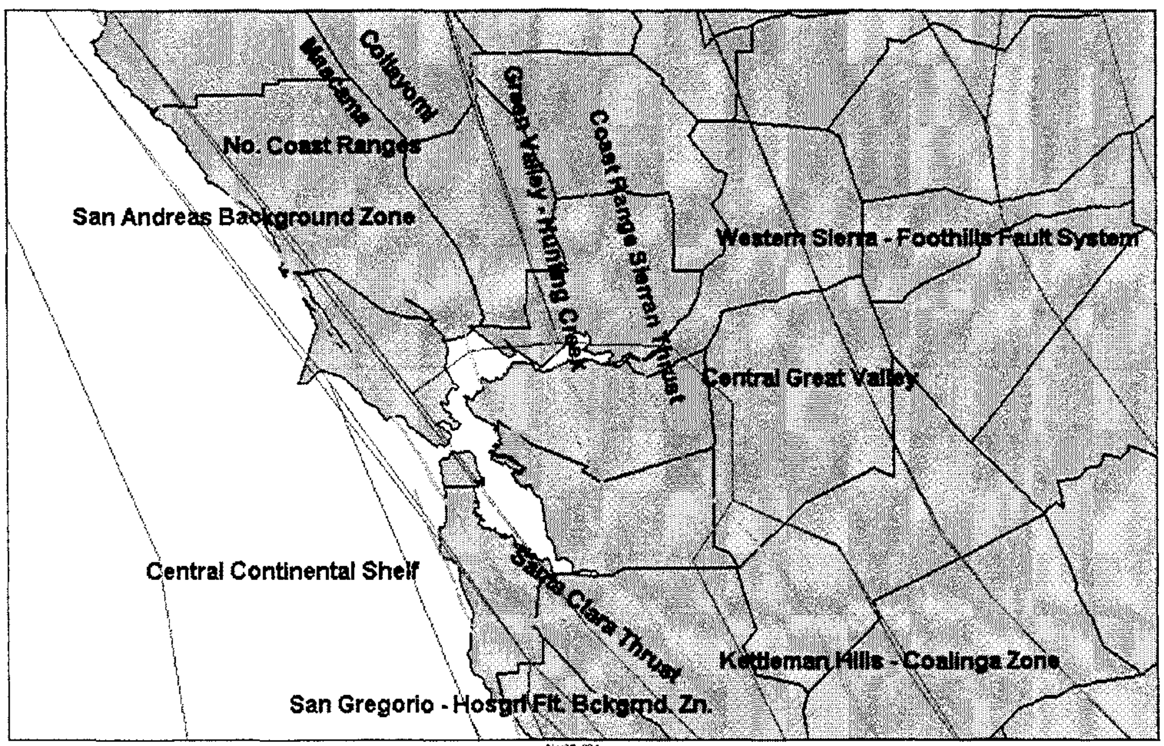


*Figure 3-10 – Additional seismic sources used in probabilistic analysis*

**Scenario analysis results.** Table 3-4 and Table 3-3 show that the most costly scenario event from fire would be a magnitude 6.25 event in the San Francisco Bay area background zone, if it were centered directly underneath downtown San Francisco. The tables show estimated damage, fatalities, and cost per life saved. Note that net cost per μmt per occupant, in dollars, is exactly the same as cost per life saved in millions of dollars, because both numerator and denominator are divided by number of occupants. The "micro" in μmt accounts for the $10^6$ difference in units.

$$\text{Cost per life saved} = \frac{\text{Retrofit cost net of damage reduction}}{\text{Reduced number of deaths}}$$

$$\text{Cost per } \mu\text{mt} = \frac{\text{Retrofit cost net of damage reduction, per occupant}}{\text{Reduced risk in micromorts, per occupant}}$$

Note also that scenario results do not represent losses with 475-year return period. Rather they are losses associated with the earthquake occurrences that have a 475-year return period on the given fault.

**Probabilistic analysis results.** Table 3-6 provides results of the probabilistic analysis in terms of annualized retrofit costs, damage, and fatalities. We amortized retrofit costs using an interest rate of 7.25% minus 2.18% annual inflation, and a 50-year payment period (based on the design life of the building). The table breaks out costs by occupancy type: daytime occupancies being workplaces, nighttime being residences, and 24-hour occupancies being hospitals. As with the scenario analysis, net cost per life saved in millions of dollars also equals cost per microhazard (μhz) in unit dollars. Figure 3-11 illustrates the distribution of fatalities, with and without seismic bracing and anchorage of AS components.

Note that these results are not scenario results somehow amortized to an annual basis. As noted above, probabilistic analysis results represent outcomes of on the order of 100,000 earthquake scenarios of varying magnitude and location, combined according to recurrence probability.

It is also worthwhile to discuss briefly an ethical question raised by employing the interest rate just mentioned. It could be misinterpreted as an economic discount rate for human life. Ethicists point out that if it is worthwhile to spend $1 million this year to save a life this year, it is also worth $1 million this year to prevent a death 50 years from now. Perhaps so, but it would be difficult to convince a building owner that $1 million spent today is interchangeable with $20,000 spent annually for the next 50 years, regardless of the life-safety purpose of the money. The building owner will argue that she must borrow to purchase the additional safety, and the lender will change interest.

Regardless of this point, omitting the discount rate merely strengthens the efficiency argument. If initial retrofit costs were not discounted but merely distributed over the 50-year period, annualized retrofit cost would be lower than the figures shown in the table, and cost per life saved would likewise be lower.

## 3.6 Observations

**Practicality.** We have already noted the proposed tolerable failure probability for life-safety CES, $10^{-3}$ for ordinary buildings and $10^{-4}$ for essential facilities, may not be practical in cases of inherently fragile, distributed CES. The principle of "as low as reasonably possible" must apply in such cases, and a caveat to that effect must be included in the recommended guidelines.

**Necessity and efficacy.** We have already noted that codewriters tolerate 100 deaths per million occupants from structural damage, given the DBE. Equivalently, an occupant of a highrise building should expect to face a $10^{-4}$ risk of death from structural failure, given that he or she is in a highrise building during the DBE.

For 450,000 occupants, the codewriters would tolerate an expected value of 45 deaths from structural collapse. Table 3-5 shows that the estimated death risk from highrise building fire and AS failure exceeds this tolerability limit by an order of magnitude. That is, an individual occupant faces a death risk on the order of $10^{-3}$ given the DBE, solely from the hazard of fire and regardless of structural collapse.

Figure 3-11 illustrates the risk on a probabilistic basis, overlain on Helm's tolerability regions. In the figure, arrows indicate seismic retrofit to brace sprinkler lines, ceilings, etc. "Day" refers to risk in daytime occupancies; "night", nighttime occupancies. The figure shows that fatalities associated with post-earthquake fire and AS system failure exceed Helm's limit of local tolerability. On an expected-value basis, probabilistic risk per occupant can be evaluated by dividing expected annual deaths by number of building occupants. For daytime occupancies (workplaces), the risk under as-is conditions is 2.5 per year (Table 3-6) divided by 365,000 occupants, or just under 7 µhz. For nighttime occupancies (residences), the risk is similar: 0.75 deaths per year among 98,000 occupants, or 8 µhz. These figures are two orders of magnitude above that considered unacceptable for involuntary exposure according to Starr (Figure 2-6), and one order of magnitude above Starr's estimate of overall risk from natural disaster for the average person.

Thus, existing life-safety risk due to AS failure is one to two orders of magnitude above that considered tolerable by any of the authorities discussed above. Seismic retrofit is estimated to reduce risk by one order of magnitude using probabilistic measures, or by a factor of two to five when viewed on a scenario basis.

While seismic retrofit makes a difference in this risk, it does not always reduce it to tolerable levels. Figure 3-11 shows that seismic retrofit reduces losses to tolerable levels, although just barely. Recall that the region between local tolerability and local scrutiny is "tolerable only if risk reduction is impracticable or if its cost is grossly disproportionate to the improvement gained," as is the case here. When risk is viewed on a scenario basis, seismic retrofit does not meet UBC or other goals, but does substantially reduce it.

**Efficiency.** Table 3-5 and Table 3-6 indicate that, given the occurrence of any of the major San Francisco Bay area scenario events, seismic retrofit of AS systems is cost-effective, compared with government standards. Now compare the cost per micromort (μmt) in Table 3-5 with Howard's estimated personal value per μmt in Figure 2-8. The tables indicate that, if the occurrence of one of these events were certain, most occupants should be willing to pay the estimated net cost of AS retrofit to reduce their risk. Net retrofit cost per microhazard (μhz) from Table 3-6 is also significantly less than Howard's estimated personal value per μhz in Figure 2-9. Therefore, by several measures, seismic retrofit of AS system components in highrise buildings is cost-effective.

**Equity.** The test case indicates that all occupancy types benefit efficiently from seismic bracing of AS, so none need be excluded from the recommended guidelines. Equity is therefore maintained. It must be acknowledged that landlords pay for the retrofit, and that damage reduction only partly offsets the capital costs, whereas tenants reap the benefit of increased safety. However, the situation is the same for seismic strength aspects of structural design codes. Furthermore, landlords are likely to pass on these costs to tenants anyway in the form of increased rent.

*Table 3-4 – Scenario damage results*

| Source | Retrofit cost, $M | Occupants (1000s) | Unbraced Dmg ($M) | Retrofitted Dmg ($M) | Net cost ($M) | Net cost per occ ($) |
|---|---|---|---|---|---|---|
| SF Bay area bkgd zone | 448.9 | 454 | 727.8 | 415.6 | 136.7 | $301 |
| San Andreas fault | 448.9 | 454 | 595.9 | 273.5 | 126.5 | $279 |
| Hayward fault | 448.9 | 454 | 440.3 | 147.8 | 156.4 | $345 |
| San Gregorio - Hosgri | 448.9 | 454 | 404.2 | 145.2 | 189.9 | $418 |
| Calaveras | 448.9 | 454 | 258.9 | 51.2 | 241.2 | $531 |

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*Table 3-5 – Scenario casualty results*

| Source | Deaths† -- day Unbr | Retr | Cost / life saved* $M | Deaths† -- night Unbr | Retr | Cost / life saved* $M |
|---|---|---|---|---|---|---|
| SF Bay area bkgd zone | 438 | 240 | 0.69 | 71 | 33 | 3.63 |
| San Andreas fault | 348 | 152 | 0.65 | 57 | 19 | 3.35 |
| Hayward fault | 247 | 76 | 0.91 | 40 | 9 | 5.06 |
| San Gregorio - Hosgri | 231 | 76 | 1.22 | 35 | 8 | 7.19 |
| Calaveras | 135 | 20 | 2.10 | 19 | 1 | 13.78 |

† Injuries = 15 x deaths

* Also equals $/μmt

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*Table 3-6 - Probabilistic analysis results*

| Occu-pancy | Retrofit cost ($M) | Amortized retr. cost ($M) | Damage, unbraced ($M) | Damage, w/retrofit ($M) | Net amort retr cost ($M) | Deaths, unbraced | Deaths,w/ retrofit | Cost / life saved ($M)* |
|---|---|---|---|---|---|---|---|---|
| 24-hour | $5.0 | $0.28 | $ 0.26 | $ 0.03 | $0.05 | 0.13 | 0.01 | $0.39 |
| Day | $302.4 | $16.74 | $ 14.09 | $ 1.77 | $4.42 | 2.50 | 0.29 | $1.99 |
| Night | $136.6 | $7.56 | $ 3.23 | $ 0.38 | $4.71 | 0.75 | 0.08 | $7.09 |

* Also equals $/μmt, (i.e., net amortized retrofit cost / reduced in annual death risk)

