Earthquake Aftershocks—Entering Damaged Buildings

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Funded by the U.S. Geological Survey as part of the ATC-35 Research Utilization Project

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ATC TechBrief

Summary

Earthquake aftershocks can cause significant damage to buildings. Occasionally, they can result in building collapse. This risk is highest for previously damaged buildings (Figure 1).

Entry into damaged buildings as soon as possible is often necessary for a variety of emergency reasons, including search and rescue, building stabilization and repair, and salvage and retrieval of possessions. Because people entering damaged buildings are at risk should an aftershock occur, the decision to permit entry must consider both the level of initial damage and the probability of aftershocks.

This TechBrief offers guidelines for entering damaged buildings under emergency conditions as a function of time after the initial damaging event. These guidelines are based on aftershock research carried out by the U.S. Geological Survey and the postearthquake building safety evaluation procedures of ATC-20 (ATC, 1989, 1995).

After a damaging earthquake, local building departments inspect and post buildings as INSPECTED, RESTRICTED USE, or UNSAFE using the ATC-20 procedures. Table 1 summarizes these postings and provides recommended guide-

Figure 1: Buildings such as this office building in Kobe, Japan, are generally unstable and may collapse in an aftershock.

lines for emergency entry of damaged buildings. For buildings posted UNSAFE (red placard), entry depends on whether the building is considered *stable* or *unstable*. (Guidelines for classifying a building as *unstable* are provided in Table 2.)

For buildings considered stable, wait times depend on the main shock magnitude and the duration of occupancy, as both of these factors affect the probability of a large aftershock occurring during the period of occupancy. Table 3 provides recommended days to wait before entering buildings posted UNSAFE, but stable.

Table 1: Guidelines for Emergency Entry of Damaged Buildings

Posting	*Placard Color*	*Condition*	*Entry Allowed* [a]
None (not yet inspected)	—	Serious structural damage	Only for search and rescue, and at own risk.
INSPECTED	Green	Minor structural damage	Yes.
RESTRICTED USE	Yellow	Some structural damage, generally of limited severity	Yes, but according to restrictions. Entry into the restricted area only with permission of the local building department.
UNSAFE	Red	Structure has serious structural damage, but is *stable*	Yes, according to Table 3 guidelines.
UNSAFE	Red	Structure has serious structural damage and is *unstable*	No. Table 3 does not apply. Entry only with written permission of the local building department.
UNSAFE	Red	Posting due to *other* than structural damage	No. Table 3 does not apply. Entry only with written permission of the local building department.

a. During the first 24 hours, entry into seriously damaged buildings should be avoided in case the damaging shock is a foreshock and a subsequent event is the main shock.

Table 2: Guidelines for Classifying Damaged Buildings as Unstable

UNSAFE Buildings that Have at Least One of the Following Characteristics Should be Classified as Unstable

1. May collapse or partially collapse under its own weight.
2. Likely to collapse in a strong aftershock, from additional damage.
3. Ongoing (progressive) lean.
4. Ongoing creep or structural deterioration.
5. So heavily damaged that its stability cannot readily be determined.

Table 3: Recommended Days to Wait Before Emergency Entry of Buildings Posted UNSAFE, but Stable[a, b]

Mainshock Magnitude (M)	*Enter for 2 hours*	*Enter for 8 hours*	*Enter for 24 hours*[c]
M equal to 6.5 or greater	1 day	3 days	8 days
M equal to 6.0 or greater, but less than 6.5	1 day	2 days	4 days
M less than 6.0	1 day	1 day	2 days

a. Refer to Table 1 for other posting conditions.

b. Recommended days to wait refers to the date of the mainshock, not the date of posting.

c. For continuous emergency access only. Full-time occupancy is permitted only when approved by the local building department.

Safety Evaluation of Earthquake-Damaged Buildings

After a large earthquake, a state of suspended animation often exists. If the mainshock has caused widespread damage, some buildings may have collapsed and others may be poised to collapse. Many buildings may be damaged and some may have falling hazards (that is, a hazardous situation exists from an item poised to fall) caused by broken chimneys or damage to other nonstructural components. Seriously damaged buildings, such as the one shown in Figure 1, are posted UNSAFE, and entry is prohibited.

Rescue workers, residents, and business personnel often have legitimate—sometimes urgent—needs to enter damaged buildings to find and rescue trapped occupants, to perform essential functions, or to retrieve personal property. These factors, when placed in the context of chaos and poor communication, create a potentially hazardous environment within an aftershock zone.