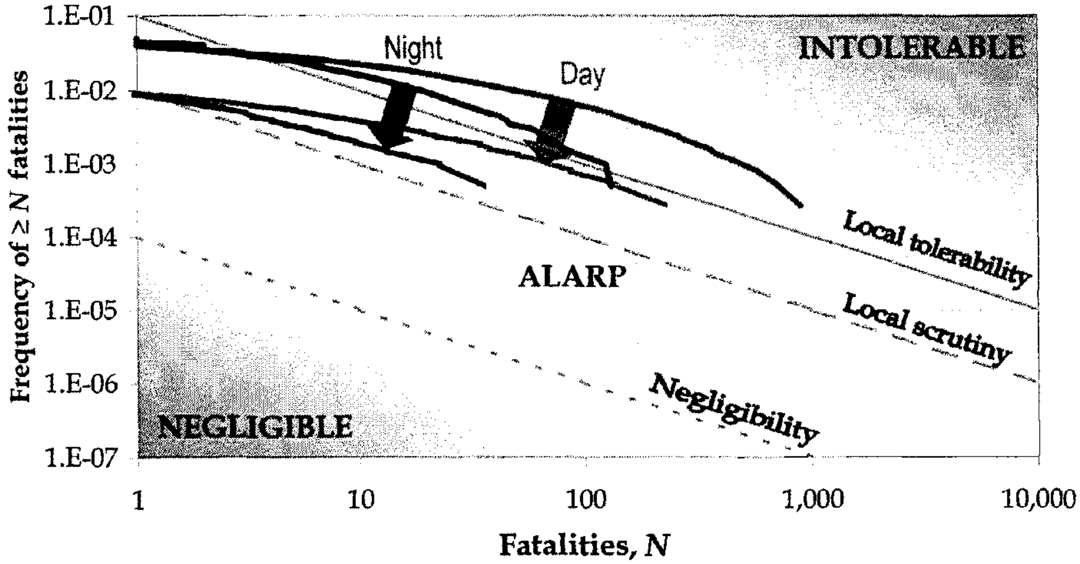


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*Figure 3-11 - Efficacy of AS seismic retrofit in terms of Helm's frequency-severity relationship*

## SECTION 4
## PERFORMANCE GOALS FOR OPERATIONAL EQUIPMENT

Far less guidance exists for recommending consistent tolerable economic risk in earthquakes than for tolerable life-safety risk. Building codes have little to say on the subject, probably because most local governments do not consider financial risk (beyond consumer protection) a public-policy issue. Financial risk from natural disasters lies more typically within the domain of insurers, investors, and business owners. Individuals in these groups each express their own risk attitude and sensitivity to operational failure, and typically must assess a tolerable probability of operational failure compatible with their own operational goals.

Our analysis and recommendations, therefore, are more in the line of suggested guidelines. Some guidance can be drawn from Vision 2000's developing standard, and from common practice handling economic aspects of seismic risk to buildings. We have reviewed these precedents below, and developed a provisional tolerable failure probability that is one order of magnitude greater than that for life-safety equipment. That is, absent explicit operational objectives for the facility, it is reasonable to attempt to achieve a maximum failure probability of $10^{-2}$ for ordinary facilities given the 475-year event, $10^{-3}$ for essential facilities. These are equivalent to risk scores of 2 and 3 in the context of the *Seismic Reliability Assessment* guidelines.

***Important***: operational equipment in emergency-response facilities only refers to equipment that is not required to provide emergency medical services, for example, payroll computers, etc. Medical equipment, lighting for surgery, power systems necessary for life-support, etc., should be treated as life-safety equipment, and would not fall under the present discussion.

### 4.1 Building-code precedent

Little building-code precedent exists for recommending a minimum seismic score for equipment systems whose value is wholly economic. ICBO, SEAOC, CalTrans, and other code-writing bodies have explicitly limited themselves to considering earthquake risk only from the point of view of life safety, and have avoided addressing economic risk in detail.

Some guidance does exist in the form of Vision 2000's recommendations for functionality. While Vision 2000 explicitly allows failure of non-life-safety equipment in the 475-year event, it does require ordinary and high-occupancy buildings to remain operational after the 72-year earthquake, and fully operational after the 43-year event. By *operational*, Vision 2000 means that, at worst, essential operations are protected, although non-essential operations may be disrupted. By *fully operational*, Vision 2000 means that non-essential operations are not disrupted. Clearly these are requirements based solely on economic considerations, and therefore represent provisional guidance on economic risk.

These requirements can provide the basis for a maximum allowable failure probability for non-life-safety equipment systems. Observe that the tolerable conditional probability of failure for essential operational equipment under the 72-year event can be equated with that of life-safety equipment under the 475-year event. Likewise, non-essential equipment systems should have the same conditional failure probability under the 43-year event.

Consider Figure 4-1, already shown in Figure 2-2 but duplicated here for convenience. The DLE ground-shaking intensity is associated with 90% probability of nonexceedance in 50 years. The *Seismic Reliability Assessment* guidelines were designed using the 0.4g contour level. Follow this contour back to the point associated with 50% nonexceedance probability in 50 years (annual risk = 0.0139). It appears that the equivalent 72-year EPA is 0.22g. The 43-year event (annual risk = 0.0231) is associated with an EPA of 0.18g. This suggests that the risk to life-safety equipment acceptable at 0.40g -- say $10^{-3}$ -- is the same as essential operational equipment in ordinary construction at 0.22g, and nonessential operational equipment at 0.18g.

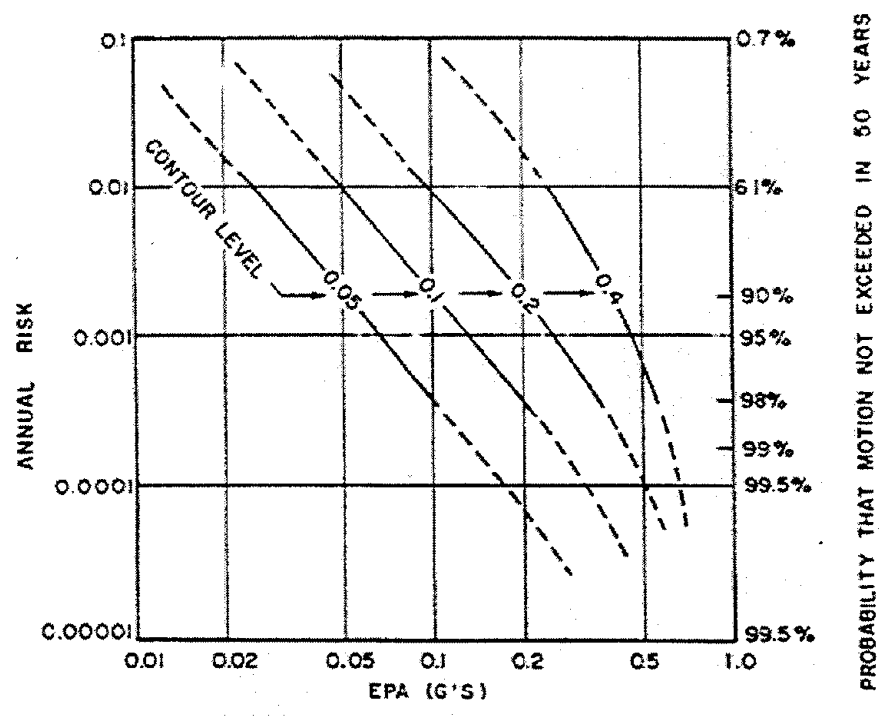


*Figure 4-1 – Annual probability of exceeding various EPAs*

An analysis of AS system fragility detailed later in this report indicates a 6-times increase in failure probability between 0.22g and 0.40g. The difference between failure probability at 0.18g and 0.40g is approximately 13 times. Compare these with a 5 to 10 times higher failure probability for structural components and structural collapse given similar changes in EPA (Figure 2-1).

Hence, if $10^{-3}$ is an acceptable level of risk for life-safety equipment in ordinary buildings under the 475-year EPA, $10^{-2.2}$ would be acceptable for essential operational equipment in the same event; $10^{-1.9}$ for non-essential operational equipment. The difference between the last two figures is small enough to be ignored for present purposes. One can conclude that operational equipment in ordinary facilities should have a maximum $10^{-2}$

failure probability under the 475-year event, corresponding to a risk score of 2. For essential facilities, similar reasoning suggests a provisional minimum risk score of 3. We now compare or reconcile these provisional goals with other measures of tolerable economic risk.

### 4.2 PML and insurer risk tolerance

The most often-used metrics of economic risk in earthquakes tend to be oriented toward insurance applications, because of insurers' long history of dealing with the costs of natural disasters and other uncertain events. Recently, lenders have adapted insurance methods to control risk of mortgage default due to natural disasters. Common measures of earthquake risk have developed to measure the risk to insurer liquidity and to ensure profitability. Some of these measures are useful in recommending equipment reliability.

The issue of liquidity involves the estimation of losses from rare, large events, and is most often measured in terms of *probable maximum loss*, or PML. The term developed originally in connection with fire insurance, and was later extended to earthquake insurance by Karl Steinbrugge, Harold Engle, and others (Steinbrugge, 1982) for use by the California Department of Insurance (CDI). The term referred to a high-end level of economic loss that an insurer might suffer in a major California earthquake. CDI's interest in estimating a PML is consumer protection: verifying insurers' ability to remain solvent and pay all claims in a major earthquake.

The Steinbrugge definition of earthquake PML for an insurance portfolio, class of buildings, or individual building is somewhat hypothetical. It refers to the 90th percentile of monetary loss that buildings experience under the 300-year maximum probable earthquake, if they are located on a particular soil type. (See Steinbrugge pp. 30 and 204.) This PML addresses the risk posed only by the dominant fault in the region. It does not deal with each building's distance to the fault, the faulting mechanism, specific engineering features of individual buildings, or any hazard other than ground shaking. These latter factors all affect probable loss level.

During the 1980s, EQE redefined earthquake PML to be both more site-specific and comprehensive. This definition takes into account site-specific features: site soils; unique engineering features; lesser, closer faults; and non-shaking hazards (liquefaction, landslide, fire following earthquake, etc.). The return period is greater than Steinbrugge's: EQE uses the 475-year DBE, as opposed to the 300-year event proposed by Steinbrugge.

Under contracts with commercial and industrial building owners, EQE engineers employed this definition of PML in physically examining and assessing earthquake risk for more than 15,000 structures in California and elsewhere beginning in the early 1980s. The same measure was employed to refer to insurer or lender seismic risk when EQE developed the computerized analysis tools EQEHAZARD™ and USQUAKE™ for insurance and mortgage portfolios (EQE, 1989; EQECAT 1997).

Other engineering firms who perform site risk assessments also estimate losses in terms of PML, as do other major earthquake-risk computer models for insurers such as IRAS

(RMS, 1994), which appears to adheres to the CDI definition. However, no universal standard definition of earthquake PML for site assessments yet exists. The Structural Engineers Association of Northern California is developing one for the structural engineering community. In the mean time, EQE's definition is generally accepted by insurers, lenders, building owners, and the California Department of Insurance (Morrow, 1995).

Because of the CDI approach, property insurers tend to think of insolvency risk in terms of PML, and create plans to survive those events. They typically buy reinsurance with the primary goal of limiting net loss to a small fraction of available surplus, given the PML event or smaller. The fraction is typically on the order of 5 to 20%. (Surplus is the difference between assets and liabilities, and therefore represents the insurer's ability to pay net claims.) CDI acts against insurers whose surpluses are more seriously depleted by a major catastrophe, as it did the case of 20th Century Insurance Co. after the Loma Prieta earthquake.

This approach provides fairly strong assurance of survival if an actual loss is less than the PML. The probability of exceeding the PML, on the other hand, dominates the earthquake-related risk of a property insurer's financial ruin. The probability that an earthquake occurring whose loss exceeds the PML is almost by definition 10% given the DBE, itself a 1-in-300 or 1-in-475-year event. If the loss is below the PML, the properly reinsured insurer survives. If significantly above, losses easily absorb the surplus of an insurer whose book of business is concentrated in a seismic region like the San Francisco Bay area. Such a company's surplus is typically small compared with total sums insured.

Financial failure from PML-plus events is less of a concern for insurers that can draw on resources from other corporate divisions, but some conglomerate insurers have begun requiring divisions to be largely self-sufficient in catastrophes. There remains the possibility that more than one major loss event will occur in a short period of time, before the insurer can afford to reinstate its reinsurance and recover its surplus. This possibility has recently been shown to be significant by a string of catastrophes producing multi-billion-dollar industry losses every year since 1989. However, this case has not been dealt with in a significant way by insurance regulators or industry practice, other than by insurers trying to leave high-risk markets.

At any rate, it appears that the average property insurer accepts risk of financial failure from a PML in a DBE somewhere on the order of 10%. This precedent would be useful in the present study for the case of a property owner whose financial health relies on continued operation after the DBE. If this precedent were used as a guideline, the target failure probability in a DBE for operational equipment would be 0.1. It appears however that upcoming building codes (as illustrated by Vision 2000) will indirectly require greater reliability, because of guidelines for lesser, more frequent events.

### 4.3 Other measures of acceptable economic risk

Less commonly used than PML but increasingly popular are probabilistic measures of insurance risk, that is, the sum of losses from all possible events multiplied by their probability of occurrence. When probabilities are estimated on a per-year basis, this measure is often called *annualized loss.* Two measures of probabilistic economic risk of particular interest are *per-occurrence* and *annual aggregate loss.* The distinction is that the annual aggregate shows annual probability that total losses from the entire year will exceed x dollars, considering the probability of more than one loss-producing event occurring in a single year. By contrast, per-occurrence loss shows annual probability that a single event will produce losses exceeding x dollars. Actuaries refer to mean annual aggregate loss as *pure premium,* a measure closely related to profitability.

Insurers charge actual premiums that are higher than pure premium to cover profit, overhead, taxes, risk due to loss volatility, and expenses such as claims-adjustment costs. Although actual premium is therefore based partly on risk, it is also influenced by market forces and by regulation of insurance commissioners. Consequently, earthquake insurance premium is a hybrid measure of the estimate of risk made by the insurer, consumer, and regulators. Insurance cost data become indicators of tolerable economic risk.

In an unrestricted earthquake insurance market, insurance premiums would measure an agreement of what insureds and insurers consider acceptable risk. Insurers consider a risk acceptable (to take on) if they are paid at least the market price for it, and consumers consider the risk acceptable (to carry themselves) if the market price is any higher.

Data on insurance costs are generally available for homeowners insurance in California because of CDI's emphasis on consumer protection. CDI does not concern itself as much with commercial earthquake insurance, so costs are not readily available from public sources.

Until the California Earthquake Authority (CEA) was created in 1996, California required insurers selling homeowner policies in the state also to offer earthquake insurance to insureds at regulated prices. In May 1995, California earthquake insurance for homeowners cost $3 to $4 per $1,000 insured per year (CDI, 1995). Deductibles for these policies ranged from 5% to 10%, with higher deductibles being far more common.

Despite CDI's influence, the controlled market did find an acceptable cost threshold from the insured's point of view. This is shown by the fact that 42% of homeowners in the Northridge earthquake damage area with a standard HO-3 homeowners policy had purchased an earthquake endorsement (CDI, 1996). That only half of homeowners bought insurance suggests that homeowners considered $3 to $4 per $1000 the threshold of tolerable economic risk. This is further supported by the case of the CEA, which has been charging similar premiums (statewide average $3.29 per $1,000), while offering more limited coverage and higher (15%) deductible (CDI, 1997). As of October 1997, CEA has had few buyers. This further supports the notion that traditional homeowner earthquake insurance straddles the line of tolerable risk. Considering a homeowner's point of view, then, one may say that the rare loss of home equity because of earthquake is tolerable if the avoidance cost is much more than $4.00 per $1000 per year. (Annuitized over a period of 30 years at 10% interest, this equates with $37 per $1,000, or 3.7% of the insured value.)

The public's sense of its risk is in flux, primarily because of the Loma Prieta, Landers-Big Bear, and Northridge earthquakes. CDI reports that in 1990, just after Loma Prieta, approximately 30% of Los Angeles and San Francisco-area homeowners were insured for earthquake. At the time of the 1971 San Fernando earthquake it was less than 10%. CDI estimated that, had adequate insurance industry capacity existed, the figure could have reached 60 to 80% after Northridge, despite premium rises.

Another opinion on acceptable earthquake risk comes from financial rating agencies. AM Best rates the strength and operating performance of financial institutions. Among these are property and casualty insurers exposed to catastrophe losses. After the string of major natural disasters in the early 1990s, Best added catastrophe-modeling requirements to its review process. Large companies are required regularly to estimate catastrophe losses, and provide for solvency given the 100-year windstorm or 250-year earthquake AM Best, 1996). No reference is made to probable maximum, implying an acceptable 50% probability that A-rated insurers become insolvent due to earthquake in a 250-year earthquake. This is a significantly higher risk than CDI allows.

### 4.4 Risk of ruin

One additional measure of economic risk comes from ruin theory. An insurer's *risk of ruin* estimates the chance that claims and other business processes will result in a company's surplus dropping below a predefined *ruin barrier.* The ruin barrier is typically defined either based on regulatory solvency requirements or corporate goals. A tool of ruin theory called *dynamic financial analysis* (DFA), is developing that attempts to identify all sources of income and loss, and to model stochastically the wealth of the company. In addition to its main goals of evaluating reinsurance alternatives and assessing risk-return tradeoffs for financial decisions, DFA incidentally estimates annual aggregate probability of ruin. An example DFA application is that of Guy Carpenter & Co., Inc. (1997).

Daykin (1994) provides a thorough discussion of the theory behind these approaches. In Figure 4-2, from Daykin, the horizontal axis is time, a simulated period of the next 30 years. The vertical axis is solvency ratio, a measure of the company's wealth. Each line in the graph is a simulation of the company's performance over the next 30 years. Asterisks indicate when the simulation crosses the ruin barrier. The number of insolvencies (asterisks) divided by the number of simulations is the estimated risk of ruin.

DFA is fairly new, and few companies so far have used it. No guidelines have developed around DFA to identify an acceptable probability of ruin. Consequently, actual practice varies country to country and company to company, based on the judgment of company executives. Actuaries who regularly use DFA tools report that companies highly tolerant of risk accept up to 1% annual failure probability from all sources of risk. Risk-averse companies accept on the order of 0.1%.

It is useful to convert these annual probabilities to the same 475-year basis as the DBE. They equate with a failure probability from all causes of $1-(1-p)^{475}$ = 99.2% for the least risk-averse company, or 37.8% for the most risk-averse. Recall that the PML is supposed to have only 10% probability of being exceeded, implying a 10% probability of the insurer becoming insolvent given the DBE. Compare this 10% with the 37.8% to 99.2% for all sources. This suggests insurance executives consider large earthquakes to represent a significant fraction of overall aggregate risk.

Some researchers have attempted to relate risk of ruin to standard insurance practices. Hofflander and Duvall (1967) and Anderson (1974) related risk of ruin to the premium-to-surplus ratio. Both papers assume a desired annual probability of ruin of $1.6*10^{-4}$ due to all causes (3.6 sigmas below the mean in a normal distribution). This is substantially below the 0.1% to 1% level, but approximately equal to the probability of an insurer exceeding the PML in a DBE: $1 - (1 - 1.6*10^{-4})^{475} = 7.3\%$.

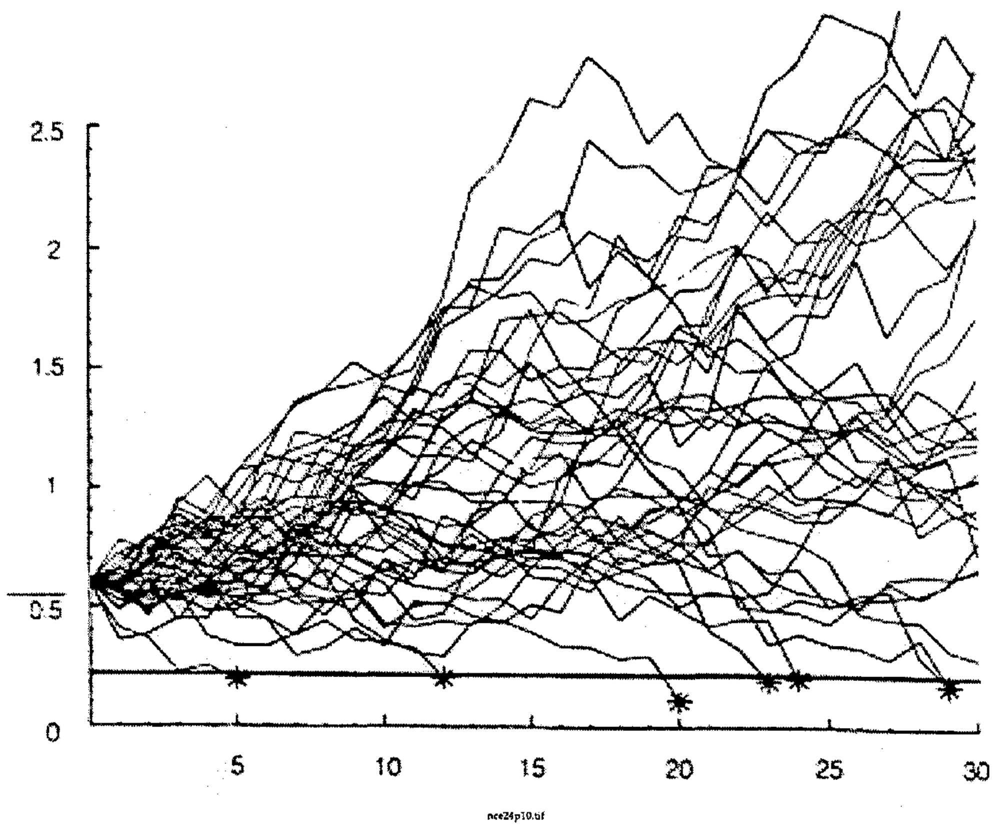


*Figure 4-2 – Stochastic modeling of risk of ruin*

## 4.5 Investor-owner PML tolerance

Within the past 10 years, commercial use of PML analyses has extended beyond insurance regulations to investor-owners. The primary cause is as follows. First, insurers have begun to use single-site PML as a loss-control technique, as opposed to their use of portfolio PML in the regulatory arena. Insurers often refuse to underwrite a building if the PML exceeds a tolerable threshold, or else increase the premium to cover the risk. At the same time, lenders have begun requiring earthquake insurance if a PML exceeds a certain threshold level, typically around 20% of building replacement cost. By these means, investor-owners of commercial real estate have become aware of PML as a measure of earthquake risk. In addition, investor-owners have begun to adopt this same level of damage as a maximum allowable before they enter into a contract to purchase a building. They do this to limit insurance costs and exposure to litigation from deaths and injuries.