A major question becomes: How soon should a damaged building be entered? The answer is different for each damaged site. It depends on, among other things, the degree of damage, the probability of damaging aftershocks, and the urgency of the need to enter.

Building officials are responsible for determining when damaged buildings are unsafe to enter. Most jurisdictions in California follow ATC-20 procedures (ATC, 1989, 1995). Using the ATC-20 procedures, inspectors can identify when the damage is apparently not significant, when a building's use should be restricted, or when the building is unsafe to enter and to post the building accordingly. Such postings are initially based on a rapid survey and may be changed after a more detailed inspection.

The ATC-20 posting system was developed to inform owners, occupants, and the public about the condition of a damaged building in terms of its suitability for occupancy and general use following an earthquake. The posting criteria take into account the possibility that aftershocks will aggravate the existing damage. The three posting classifications are defined in the paragraphs below.

INSPECTED (Green Placard): The building has been inspected by the local jurisdiction. It may or may not have been damaged. If damaged, the observed damage does not pose a significant safety hazard. There is no limit on the use or occupancy of the building.

RESTRICTED USE (Yellow Placard): The building has been inspected and found to have damage or some other condition (e.g., falling hazard) that precludes unrestricted occupancy. The

Figure 2: A house with a broken chimney, while posted yellow, RESTRICTED USE, may be entered except for the restricted area.

building can be entered and used, but some restrictions have been placed on its use. The house in Figure 2 has received a RESTRICED USE posting because of the leaning chimney. The house can be occupied, but the fireplace may not be used, the room with the broken chimney may not be entered, and an area outside the house and under the chimney is restricted.

UNSAFE (Red Placard): The building has been inspected and found to be seriously damaged or have a serious hazard (e.g., toxic spill). Generally, buildings posted UNSAFE have serious structural damage. Many, but not all, are at risk of partial or complete collapse. Some UNSAFE postings are made when normal occupancy is inadvisable, such as when an old house has fallen off its foundation. Generally, entry into a building posted UNSAFE is not permitted without the approval of the local jurisdiction.

The ATC-20 posting procedures provide a valuable tool for building officials to communicate safety information immediately to the public. In the days that follow a damaging mainshock, there is an additional need, though, to determine when the chance of aftershocks has diminished to the point that restrictions on entry and occupancy can be relaxed.

About Aftershocks

Foreshock, Mainshock, and Aftershock

Earthquakes typically occur in clusters. Seismologists have coined three terms to distinguish the events in a cluster: foreshock, mainshock, and aftershock. In any cluster of earthquakes, the one with the largest magnitude is called the mainshock. Earthquakes that occur before the mainshock are called foreshocks, while those that occur after are called aftershocks. In this discussion, it is assumed that the foreshocks have been inconsequential, the damage has occurred in the mainshock, and the safety concerns center on the aftershocks that are to come.

Aftershock Sequences

Generally speaking, the stress on the earthquake fault drops drastically during the mainshock and the small redistributions of stress and frictional strength cause that fault to produce most of the aftershocks. The patterns that aftershock sequences follow can be described and used to estimate the probability of significant aftershocks occurring. The specific location, time, and size of individual aftershocks, however, cannot be predicted.

The sequence of aftershocks that occurred after the 1994 Northridge, California, earthquake followed a typical pattern. All significant aftershocks occurred

Figure 3: The *M* 6.2 aftershock of the *M* 7.5 1992 Landers, California, earthquake caused this gable end wall to collapse.

within a 35-km-diameter area surrounding the fault segment that ruptured during the mainshock.

The drop in stress on the mainshock fault causes a redistribution of stresses in all nearby faults. Sometimes, an increased stress is great enough to trigger aftershocks on these nearby faults. For example, three hours after the magnitude 7.5 1992 Landers, California, earthquake, a magnitude 6.2 aftershock occurred in the vicinity of Big Bear Lake on another fault system approximately perpendicular to the Landers fault system. The aftershock epicenter was 35 km from the mainshock epicenter. The aftershock caused significant damage, including partial collapse of a building, as shown in Figure 3.