The 20% PML figure is by no means a solid rule, but it is a common figure quoted by clients of EQE, and merits examination. This level of structural damage does not prevent loss of use. It is usually associated with a high likelihood that structural and nonstructural damage will render the facility temporarily nonoperational. ATC-13, for example, repeats Reitherman's (1982) estimate that 25% structural damage is associated with 2 to 12 weeks' loss of use. It agrees well with ATC-13's own mean restoration estimate for commercial buildings in this damage state: 10 days until 30% functional restoration and 10 weeks for full functional restoration. The implicit acceptance of temporary loss of use confirms Vision 2000's position that operational equipment in ordinary buildings need not survive the 475-year event intact, at least form investor-owners' point of view. This is reasonable because the consequence of nonfunction for investor-owners of loss is not severe. That is, if a building becomes inoperative for two weeks, the investor-owners do not go out of business, hence the implied high tolerance level for loss of function in the DBE.

### 4.6 Owner-occupants sensitive to loss of function

In some cases, loss of function can have serious financial consequences for owner-occupants whose market share or reputation is highly dependent on their ability to deliver a product or service despite an earthquake. EQE has performed seismic retrofit work for certain manufacturers of high-technology hardware, where the retrofit goal was to ensure a very high level of reliability for building-service equipment. In these cases, extended operational failure for the facility was considered likely to result in financial failure of the corporation. Certain bank data centers would fit into this category.

A reasonable lower bound to tolerable risk in such cases is that developed above for life-safety equipment systems, namely, $10^{-3}$ given the DBE. The upper bound might be $10^{-2}$, as Vision 2000 seems to imply. Though these figures may provide reasonable bounds, they do not substitute for a thorough cost-benefit analysis (CBA). In such a CBA, costs of operational failure under various reliability levels and the DBE would be compared with the cost of seismic retrofit or of other strategic alternatives to reduce vulnerability to equipment damage.

### 4.7 Other owner-occupants and seismic retrofit

When owner-occupants are not less sensitive to loss of facility function, they may still attempt to reduce risk by seismic retrofit, under certain circumstances. We have observed in consultation with large commercial and industrial clients that they perform seismic retrofit under three conditions:

- Facility has a significant PML (around 15 to 20%)
- Cost of seismic retrofit is less than 15 to 20% of facility replacement cost
- Seismic retrofit is estimated to reduce the PML by more than its cost.

In practice, owners consider a risk to be *negligible* if PML is less than 15%. By negligible, we mean that owners tend to take no further action to reduce risk if it is below this level.

Owners consider risk to be *tolerable* if the PML is greater than 15 to 20% but the cost to reduce it through retrofit exceeds the benefit. This is an issue of retrofit, repair and business-interruption costs, rather than simply fragility. The present study has not attempted to deal extensively with time to restore functionality. Consequently, for this type of situation, there is no way to measure tolerable reliability in the sense of the *Seismic Reliability Assessment* guidelines.

### 4.8 Cost-benefit analysis

Cost-benefit analysis would be a reasonable approach to finding an optimal, minimum-cost failure probability for operational equipment. The problem is that the cost side of the equation requires one know how long the equipment will remain inoperative. Unfortunately, the time dimension is missing from the *Seismic Reliability Assessment* methodology, although Johnson believes that the methodology could be enhanced with additional research to include such a dimension. The value of such a capability would be substantial.

### 4.9 Conclusions on acceptable risk and seismic score for operational equipment

Our review of acceptable risk for operational equipment suggests two levels of reliability for operational equipment systems, one for emergency facilities such as hospitals and telephone central offices, one for ordinary buildings.

**Essential facilities.** Operational equipment systems required for emergency response should function if the building does not collapse. This latter probability has been estimated to be on the order of $10^{-4}$ in the DBE. In the context of the Seismic Reliability Assessment guidelines, this equates with a minimum seismic score of 4. Operators of essential facilities may wish to allow operational equipment that is not needed for emergency response to meet a lower standard. We recommend $10^{-3}$, or a seismic risk score of 3.

**Ordinary buildings.** Codes do not now require operational equipment in ordinary buildings to continue functioning after the DBE, not are they likely to in the future. However, it appears that requirements under development in the Vision 2000 project will cause the frequent (43-year) and occasional (72-year) earthquakes to control the design and installation of these equipment systems. These requirements result in a recommended minimum seismic risk score of 2 under DBE conditions. If the financial consequences of operational failure are grave, the life-safety level (3 in ordinary buildings) can be used instead.

## SECTION 5
## CONCLUSIONS AND RECOMMENDATIONS

**Life-safety CES.** As shown in Table 5-1, we have proposed guidelines for failure probability of life-safety CES in DBE conditions: $10^{-3}$ for ordinary buildings and $10^{-4}$ for essential facilities, equivalent to minimum tolerable risk scores of 3 and 4, respectively. These probabilities are consistent with the philosophy that these CES should be as reliable as the structural system.

It appears from the test case that these goals are not necessarily achievable for dispersed, inherently fragile CES such as automatic sprinklers. However, even if $10^{-2}$ is the best that can be achieved, the improvement can make the difference between intolerable and tolerable risk, but *only* if this is the best that can be practically achieved. For both DBE scenarios and probabilistic (annualized) losses, seismic retrofit in the test case was shown to be necessary, effective, equitable, and cost-efficient.

**Operational CES.** Operational equipment in essential facilities that serves a life-safety role (such as telephone switching equipment in telephone central offices) should be treated like life-safety CES, and meet the guidelines discussed above. For other equipment, and absent explicit performance objectives from facility operators, we recommend that operational equipment achieve a seismic risk score of 2 in ordinary buildings ($10^{-2}$ probability of failure), 3 in essential facilities ($10^{-3}$ probability of failure).

***Table 5-1 – Recommended minimum seismic risk scores***

| Facility class | Life-safety CES | Operational CES |
|---|---|---|
| Essential (emergency response) | 4 | 3 |
| Ordinary | 3 | 2 |

**Using these guidelines to achieve cost-effective risk mitigation.** The basic methodology for using the tools discussed here is as follows.

1. Identify equipment systems that are important either for the normal operation of the facility or for life-safety protection. (Common systems and their components are tabulated in Porter et al., 1993.)
2. Create a tree diagram of the system as described in Johnson et al. (1998).
3. Complete rapid-visual-screening score sheets for components at the bottom of the tree.
4. Use the math recommended by Johnson to determine the system score, and compare with the minima recommended above. If the score exceeds these minima, and is also consistent with explicit risk goals of your own organization, no further analysis is required. *Important:* your organization may already have operational reliability goals. Seek them out. Bear in mind that the system risk score *S* is intended to measure failure probability $P_f$ through the relationship $P_f = 10^{-S}$. Thus, a system score of 2 indicates an estimated failure probability of 0.01,

or 1 in 100, given the occurrence of the DBE (design-basis earthquake, typically a 475-year event).

5. If the score is below the minimum, consider seismic retrofit. There are two basic options: strengthen existing equipment or add redundant equipment. In an industrial setting, personnel training may also reduce risk, but that is not a viable alternative in the case of a highrise office building, for example. To pursue seismic retrofit, examine the tree math to identify the main detractors of risk score from among the basic equipment components.
6. Among these detractors, identify performance modification factors (PMFs) that may be eliminated by seismic retrofit. For example, anchoring equipment to the floor may increase a component's score. Alternatively, changing system configuration by the addition of parallel or backup components can also increase risk score. Compile reasonable sets of these measures into distinct retrofit alternatives.
7. Evaluate the effect on overall risk score of each alternative. Often, retrofitting a small set of components can produce an acceptable score.
8. Identify the least-cost alternative that produces an adequate score. This is most likely the preferred alternative. For preferred alternatives that entail substantial cost, verify the analysis with detailed examination by a licensed professional engineer.

As noted in section 2, these guidelines have been justified primarily for regions where the Johnson procedures are applicable, i.e., where the 475-year earthquake represents a significant seismic threat to life safety. They may be less appropriate for regions of low to moderate seismicity but high catastrophic earthquake loss potential from rarer events.

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## APPENDIX A
## SQUARE-FOOT REPLACEMENT COST NEW

Table A-1 summarizes square-foot replacement costs new (RCN) for highrise occupancies. In the table, *building* refers to structure, architectural features, mechanical, electrical and plumbing (MEP), and designer and contractor fees. *Contents* refers to real property aside from financial instruments and documents, such as furniture, computers, etc. Time value, expressed in dollars per 12 months, depends on the interested party. For landlords, time value is typically lost rent. For business tenants, it may be administrative and labor costs of a move (assumptions are detailed below). For residential tenants, temporary housing is the primary issue.

As hinted above, the justification of each value in the table follows in alphabetically ordered subsections. The reader will notice that value to landlords and tenants are described separately, so that risk can be examined later from the point of view of each party. Note well that most or all of these values are specific to highrise buildings in the San Francisco Bay area, and may not be comparable with values elsewhere or with low- or midrise buildings of the same occupancy type.

*Table A-1 – Square-foot replacement cost new (RCN)*

| Party | Building | Contents | Time |
|---|---|---|---|
| Apartment owner | $113.00 | $7.25 | $15.00 |
| Apartment tenant | $0.00 | $56.50 | $17.00 |
| Church | $113.00 | $79.00 | $0.00 |
| Condo association | $93.50 | $7.24 | $0.00 |
| Condo occupant | $19.50 | $79.10 | $17.00 |
| Entertainment | $100.00 | $30.00 | $15.00 |
| Garage | $34.80 | $0.00 | $5.25 |
| Hospital | $145.00 | $260.00 | $21.75 |
| Hotel or motel | $127.60 | $63.80 | $19.00 |
| Industrial light manufacturing | $108.00 | $54.00 | $16.20 |
| Mercantile/service landlord | $123.00 | $226.00 | $18.50 |
| Mercantile/service tenant | $0.00 | $226.00 | $18.50 |
| Office landlord | $123.00 | $0.00 | $20.00 |
| Office tenant | $0.00 | $86.00 | $20.00 |
| School | $118.00 | $86.00 | $0.00 |

### Apartments

The average total area of apartment buildings in San Francisco Bay area highrises is estimated to be approximately 174,000 sf. According to RS Means (1994), construction costs (Means reference M.030) for a similar-sized 8-24-story apartment buildings ranged from $74.00 to $82.00/sf on average, with San Francisco Bay area construction costing around 26% more than average. According to Kiley (1996), these costs brought forward three years should be increased by 15%. Total current building RCN: $78.00 * 1.26 * 1.15, or $113.00/sf. All of building value is the property of apartment owners.

Means does not include appliances in its building-cost estimate; it suggests $5.00/sf. Factored for time and location, this is $7.25/sf. This value is attributed to owners. As for tenants, insurers usually conservatively assume a content value of 0.7 times structure value for homeowners. ATC-13 suggests a value half as large. Reality probably lies somewhere in the middle. Small-sample surveys we have performed among apartment tenants tend to confirm this judgment, and suggest tenants actually own moveable property with RCN of 0.5 times structure value. We have taken apartment-tenant content value to be $113.00 * 0.5 = $56.50/sf

The primary time loss for apartment landlords is rent. From the American Housing Survey's 1989 San Francisco housing database, of apartments in buildings with more than 4 stories, the median rent per square foot was $0.91/sf in 1989. Brought forward at 4% inflation over 8 years, this would be approximately $1.25/sf/mo, or $15.00/sf/yr. Apartment tenants' costs include temporary hotel accommodations plus movers. Insurers' standard coverage for additional living expenses (ALE) is 20% of building value, and past studies indicate that at most ¾ths of this amount is typically claimed. We have used 15% of $113.00/sf = $17.00/sf/12 mos.