Aftershock Hazard Area

As a general rule, earthquakes are considered to be aftershocks if they are located within a characteristic distance from the mainshock and occur more often than the background level of seismicity. The characteristic distance is usually taken to be one or two times the length of the rupture associated with the mainshock. For example, if the mainshock ruptured a 100-km length of a fault, aftershocks are expected to occur within a 200-km-long elongated area surrounding the fault that ruptured during the mainshock. The fault rupture length was approximately 15 km in the 1994 Northridge earthquake, and 430 km in the great 1906 San Francisco earthquake. While there is not a hard "cutoff" distance beyond which triggered aftershocks cannot occur, the vast majority of aftershocks are located relatively close to the mainshock fault rupture.

Additionally, the local geological setting of the site can affect the degree of ground shaking when aftershocks occur. Buildings on some landfill and water-saturated or unconsolidated soils face higher hazard from aftershock shaking than those on hard rock sites, all other things being equal. A general rule for rapid field assessment of the geological factor at a particular site is to assess visually the average damage in other buildings induced by the mainshock in the

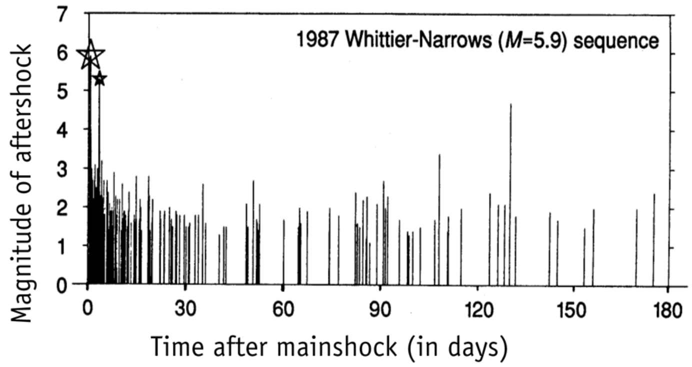

Figure 4: The aftershock sequence after the *M* 5.9 1987 Whittier Narrows, California, earthquake. Each line represents an aftershock.

vicinity of the site and compare this damage with other damaged areas of similar distance from the mainshock fault rupture. If damage was heavy in the mainshock, the site is more likely to experience additional damage in an aftershock. Such was the case in the Marina district of San Francisco after the 1989 Loma Prieta, California, earthquake. Conversely, in areas that sustained little or no damage in the mainshock, the aftershock ground shaking hazard can be expected to be lower. In general, it is reasonable to assume that if a building has been inspected and posted RESTRICTED USE or UNSAFE, it may experience significant additional damage if a large aftershock occurs nearby.

A mainshock large enough to cause damage will probably be followed by several felt aftershocks within the first hour. The rate of aftershocks dies off quickly with time, as is illustrated visually in Figure 4, and the rate is inversely proportional to the time since the mainshock. Aftershocks at each magnitude level decrease with time at the same rate. *On average*, the second day will have approximately 1/2 the number of aftershocks of the first day, and the tenth day will have approximately 1/10 the number of the first day. These patterns describe only the average behavior of aftershocks; the actual times, numbers, and locations of the aftershocks are random. One large aftershock sometimes occurs as much as six months after the main event. For example, a magnitude 5.4 aftershock occurred six months after the magnitude 7.1 Loma Prieta mainshock.

Larger earthquakes have more and larger aftershocks than smaller earthquakes. Smaller aftershocks are more numerous than large ones. The difference in magnitude between the mainshock and largest aftershock can be 3 or more, but averages 1.2. In the 1987 Whittier Narrows earthquake sequence illustrated in Figure 4, the largest aftershock (*M* 5.3) was only 0.6 smaller than the mainshock.

What Magnitude Aftershock Causes More Damage?

The answer depends, among other things, on the site conditions, building type, and distance from the aftershock. While any felt aftershock may cause additional damage or create new falling hazards, those of magnitude 5 and larger are generally considered likely to cause some significant new damage or to worsen existing damage. Seriously damaged buildings are, of course, particularly vulnerable.

While the mainshock may have produced widespread damage, the effects of an aftershock will usually be confined to a smaller area. Within that area, though, the effects can occasionally be severe. Other damaged areas more distant from a specific aftershock or with better soil conditions will be less affected by it. The location of the aftershocks, however, is not predictable.

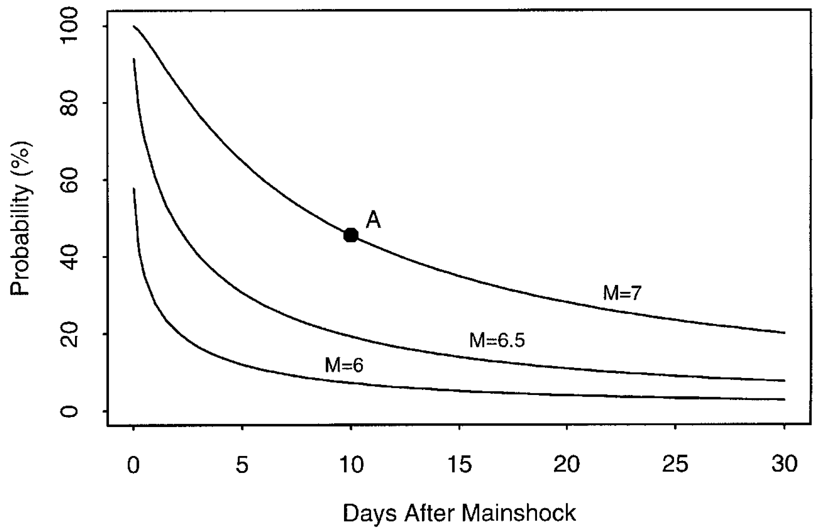

Figure 5: Probability of an aftershock with a magnitude 5.0 or larger occurring somewhere in the aftershock zone during a 7-day period starting at a specified time after a mainshock. Curves shown are for mainshocks of magnitude 6, 6.5, and 7. For example (point A), the probability is 46% during the 7-day period beginning 10 days after an *M* 7 mainshock. Curves are based on general trends from past earthquakes.

Probability of Aftershocks

Figure 5 displays the probability of aftershocks of magnitude 5 or larger occurring in a 7-day period, as a function of the magnitude and time since the mainshock. While these curves were developed for California earthquakes, they can be useful elsewhere, in the absence of more specific information. Point A in Figure 5 indicates that 10 days after a magnitude 7 earthquake, the probability of an aftershock with a magnitude of 5.0 or greater in the next seven days, somewhere in the aftershock zone, is slightly less than 50%. Smaller magnitude aftershocks are more likely, and larger magnitude aftershocks less likely.

Guidelines for Entering Damaged Buildings

One of the most difficult problems facing building officials and structural engineers is when to permit entry into damaged buildings, particularly those posted UNSAFE. Entry into an undamaged building merely requires a determination that it has not been seriously damaged and has been posted INSPECTED. However, entry into a seriously damaged building (i.e., one posted UNSAFE) carries a high risk, particularly during the period of frequent aftershocks. There is a possibility that an aftershock will cause additional damage, life-threatening injuries, and even death. The more time spent inside the building, the greater the risk.

Limiting Entry Risk

Because the aftershock hazard diminishes with time, it is possible to determine in general when the risk of entering an UNSAFE building, for a given period of time, reaches an acceptable level. First, however, a level of acceptable risk must be established that considers the urgency of the need to enter. In this analysis, the choice of risk level was guided by the risk to which a firefighter is exposed in fighting a structural fire, since both situations involve the risk of injury consciously accepted by knowledgeable individuals with a specific purpose. The mean rate of injuries sustained by firefighters engaged in battling structural fires in the United States is approximately 40 injuries per 1,000 fires (U.S. Fire Administration, 1997). Assuming an average fire-fighting crew size of 10, this translates to a probability of injury of 0.4% per firefighter per event.

To estimate the risk involved in entering a damaged building, several factors were considered, including the probability of a strong aftershock, the length of time to be spent in the building, and the condition of the building. To account for the wide variations expected in these factors, some simplifying, worst-case approximations were included in this analysis. It was assumed that an UNSAFE building to which this methodology is applied could sustain injury-causing additional damage if it experiences ground shaking at the Modified Mercalli Intensity (MMI) VII level or stronger.

Consistent with the firefighter risk, the calculated waiting times are based on a 0.4% chance of having a $M \geq 5.0$ aftershock located sufficiently close to the building site that it may cause shaking with MMI VII intensity. It is recognized that the comparison between trained, equipped firefighters and ordinary citizens is, at best, an informal one. While it is not possible to conclude that the individuals in these rather different situations will experience equal risk, the firefighter analogy provides a rough guideline for the development of reasonable waiting times.