**Church**

Some church occupancy shows up in the assessor files for highrise buildings. It seems reasonable that this is a church on the ground floors of a church-owned apartment building. Consequently, we have used apartment landlord building value: $113.00/sf. As for contents, ATC-13 suggests 20%; of building value. As with apartment contents, ATC-13 seems to underestimate this value. We have used 40% of building value, or $45.00/sf. Zero time-value has been applied, since it may be assumed that churches will share space gratis until replacement facilities can be acquired.

**Condominium**

Building value must be split among the condo association, with interior finishes sometimes being the responsibility of the tenant, sometimes the association. We have taken total building value the same as for apartments: $113.00/sf. Means (type M.030.6.0) suggests 29.7% of the total structure value is interior construction, or $113.00 * 0.297 = $33.56. Of this, floor covering is always the occupant's property (16% of interior construction value; ref. M.030.6.6): $33.56 * 0.16 = $5.37. The association is sometimes liable for the remainder ($33.56 - $5.37 = $28.19), sometimes not, depending on the contract. We have assumed that half the time, the association owns the rest of interior finishes, half the time it is property of the occupant. Hence, the associations building value is $113.00 - $5.37 – 0.5*$28.19, or $93.50. This leaves $19.50/sf structure value for the condo occupant.

Unlike apartment landlords, the condo association is not liable for appliances; these are the property of the tenant. We have used zero content value and zero time value for the association. As for tenant content value, we have applied the standard ratio from insurers, 70% of structure value, for condo tenants, or $79.10/sf. Time value is taken to be the same as for apartment tenants.

### Entertainment

Most or all of this is theater space in San Francisco's theater district. Theater space in a highrise building is fairly rare, and does not appear in standard cost manuals. This is a very small portion of the total inventory, so we have relied on judgment to assign values of $100.00/sf building value, $30.00/sf content value (ATC-13 suggests 20%, which seems low), and $15.00/sf/yr time value.

### Garage

Means M.270 suggests $24.00/sf, which factored for time and location is $34.80/sf. Content value is taken as zero. Time: we used 15% * $34.80 = $5.25/sf/12 mo.

### Hospital

Means class M.340 suggests a value of $99.00/sf for a hospital of 200,000 sf. Factored for time and location, this is $145.00/sf. ATC-13 recommends content value of 180% building value, or $260.00/sf. Time value is difficult to estimate; we have used 15% of building value, or $21.75/sf/12 mo.

### Hotel or motel

Means reference M.360 suggests 8-24-story hotels (200,000 sf) cost $75.00-$85.00/sf. Factored for time and location, this is $80.00 * 1.45, or $116.00/sf. We added 10% for common additional features such as bar, laundry, sauna, etc., and developed a final figure of $127.60/sf. We have assumed 50% or building value for contents, or $63.80/sf, and 15% of building value for time, or $19.00/sf/12 mo.

### Industrial light manufacturing

These are largely miscellaneous industrial and warehouse structures. Standard cost manuals do not deal with such rare structures as highrise industrial or warehouse structures. It seems reasonable to assume these are bare highrise office buildings, i.e., without floor and ceiling finishes or much in the way of interior partitions. Means reference M.480.6.1, 6, 7 suggest that these finishes account for 12% of total, so the remaining 88% amounts to $123.00/sf * 0.88, or $108.00/sf. Content value according to ATC-13's Table 4.11 is 50% of building value, or $54.00/sf. Time value is taken as 15% of the building, or $16.20/sf/yr.

### Mercantile and service

These are stores and services in the retail levels of highrise office buildings. For that reason, we used $123.00/sf for structure value. One can estimate mercantile inventory from accounting rules of thumb for median rent as a fraction of gross revenue, and gross revenue as a multiple of inventory value. We have added to inventory value the value of furnishings and fixtures from ATC-13, and estimated $1.84 content value per $1.00

structure value, or $226.00/sf, all attributable to the tenant. To each we have assigned 12-month time value of 15% of structure value, or $18.50/sf/12 mo.

### Offices

The assessor data indicate that the average square footage of office buildings is 284,000 sf, indicative of a 15-to-20 story building. From Means reference M.480, structure costs for this size structure are approximately $85.00/sf. With time and location, this is $123.00/sf. In some cases tenant improvements or build-outs make part of this value assignable to the tenant; we have ignored this wrinkle for present purposes and assigned all building value to the landlord. Regarding content value, ATC-13 suggests 35% content ratio, or $43.00/sf. However, insurance rules of thumb indicate twice this value, and we have therefore used $86.00/sf for office contents, all of which are assigned to the tenant.

Office landlords' time value springs from rent. Office rents in San Francisco and the Peninsula range between $0.75/sf/mo and $1.65/sf/mo, according to Realtor web pages in March, 1997. Highrise buildings are generally in the high-rent CBD, so we have assumed landlord time value at the high end of this spectrum, $1.65/sf/mo, or $20.00/sf/yr.

When tenants are displaced suddenly, the costs associated with time result can result from several sources. From these costs we exclude rent above their current deal, on the assumption that the supply of office space is not significantly impacted, and the cost of rental space in lieu is the same as at the original office. We also neglect the potential cost of completed work that is lost, that is, we have assumed that files and undelivered work papers survive, and do not need to be recreated.

For the tenant displaced by a fire or other accident, the main variables remaining are assumed to be as follows. One to two weeks' administration, move-out, move-back, telephone changes, notices, 2-6 working days of staff labor packing & unpacking (potentially overtime), LAN work, rental furniture, lost business, and revenue lost during moves. We estimate that these costs add up to something like 2 weeks' revenue (4% of annual revenue). Annual revenue, on a per-square-foot basis, varies by profession, but typically ranges between 20 and 40 times rent expense, or $400 to $800/sf/yr. At 4% of this value, office-tenant expenses resulting from a fire or EQSL accident would be around $16.00 to $32.00/sf. This equates basically with the same 15-20% of building value. We have used $20.00/sf/year.

## APPENDIX B
## OCCUPANCY LOADS

Assessor data do not indicate how many people live or work in the assessed buildings. Census data deal with number of residents per housing unit, but no government agency of which we are aware tallies actual workplace occupancy loads. Government agencies such as fire departments do set maximum occupancy figures, but these are typically far in excess of actual, day-to-day occupancy. For workplaces, we therefore fall back on surveys and judgment in ATC-13, fire-protection references, and our own data and judgment, as described below. Table B-1 summarizes our results.

*Table B-1 – Occupant loads by use*

| Party | Building area per occupant (sf) | Time |
|---|---|---|
| Apartment owner | - | - |
| Apartment tenant | 460 | Night |
| Church | 5000 | Day |
| Condo association | - | - |
| Condo occupant | 560 | Night |
| Entertainment | 100 | Night |
| Garage | - | - |
| Hospital | 150 | 24 hours |
| Hotel or motel | 830 | Night |
| Industrial light manufacturing | 590 | Day |
| Mercantile/service landlord | - | - |
| Mercantile/service tenant | 200 | Day |
| Office landlord | - | - |
| Office tenant | 300 | Day |
| School | 710 | Day |

### Apartments and condominiums

Nonresident apartment owners have negligible personal health or life risk in their buildings. Renter and condominium occupancy load can be taken as occupants per household divided by square feet per household. Census data (Mailers Software, 1997) indicate an average of 2.55 persons per household in the 10 San Francisco Bay area counties, weighting county statistics by total square footage. American Housing Survey statistics for apartments in San Francisco (Bureau of the Census, 1995) indicates an average area of 1,118 sf. Average condominium area is greater, at 1,410 sf. Using a 95% apartment occupancy rate, and 100% condo occupancy rate these figures suggests an average area per occupant as follows:

$$C = A / (U * D)$$

where

C = total apartment area per occupant (accounting for vacant apartments)
A = area per apartment
U = occupancy rate, i.e., fraction of all apartments that are occupied
D = occupants per occupied apartment

Noting that units cancel properly,

C = 1118 / ( 0.95* 2.55 ) = 462 sf per apartment occupant
C = 1410 / ( 1.00 * 2.55 ) = 560 sf per condominium occupant

**Churches**

Church occupancy loads have very high variance, being densely loaded for a few daytime hours a week. These hours do not overlap with occupancy times of most other workplaces in highrise buildings, so for consistency we considered only weekday, daytime occupancy. By judgment, we applied an occupancy load of 5000 sf/person.

**Hospital, hotels, manufacturing, and mercantile**

For hospitals, ATC-13 suggests 180 sf per bed. We assumed 70% occupancy plus one staff member per bed, or 1.2 people per 180 sf, or 150 sf per person. For hotels and motels, we assumed 70% occupancy rate, one person per room, and (per ATC-13) 580 sf per room. This equates with one person per 830 sf. For industrial light manufacturing, We used ATC-13's estimate of 590 sf per person. We assumed one person per 200 sf for mercantile and service, based on judgment.

**Offices**

NFPA (1991) Table 7-2E tabulates surveyed occupant load per floor in 10 highrise office buildings. The table presents number of stories, average occupants per floor at time of survey, and maximum occupants according to National Building Code provisions. It does not present floor area. To make use of the NFPA statistics, we applied average floor area from our database (by number of stories) to NFPA's occupant loads (Table B-2). The result varies from 74 to 292 sf per person, with a total of 140 sf per person. NFPA (1991) Table 7-2C quotes NFPA 101, Life Safety Code, saying that business has 100 sf/person "based on actual counts of people in buildings and on reviews of architectural plans." These figures are at odds with ATC-13, which recommends 280 sf per office tenant, and with our own survey of several of our own offices, which produced an estimate of 310 sf per person. An occupant density twice as high as our own does not fit our experience of other offices, either. We have used a figure of 300 sf.

*Table B-2 – Office occupant loads per NFPA*

| Building | Stories | Occupants per floor at time of survey | Maximum occupants per floor by NBC provisions | Estimated floor area (sf) | Estimated area per occupant (sf) |
|---|---|---|---|---|---|
| 1 | 7 | 61 | 600 | 9200 | 150 |
| 2 | 7 | 108 | 480 | 9200 | 85 |
| 3 | 9 | 133 | 480 | 9800 | 74 |
| 4 | 9 | 111 | 300 | 9800 | 88 |
| 5 | 11 | 110 | 240 | 10500 | 95 |
| 6 | 11 | 100 | 240 | 10500 | 105 |
| 7 | 12 | 67 | 240 | 10800 | 161 |
| 8 | 13 | 38 | 360 | 11100 | 292 |
| 9 | 18 | 50 | 240 | 12700 | 254 |
| 10 | 22 | 80 | 180 | 14000 | 175 |
| | | | | **Total** | **140** |

**Schools**

Most of these are institutional buildings in Alameda County such as the University of California at Berkeley. We assume that half are dormitories, with occupancy similar to apartments, the other half, office buildings. The average occupancy load for these two classes is 355 sf per person, but we note that offices and dormitories are occupied at opposite hours, so we used half that density, or 710 sf per person.

# APPENDIX C
# INVENTORY

An inventory of taxable high-rise buildings in spreadsheet format (Excel 97 and Lotus 1-2-3 version 3, leaf "Inventory" or "B", respectively) is located in the Publications section of MCEER's web site (*http://mceer.buffalo.edu/pubs.html*) or on PC-formatted 1.44 MB floppy diskette (available by calling MCEER Publications at 716-645-3391, ext. 4). Field definitions are provided in Table C-1, below, and in a separate leaf "Fields" and "C", respectively, in the Excel and Lotus files.