Guidelines for Permitting Entry

Table 1, shown on page 2, provides guidelines for entering damaged buildings immediately after posting. It is organized according to the ATC-20 (ATC, 1989, 1995) posting categories and is consistent with the ATC-20 methodology. There is no limit on how long buildings can be entered when posted INSPECTED or RESTRICTED USE (except for the restricted area).

During the first 24 hours after any damaging mainshock, entry into most

Figure 6: This two-story hillside home slid off its foundation in the 1992 Landers, California, earthquake. It was posted UNSAFE and after close inspection was judged to be stable.

seriously damaged buildings should be avoided in case the aftershock sequence turns out to be particularly vigorous, or in case the mainshock turns out to be a foreshock of a larger event. Exceptions may be made for buildings such as pre-World War II houses that have been shaken off their foundations but that pose no further life-safety threat.

After 24 hours, the recommendation on entering a building posted UNSAFE depends on whether the building is stable or unstable. A *stable* structure is not expected to collapse or partially collapse under its own weight. In general, stable structures may sustain potential injury-causing additional damage but they are considered unlikely to collapse in an aftershock. The buildings in Figures 6 and 7 are both considered stable. Particular care must be taken when inspecting buildings that are leaning to ensure they are not in a state of progressive collapse (e.g., ongoing lean).

An *unstable* structure is one that may collapse or partially collapse at any time, particularly in an aftershock. Character-

Figure 7: This reinforced concrete building was determined to be stable even though leaning slightly, because of the presence of substantial concrete shear walls on all sides.

istics that warrant a structure to be classified as *unstable* include: an ongoing (progressive) lean; ongoing creep or structural deterioration; or damage so severe that the structure's stability cannot readily be determined. Evaluation of the stability of a damaged building may be a difficult task and is best judged by a structural engineer. Guidelines for classifying a building as *unstable* are provided in Table 2 on page 2.

The importance of assessing the stability of a structure is demonstrated in the following example. In the 1989 Loma Prieta, California, earthquake, one seriously damaged residential building developed a lean at the first level. The building was posted UNSAFE and was judged to be unstable when the local building department monitored the lean and determined that it was increasing due to the weight of the building. Collapse occurred within 48 hours. Figure 8 shows a collapsed building that had been standing after the Kobe, Japan, earthquake, but was unstable.

Estimate for Re-entry

Table 3, shown on page 3, provides guidelines for when to allow limited emergency reentry into damaged buildings posted UNSAFE and considered stable. Table 3 gives the waiting period (in days after the mainshock) that must pass before the estimated risk to an individual entering the building for a given length of time will drop to the acceptable level.

For example, following an earthquake with a magnitude of 6.5 or greater, three days must elapse before the risk is acceptable for an eight-hour entry period. The table recommends that an additional five days elapse before allowing occupancy for a full 24 hours. Table 3 may be used immediately after the mainshock to estimate waiting times before entry can be permitted.

Since the risk of injury or death depends on the length of exposure time, three durations of occupancy are shown in Table 3. The two-hour period of entry is intended to permit emergency shoring activities, rapid retrieval of small personal items, or maintenance of critical equipment. The eight-hour duration is intended to permit the systematic relocation of all building contents, to permit the day-long emergency operation of a critical facility, or to allow short-term emergency or construction activities. The 24-hour period is intended to cover the need for around-the-clock repairs. It is not an indication to return to normal use or occupancy. This normal use requires approval of the local building department. Interpolation may be used for other durations of occupancy greater than two hours.

Several approximations and "worst case" assumptions were used to derive the waiting times in Table 3. For most purposes, it is generally advisable not to permit any access into UNSAFE buildings for at least one day, regardless of the mainshock's magnitude. However, in some situations, this restriction may not be appropriate. For example, emergency shoring of a building with severe wall

Figure 8: This Kobe office building was unstable after the mainshock and collapsed under its own weight in less than 24 hours.

damage, or shoring the walls and roof of a tilt-up building with separations between the walls and roof may need to be done immediately to prevent further, more consequential, damage. The risk must be weighed against benefits, and a higher risk than that assumed in this TechBrief may be appropriate. Table 3 is intended to provide general guidance—it should not be used as a rigid rule.