We emphasize that the inventory is provided for documentation purposes only. It is an estimate based on a reasonable reading of assessor data. Where assessor data were inadequate to our purpose, we made reasonable assumptions, documented here, required to complete the inventory. We consider the result to be adequately accurate for present purposes, but the reader is warned that it may not be appropriate for other uses, and is in no way guaranteed to be definitive or 100% accurate.

*Table C-1 - Field definitions for inventory database*

| Field | Meaning |
|---|---|
| Serial | Unique ID referring to one address, party, and exposure type |
| Number and street | Number and street, without suites, apartments, etc. |
| City | City name |
| County | County name |
| County FIPS | County FIPS code |
| State | State postal abbreviation |
| ZIP Code | 5-digit ZIP Code |
| Census block | SSCCCTTTTTTGBB(B): S = FIPS state; C = county; T = tract; G = block group; B = block |
| Latitude | Site latitude, degrees north |
| Longitude | Site longitude, degrees east |
| Area (sf) | Total building area recorded by tax assessor, square feet |
| Number of stories | Number of stories |
| Party | Party in owning or using the building. |
| Exposure type | Building, contents, time, or lives exposed |
| Exposure quantity | For building or contents, this is dollars replacement cost new. For time, dollars per 12 months loss of use. For lives, this is mean number of occupants during normal use. |

# APPENDIX D
# GLOSSARY

475-year event. An event (here, an earthquake) with 10% probability of exceedance in 50 years.

β: see *reliability index*.

ACI. American Concrete Institute.

AISC. American Institute of Steel Construction.

ALARP. As low as reasonably possible.

ANSI. American National Standards Institute.

AS. Automatic sprinklers, a type of building fire sprinkler system with water-charged, pressurized water pipe in occupied spaces, in which heat on a sprinkler head causes it to open and discharge water.

ASCE. American Society of Civil Engineers.

ATC. Applied Technology Council, Redwood City, California.

BSSC. Building Seismic Safety Council.

CBD. Central business district.

CDI. California Department of Insurance.

Census block. A geographic area defined by the Bureau of the Census, typically one city block in urban areas, or an area bounded by convenient geographic features such as railroad tracks, rivers, etc., elsewhere. It is a subset of the census block group (typically on the order of 10 census blocks), itself a subset of a census tract.

CES. Critical equipment system. An assembly of equipment components that together provide some critical function in the operation of the facility, e.g., backup power production.

*De minimis.* From Latin, *de minimis lex non curat,* the law is not concerned with trivialities. *De minimis* risk is the level of risk below which the law considers trivial.

Design-basis earthquake (DBE). See DLE.

Design-level earthquake (DLE). The earthquake for which a building is designed against collapse with a certain degree of safety.

Dynamic financial analysis (DFA). A financial tool, typically implemented in a computer algorithm, that attempts to identify all sources of income and loss, and to model as a random process the wealth of a company.

EPA. Effective peak acceleration, defined as 0.4 times the 5%-damped spectral acceleration $S_a$ of a design spectrum for the period range of 0.1 to 0.5 sec.

EPRI. Electric Power Research Institute, Palo Alto, California.

EQE. EQE International, Oakland, California.

Essential facility. A facility such as police, fire, hospital, telecommunication, emergency transportation, etc. that performs an emergency-response function.

Exposure. Something of value that may be lost from a defined hazard, e.g., lives, building value, or content value.

Fault. The interface between two tectonic plates, that is, the place in the earth's crust where two plates abut and move, sometimes very suddenly, relative to one another.

Fault-tree analysis (FTA). Analysis of a logical diagram comprised of binary variables (true-or-false; an event occurs or it does not) that are related by the logical functions AND and OR. The purpose of the analysis is typically to find the probability of the top event occurring, in terms of the probabilities of more basic events at the other end of the tree.

FIPS. Here, a numerical code for a place (state, county, etc.) defined by the Federal Information Processing Standard. A county FIPS code is a 5-digit number of the form SSCCC, where SS uniquely defines a state, territory, or other large postal entity, and CCC uniquely identifies a county, parish, or similar geopolitical entity with the state.

Fire following earthquake. Fires caused in any of the normal fashions, but precipitated by earthquake shaking, ground failure, or earthquake damage.

Fragility. The probability of some damage state being exceeded, or more generally the probability of some undesirable condition occurring. Here, fragility often implies probability of an equipment component or system failing to function as intended, the probability expressed as a function of ground-shaking intensity.

g. A measure of acceleration equal to that caused by gravity, 32.2 ft/sec$^2$, or 9.81 m/sec$^2$. Strong earthquake shaking has been known to cause momentary horizontal ground accelerations of 2 g.

Geocode. To determine the geographic coordinates of a place, e.g., in terms of latitude and longitude, usually from some non-metric system of location such as street address or ZIP Code.

gpm. US gallons per minute (liquid flow), approximately equivalent to 3.785 liters per minute.

Hazard. A ongoing condition or process that does not by itself constitute the loss of some human or property value, but which threatens to produce that loss with some uncertain probability. Key hazards discussed here include the potential for earthquake shaking and post-earthquake fire. Distinct from risk in that hazard does not in itself constitute the potential for financial or human loss, although it may bring about that loss.

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

Highrise building. Here, a building of 7 or more above-ground stories.

ICBO. International Conference of Building Officials.

LAN. Local area network.

Limit state. Here, the threshold of an unsatisfactory condition of a building or of an equipment component or system. For example, an important limit state for a building in the DLE is the existence of life-threatening damage to the structure. A limit state in more frequent events may be an unsatisfactory level of serviceability such as loss of electric power.

Load and resistance factor design (LRFD). A design philosophy whereby a structural component is designed so that its nominal strength, reduced by a resistance factor less than 1, exceeds a combination of the applied loads, each load increased by a load factor greater than 1.

Magnitude. A measure of the size of an earthquake. More precisely, a reference to the energy produced by an earthquake, often measured in terms of the maximum ground acceleration observed by a particular type of seismograph at a particular distance from the fault rupture. This is distinct from the intensity of ground shaking due to the earthquake. While an earthquake has a certain fixed theoretical energy release, the shaking intensity felt at a particular site will vary depending on magnitude, distance to the fault, soil type, and other parameters. There are various measures of magnitude, of which the most well known is Richter magnitude. While other measures of magnitude may produce slightly different values (7.0 versus 7.1, or 6.6 versus 6.7 in the cases of 1989 Loma Prieta and 1994 Northridge earthquakes), they all strive for a consistent number for a given earthquake.

Mean. Another word for average or expected value. One of several measures of central value in a probability distribution.

Median. A measure of central value in a probability distribution. Equal to the quantity with 50% probability of being exceeded. Sometimes equal to the mean (or average), sometimes less, sometimes more, depending on the shape of the probability distribution.

MEP. Mechanical, electrical, and plumbing.

Microhazard. A 1-in-a-million probability of death per year from some ongoing process.

Micromort. A 1-in-a-million probability of death from some one-time event.

Microrisk. A 1-in-a-million probability of some certain undesirable thing happening.

Microrisk value. The price at which one would accept a microrisk not yet integrated into one's life, or the price one would be willing to pay to avoid some microrisk already integrated into one's life.

Modified Mercalli Intensity. A 1-to-12 scale measure, usually expressed in Roman numerals, describing the severity of ground shaking at a particular site in a particular earthquake. Significant damage occurs above MMI IV. The highest MMI in the 1994 Northridge earthquake was MMI X. The San Francisco Marina District experienced MMI IX ground shaking in the 1989 Loma Prieta earthquake.

NEHRP. National Earthquake Hazard Reduction Program.

NFPA. National Fire Protection Association.

Ordinary facility. A facility not classified as essential or hazardous. Examples of ordinary buildings include commercial offices, residences, stores, etc.

Peak ground acceleration (pga). The highest instantaneous ground acceleration observed at a given location during the course of an earthquake.

PML. Probable maximum loss. Various definitions; see Section 4.2.

Pure premium. A theoretical constant amount of money an insurer would have to collect from an insured every year to equal the total amount of claim checks over the long term.

RCN. Replacement cost new.

Reliability. The probability of a component or system not reaching a predetermined limit state, e.g., the probability that a battery rack will operate as designed after an earthquake. Reliability is the same as 1 minus fragility.

Reliability index ($\beta$). Considering the difference between capacity (i.e., resistance or strength) and load (i.e., demand or burden), the ratio of the expected value of that difference to its standard deviation.

Risk. Here, an undesirable human or financial loss and its associated probability. Distinct from hazard, in that risk is a loss of primary concern, whereas hazard produces risk but is not in itself a loss. For example, earth shaking is a hazard, while structure damage due to that shaking is a risk.

Risk of ruin. The probability that in the course of business practice, a company's wealth falls below a threshold level of survival.

Ruin barrier. The threshold wealth level below which a company's survival is jeopardized or lost.

Safety index (β). Another name for reliability index.

SEAOC. Structural Engineers Association of California.

Severity. In the context of earthquake damage, this is the amount of damage (casualties, property loss) given that some nonnegligible damage occurs.

sf. Square foot (area), approximately equal to 0.093 $m^2$.

Standard deviation. A measure of the variability of a random number.

Stochastic. Another word for random.

UBC. Uniform Building Code.

Uninterruptible power source (UPS). A system of batteries, switches, inverters, and conduit that provides electricity immediately after an ordinary source of electric power fails, often within a fraction of an AC cycle ($1/60^{th}$ of a second) of electric power failure.

Vulnerability. Damage expressed as a fraction of total replacement cost, often expressed as a random number and a function of seismic shaking intensity. In the case of casualties, it is the fraction of people exposed who are killed or injured. Distinct from fragility, which is a probability of exceeding some defined threshold level of damage.

# APPENDIX E
# SUMMARY OF SEISMIC RELIABILITY ASSESSMENT

The system scores, whose tolerable minima are proposed in the present report, are creating using the system reliability assessment proposed by Johnson et al., 1998. The reliability assessment has four steps: (1) identify critical equipment systems and components; (2) assess the reliability of individual components using score sheets; (3) assess system reliability using a modified fault tree analysis; and if necessary (4) perform risk management to improve system reliability to tolerable levels. This appendix, copied from Johnson et al., chapter 2, summarizes these steps.

**Step 1: System and Component Identification**

| | |
|---|---|
| *What You Will Do:* | *Look at what services your facility needs to provide, which equipment items and support services are really necessary to provide that function, and how the various items are tied together.* |
| *How You Will Do It:* | *Use checklists to help identify critical systems and components. Sketch logic diagrams to illustrate how systems are tied together and where you have backup system and equipment components. [Sample checklists are presented in Table E-1 and Table E-2. A sample logic diagram is presented in Figure E-1]* |
| *What This Does For You:* | *Helps identify possible "weak links" in your system and ultimately helps to make sure fixes are limited to the most important items.* |

A facility may have specific functionality requirements during or following an earthquake, as specified by federal law or federal, state, or local regulators. For example, hospital performance requirements for critical care may be specified in a state-issued license; data processing requirements for banks may be specified in Federal law. In addition, a facility owner may determine that a function is essential if it is deemed financially important for continued operation or business recovery.

A critical system is one that is required to provide either (i) the essential facility function, as defined above, or (ii) life-safety protection as required by other laws or regulations. A component of a critical system could be either a particular equipment item; a portion of a system such as piping, ducting, etc.; or a human action that is required to provide function of the critical system.

The handbook describes how critical systems and critical components can be identified for a facility. A method is provided for systematically reviewing important systems and the impact of their failure on other important systems. A means is provided to incorporate special considerations, such as emergency plans, personnel actions, and known maintenance problems.