It may appear to some engineers that the wait times for large magnitude earthquakes are long, especially if the aftershocks are less in number and magnitude than average. This may be due to the broad use of UNSAFE postings in past earthquakes and the lack of information related to aftershocks from these events. Many buildings that receive UNSAFE postings may only need re-inspection by a structural engineer to receive a less restrictive posting. Also, the addition of temporary shoring may permit a less restrictive posting.

Search and Rescue Considerations

Search for the injured and rescue of those trapped are among the most important and urgent postearthquake activities.

Those conducting these activities can themselves become victims. Search and rescue personnel, by nature, take higher risks. Those risks can be lessened if time spent in dangerous situations is kept to a minimum and if those involved take precautions. These include awareness of falling hazards and, in protracted rescue situations, use of temporary shoring. Table 3 does not apply to search and rescue situations.

Future Research

The entry guidelines given are based on reasonably conservative assumptions and professional judgment. Future developments are expected to incorporate ongoing research in probabilistic risk management. Additional information such as the number of people allowed to enter at one time, more detailed aftershock sequence characteristics, the seismic performance of damaged structures, other possible posting levels, and the probability of significant ground motion at a specific site will be considered.

A Word of Caution

Use of judgment is essential in postearthquake building safety evaluation. The guidelines given above are for typical situations. There may be situations when this guidance is not appropriate or must be modified. An aftershock can occur at any time, and can lead to injuries to persons in the building.

Entry into an apparently stable building should not be made until the interior of the building has been inspected by a small team of structural engineers.

It is strongly recommended that persons entering severely damaged buildings do so only for emergency reasons and take safety precautions, including wearing a hard hat and strong shoes, carrying a flashlight, and exercising extreme care.

Entry into seriously damaged buildings is never risk-free.

How to Get Aftershock Forecasts On the Web

The U.S. Geological Survey began forecasting aftershocks after the 1989 Loma Prieta earthquake. After an earthquake in California of magnitude 5 or larger, the USGS posts the probability of strong aftershocks at its web site:

- http://quake.wr.usgs.gov/

Sources of Additional Information

ATC has developed a series of documents dealing with the postearthquake safety evaluation of buildings. These are listed below.

ATC, 1989, *Procedures and Postearthquake Safety Evaluation of Buildings*, ATC-20 Report, Applied Technology Council, Redwood City, California. (This document presents the original, complete ATC-20 methodology.)

ATC, 1989, Field Manual: *Postearthquake Safety Evaluation of Buildings*, ATC-20-1 Report, Applied Technology Council, Redwood City, California.

ATC, 1995, *Addendum to the ATC-20 Postearthqake Building Safety Evaluation Procedures,* ATC-20-2 Report, Applied Technology Council, Redwood City, California.

ATC, 1996, *Case Studies in Rapid Postearthquake Safety Evaluation of Buildings*, ATC-20-3 Report, Applied Technology Council, Redwood City, California.

ATC, 1993, *Postearthquake Safety Evaluation of Buildings, Training Manual,* ATC-20-T Report and slides, Applied Technology Council, Redwood City, California.

Additional information is available at the ATC website:

- http://www.atcouncil.org

USGS researchers have written a number of papers and articles on aftershocks and aftershock hazards. Some of these are listed below.

Jones, Lucile M. and Paul A. Reasenberg, 1996, *Some Facts About Aftershocks in Large Earthquakes in California*, USGS Open File Report 96-266.

Reasenberg, Paul A. and Lucile M. Jones, 1989, "Earthquake Hazard After a Mainshock in California," *Science*, Volume 243, pp. 1173-1176.

Reasenberg, Paul A. and Lucile M. Jones, 1994, "Earthquake Aftershocks: Update," *Science*, Volume 265, pp. 1251-1252.

For additional information, see the websites:

- http://quake.wr.usgs.gov/
- http://www-socal.wr.usgs.gov/
- http://quake.wr.usgs.gov/QUAKES/FactSheets/QuakeForecasts
- http://www.scecdc.scec.org/lifewafter.html

Further References:

U.S. Fire Administration, 1997, *Fire in the United States 1985-1994,* Ninth Edition, Federal Emergency Management Agency, Washington, D.C.

Acknowledgements

The Applied Technology Council and the authors appreciate the reviews by Allin Cornell, Stanford University; Richard Holguin, City of Los Angeles; Laurence Kornfield, City of San Francisco; Richard Ranous, EQE International; and Eugene Zeller, City of Long Beach. The photo credit for Figure 8 is unknown, but the photo is greatly appreciated.

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