**Step 2: Assessment of Individual Components**

| | |
|---|---|
| *What You Will Do:* | *Assign "scores" to individual items indicating reliability to continue functioning after an earthquake. A higher score means more reliability.* |
| *How You Will Do It:* | *Do a mostly visual review of each component. Use data sheets in Handbook Appendix B to calculate scores [A sample data sheet is presented in Figure E-2]. You will review for all items on the data sheets, assigning scores applying rules in the Handbook.* |
| *What This Does For You:* | *Helps identify weaknesses in individual equipment items.* |

The handbook presents a method for rapidly evaluating individual equipment components and incorporating those evaluations into a system evaluation. That method uses assessment techniques based on historical earthquake performance of similar equipment items. Assessments are made of specific items that have been known to be causes of damage in past earthquakes, or known to be seismically vulnerable for other reasons.

Scoresheets are provided for individual components, and a method for assigning scores is presented, based on the design and installation of the component, the location within a building and geographically, and other factors. Higher scores indicate higher seismic reliability.

**Step 3: Assessment of System Reliability**

| | |
|---|---|
| *What You Will Do:* | *Assign "scores" to systems and the entire facility indicating reliability to continue functioning after an earthquake. A higher score means more reliability.* |
| *How You Will Do It:* | *Use the scores from Step 2 with the graphical description of the system from Step 1. A set of simple rules to calculate the score is provided.* |
| *What This Does For You:* | *Provides the information you need to make decisions on what changes will increase reliability.* |

This handbook provides a method for rapidly, but systematically evaluating the reliability of critical systems in an earthquake. A system scoring system is provided to quantify the relative reliability of systems and components. This method can be used by an individual to identify and prioritize vulnerabilities on a system and facility basis.

For each of the major systems identified, a system evaluation should be performed. The methodology described in this handbook makes use of the system and component information developed for each system and the scores for individual components.

**Step 4: Risk Management**

| | |
|---|---|
| *What You Will Do:* | *Make decisions about actual system modifications, more detailed analyses, or other steps to take (e.g. emergency plans) to increase the reliability of your facility operating following an earthquake.* |
| *How You Will Do It:* | *Use the results from Steps 1, 2, and 3. Review how scores may change if certain steps are taken.* |
| *What This Does For You:* | *This is the real reason for doing the entire assessment, to make sure that money spent for risk reduction is being put to its best use. This gives you a basis for deciding on various options, such as structural modifications, system changes, operational or procedural changes, or other reasonable ways of reducing risk.* |

The results of the screening methodology provide a basis for making risk management decisions. The review of critical electrical and mechanical systems and their components provides the information necessary to create a specific plan for improving a facility's post-earthquake functionality.

The component and system evaluations described in this recommended practice are part of a screening assessment. It highlights important system components, their interactions, and their impact on system function. It is not the only indicator of where upgrades or repairs should be made, but it provides a consistent method for identifying obvious vulnerabilities and prioritizing risk management implementation.

Mitigation is not limited to physical repairs to equipment or systems. Mitigation can be achieved through means such as upgrades, analyses and emergency response procedures. All mitigation efforts as defined in this handbook are intended to improve overall system reliability.

*Table E-1 – Extract of Critical Systems Identification Checklist, (Johnson et al., 1998)*

| System / Sub-System | Life Safety [1] | Business Operations [2] | Not Critical [3] | Not Applicable [4] |
|---|---|---|---|---|
| **Fire Response** | | | | |
| Requirements of system: ______ | | | | |
| **Sub-Systems** | | | | |
| Detection and alarm | | | | |
| Suppression | | | | |
| Air duct fire and smoke barriers | | | | |
| Smoke purge | | | | |
| Other: ______ | | | | |
| ______ | | | | |
| ______ | | | | |
| **Gas Shutoff** | | | | |
| Requirements of system: ______ | | | | |
| **Sub-Systems** | | | | |
| Other: ______ | | | | |
| ______ | | | | |
| ______ | | | | |
| **Elevator Safety** | | | | |
| Requirements of system: ______ | | | | |
| **Sub-Systems** | | | | |
| Detection/control | | | | |
| Other: ______ | | | | |
| ______ | | | | |
| ______ | | | | |
| **Building/Evacuation Egress** | | | | |
| Requirements of system: ______ | | | | |
| **Sub-Systems** | | | | |
| Alarm/indication | | | | |
| Available routes | | | | |
| Other: ______ | | | | |
| ______ | | | | |
| ______ | | | | |

*Table E-2 – Extract: Fire-Response CES Component ID Worksheet (Johnson et al., 1998)*

# SYSTEM: FIRE RESPONSE

DEFINITION OF SYSTEM

____________________________________________________

____________________________________________________

## SUB-SYSTEM: Detection And Alarm

| | **Criticality (circle one)** E-essential, R-redundant, N-non-essential | | | **Redundant Component** List redundant item number | **Support System Required** List function (i.e., power, cooling water, etc.) |
|---|---|---|---|---|---|
| **A. Detection** | | | | | |
| A.1 Area/Spot Smoke Detectors | E | R | N | ________ | ________ |
| A.2 Line Smoke Detectors | E | R | N | ________ | ________ |
| A.3 HVAC/Plenum Smoke Detectors | E | R | N | ________ | ________ |
| A.4 Heat Detectors | E | R | N | ________ | ________ |
| A.5 Sprinkler Flow Sensors | E | R | N | ________ | ________ |
| A.6 Pull Stations | E | R | N | ________ | ________ |
| A.7 Other(define) | E | R | N | ________ | ________ |
| ____________ | E | R | N | ________ | ________ |
| **B. Alarms** | | | | | |
| B.1 Bell/Siren Alarms | E | R | N | ________ | ________ |
| B.2 Speakers | E | R | N | ________ | ________ |
| B.3 Strobe Lights | E | R | N | ________ | ________ |
| B.4 Remote Alarm Monitors (specify) | E | R | N | ________ | ________ |
| ____________ | E | R | N | ________ | ________ |
| B.5 Other (define) | E | R | N | ________ | ________ |
| ____________ | E | R | N | ________ | ________ |
| **C. Detection/Alarm Interface** | | | | | |
| C.1 Computer System | E | R | N | ________ | ________ |
| C.2 Fire Communication Center | E | R | N | ________ | ________ |
| C.3 Alarm Panel(s) | E | R | N | ________ | ________ |
| C.4 Cabling/Conduit | E | R | N | ________ | ________ |
| C.5 Other (define) | E | R | N | ________ | ________ |
| ____________ | E | R | N | ________ | ________ |

**D. General Items**

D.1 Is operator intervention required for operation of any of the above equipment? (Y/N) ________
If yes, is the area expected to be accessible?

________________________________________________

(Note: if the area is not accessible, equipment requiring manual operation should not be credited.)

D.2 Based on experience, has any of the identified equipment required an above average amount of maintenance or been inoperable or degraded for a significant amount of time due to failures? ________
If yes, explain:

________________________________________________

(Note: if the equipment is highly unreliable, it should not be credited except as a possible redundancy.)

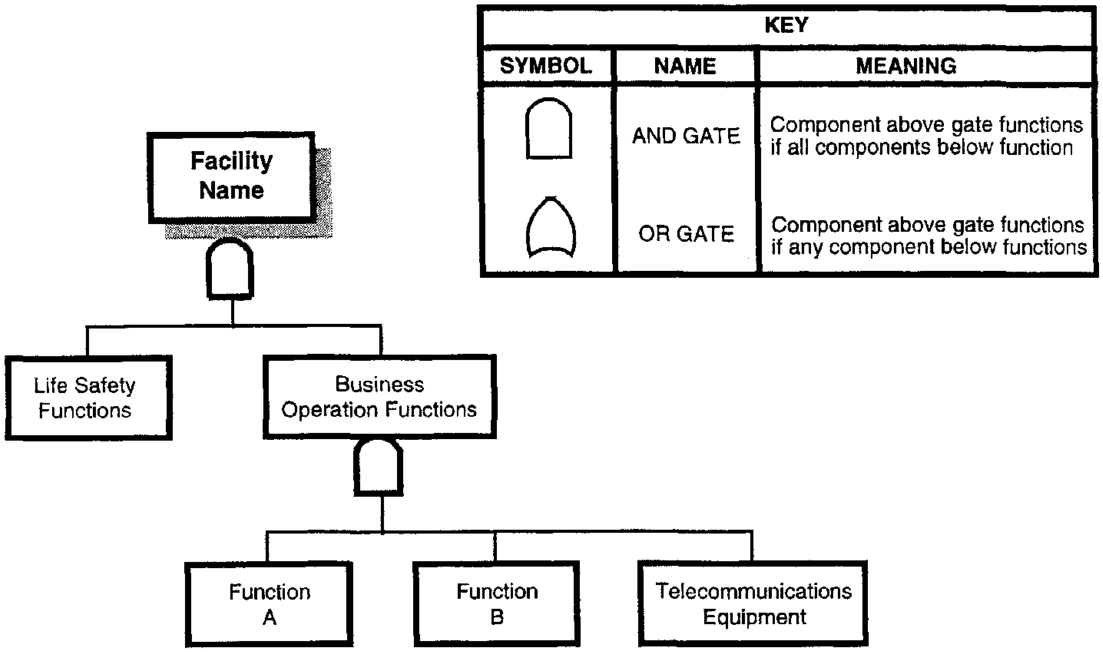



*Figure E-1 – Facility Logic Model*

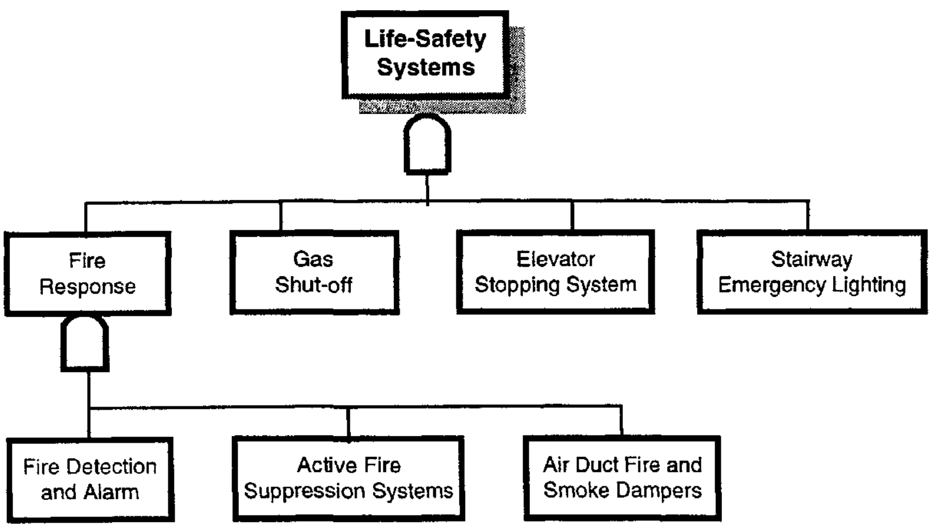



*Figure E-1 (continued) – Life-safety Logic Model*

| KEY | | |
|---|---|---|
| **SYMBOL** | **NAME** | **MEANING** |
| | AND GATE | Component above gate functions if all components below function |
| | OR GATE | Component above gate functions if any component below functions |

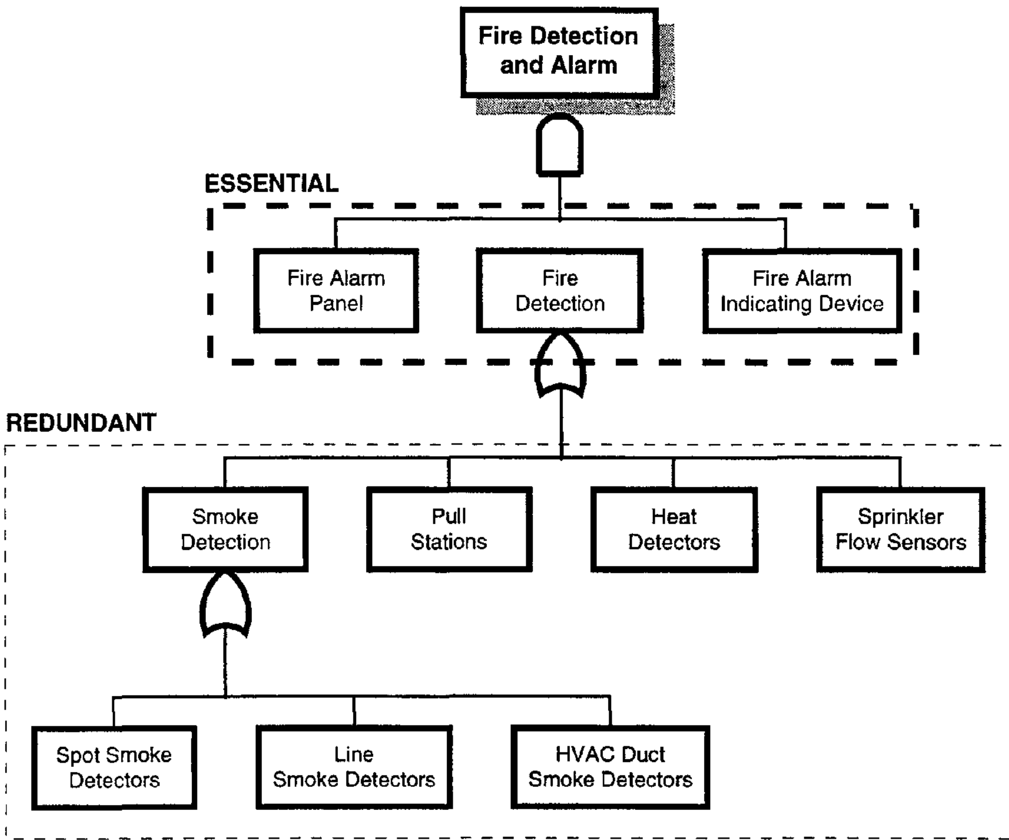
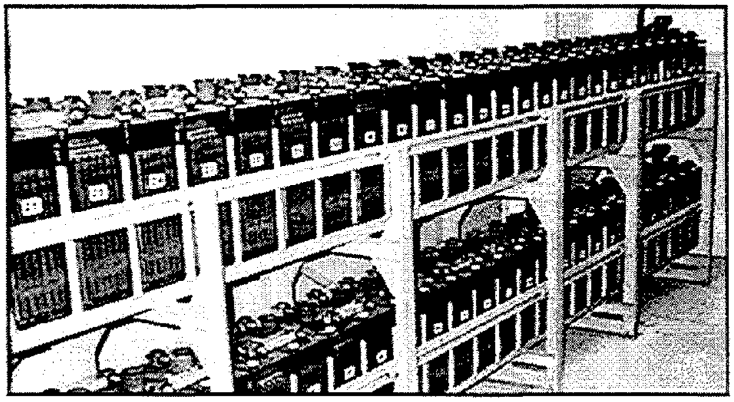



*Figure E-1 (continued) – Fire Detection and Alarm Logic Model*

*Figure E-2 – Sample Component Scoresheet: Batteries and Racks*



ID Number ______________________
Comments ______________________
______________________
______________________
______________________

**Earthquake Load Level** (circle one letter)

| | | | **Location in Building** | | |
|---|---|---|---|---|---|
| | **NEHRP** | **UBC** | **Bottom Third** | **Middle Third** | **Top Third** |
| **Z** | 1-3 | 1 | A | A | A |
| **O** | 4-5 | 2 | A | B | C |
| **N** | 6 | 3 | B | C | D |
| **E** | 7 | 4 | C | D | E |

**Scores and Modifiers - Batteries and Racks**

(circle a Basic Score and <u>all</u> PMFs that apply - use the column indicated by the Earthquake Load Level above)

| **Description** | | **A** | **B** | **C** | **D** | **E** |
|---|---|---|---|---|---|---|
| Basic Score | | 5.3 | 4.4 | 3.9 | 3.5 | 3.2 |
| | 1. No anchorage | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 |
| | 2. "Poor" anchorage | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 |
| P | 3. No battery spacers | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 |
| M | 4. No cross-bracing | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 |
| F | 5. No battery restraints | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 |
| | 6. Interaction concerns | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| | 7. Other:__________ | | | | | |
| Final Score = Basic Score - **highest applicable** PMF | | | | | | |

**Note that this is a screening process and is inherently conservative. If there is any question about an item, note it and select the appropriate PMF. See the following page for PMF guidelines.**

*Figure E-2 (continued) – Sample Component Scoresheet: Batteries and Racks*

**Performance Modification Factors (PMFs)**

1, 2 If there are no anchor bolts at the base of the frame, select PMF 1. If the anchors appear to be undersized, if there are not anchors for every frame of the rack, or if the anchorage appears to be damaged select PMF 2.

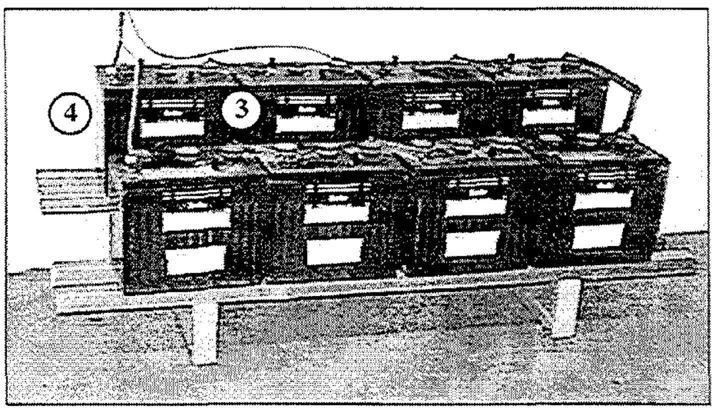
3 Look for stiff spacers, such as Styrofoam, between the batteries that fit snugly to prevent battery pounding. If there are none, select PMF 3.

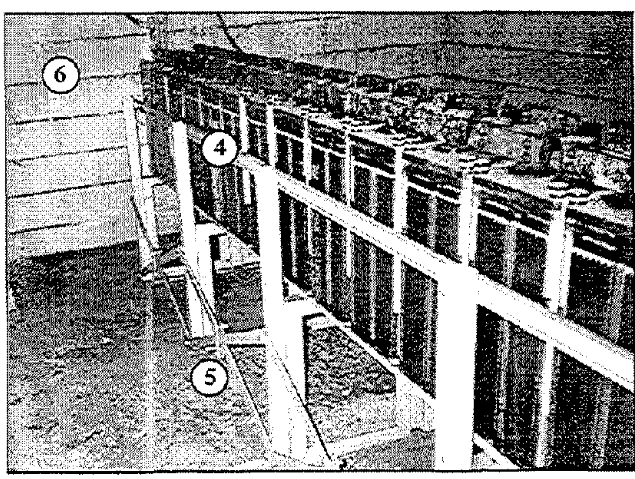
4 The rack should provide restraints to assure that the batteries will not fall off. The photo above shows a rack with no restraints, while the photo to the left shows a rack with restraints. Select PMF 4 if adequate restraint is not provided.

5 Racks with long rows of batteries need to be braced longitudinally as shown in the photo to the left. Select PMF 5 if no cross-bracing is present.

6 If large items such as non-structural walls could fall and impact the battery racks, select PMF 6.

7 For other conditions that the reviewer believes could inhibit battery function following an earthquake (e.g., a history of problems with this piece of equipment), assign a PMF value relative to the existing PMFs in the table. Add a descriptive statement for the concern.



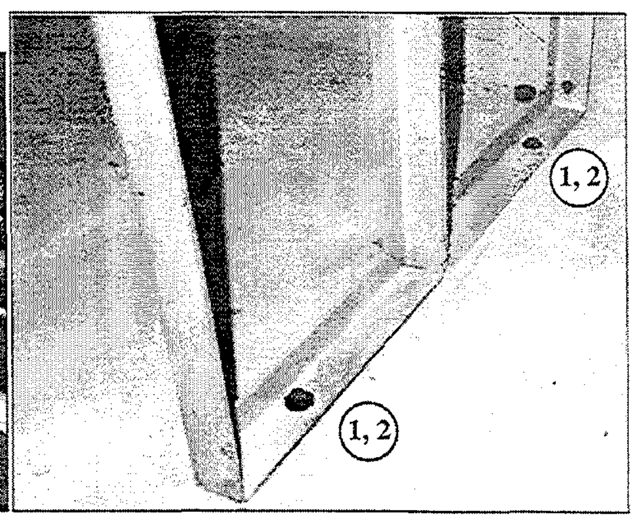
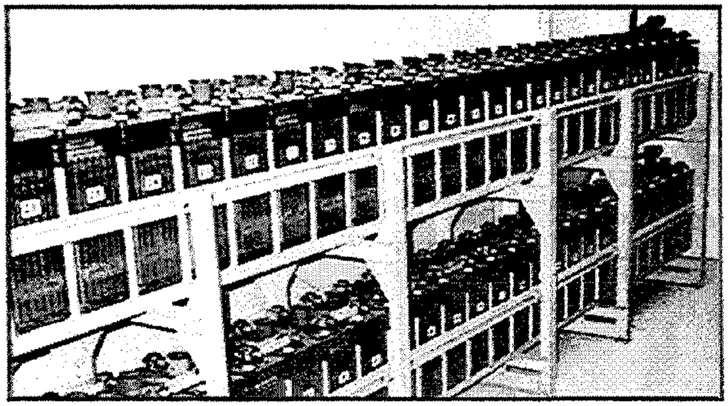



*Figure E-2 – Sample Component Scoresheet: Batteries and Racks*



ID Number ______________________________
Comments ______________________________
______________________________
______________________________
______________________________

**Earthquake Load Level** (circle one letter)

| | | | Location in Building | | |
|---|---|---|---|---|---|
| | **NEHRP** | **UBC** | **Bottom Third** | **Middle Third** | **Top Third** |
| **Z** | 1-3 | 1 | A | A | A |
| **O** | 4-5 | 2 | A | B | C |
| **N** | 6 | 3 | B | C | D |
| **E** | 7 | 4 | C | D | E |

**Scores and Modifiers - Batteries and Racks**
(circle a Basic Score and all PMFs that apply - use the column indicated by the Earthquake Load Level above)

| | **Description** | **A** | **B** | **C** | **D** | **E** |
|---|---|---|---|---|---|---|
| Basic Score | | 5.3 | 4.4 | 3.9 | 3.5 | 3.2 |
| | 1. No anchorage | 1.5 | 1.5 | 1.5 | 1.5 | 1.5 |
| | 2. "Poor" anchorage | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 |
| P | 3. No battery spacers | 0.7 | 0.7 | 0.7 | 0.7 | 0.7 |
| M | 4. No cross-bracing | 0.9 | 0.9 | 0.9 | 0.9 | 0.9 |
| F | 5. No battery restraints | 2.0 | 2.0 | 2.0 | 2.0 | 2.0 |
| | 6. Interaction concerns | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 |
| | 7. Other:________________ | | | | | |
| Final Score = Basic Score - **highest applicable** PMF | | | | | | |

**Note that this is a screening process and is inherently conservative. If there is any question about an item, note it and select the appropriate PMF. See the following page for PMF guidelines.**

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