Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Analysis of post-earthquake fire hazard

J. Mohammadi & S. Alyasin
Illinois Institute of Technology, Chicago, Ill., USA
D. N. Bak
Forensic Fire Technologies, Chicago, Ill., USA

ABSTRACT: This paper presents an overview of the risk associated with fires following a probable earthquake. The paper contains two parts. The first part describes the development of a probabilistic model capable of correlating the risk of fires to the occurrences of earthquakes of specific intensities. An event tree analysis is used to simulate the sequence of events, following the occurrence of an earthquake, that may lead to a fire. For this purpose, the chain of events that lead to a fire following an earthquake is identified and the associated probability of fire occurrence is estimated. The second part of the paper discusses an analysis of fires following the October 17, 1989 Loma Prieta, California earthquake. The fire statistics obtained following this earthquake were used for both a causal and correlation analysis linking fire occurrence and ground motion intensity.

1 INTRODUCTION AND BACKGROUND

Post-earthquake fires are major problems in affected areas and sometimes grow to such proportions that cause great damages in terms of loss of properties and casualties. Nearly all major California earthquakes of modern times have caused fires in both residential and commercial facilities. The fires after the 1906 San Francisco, California earthquake caused damage to a major portion of the city and lasted for three days (Scawthorn 1987). Fires were also reported following several other California earthquakes such as in 1933 in Long Beach, 1971 San Fernando (Mohammadi 1990) and 1987 Whittier-Narrows (Schiff 1988) earthquakes. The fire caused by the October 17, 1989 Loma Prieta earthquake in San Francisco's Marina district is the most recent example of the damage potentials of a post-earthquake fire to a heavy populated area. Post-earthquake fires have also been reported in many Japanese earthquakes. As reported by Mohammadi (1990), the 1923 earthquake in Tokyo resulted in destructive fires over 40 percent of the city. Fires initiated after these and other earthquakes indicate the importance of post-earthquake fires in terms of their potential to cause structural damage. They also demonstrate the need for a more rigorous design requirement for post-earthquake fire hazard mitigation.

Earthquake engineering research, however, has been mainly focused on the area of earthquake-resistant design and evaluation of earthquake hazards in terms of building collapse, lifelines, bridge and dam failures, landslides and liquefaction of soil. While structural safety plays an important role in seismic hazard mitigation, certain other earthquake related issues such as post-earthquake fires are equally as important. In fact advances in structural dynamics, soil-structure interaction and earthquake-resistant design have lead to techniques that can effectively be implemented in design to substantially reduce the risk of structural collapse in the event of an earthquake and thus to minimize casualty and property loss. Hence, the risk of fire may become a greater threat to the well being of the occupants during an earthquake than the risk associated with the building collapse. A method that can effectively be used to determine the risk associated with fires following a probable earthquake will be helpful in the evaluation of safety of building facilities both at the design stage and after occupancy.

Post-earthquake fire issues include identification of the risk associated with an earthquake-related fire in, for example, a typical residential dwelling, an investigation of potential causes and effect of such fire, fire spread and development of design guidelines to mitigate the risk.

Mohammadi, Bak and Alyasin (1991) report a variety of reasons that may cause post-earthquake fires. These are:

1. Gas leaks due to failure of pipes or gas appliances.
2. Electrical distribution system problems.
3. Flammable materials spills.
4. Overturning of burning candles, table lamps, gas grills etc.

Due to the nature and frequency of their use, gas and electrical distribution systems and appliances (i.e. water heater) are more exposed to the risk than elements such as burning candles and lamps. A systematic formulation of the risk for all types of fire (in terms these causes) is not easily possible. Analytical models have been used with some success to estimate the risk of appliance failure, i.e. sliding or overturning, (URS Corporation 1988) and interior gas piping system failure (Longinow et al 1990) during an earthquake. Such models can be extended further for the purpose of estimating the risk of fire that may occur due to the appliance failure. When analytical modeling cannot easily be used, techniques based on the expert opinion data (Mohammadi, Longinow and Williams 1991) and the extrapolation of fire statistics for non-earthquake conditions can be utilized. The latter case is especially applicable when the system involved (gas pipes, appliances, electrical distribution systems) are continuously exposed to the risk.

In regard to fire spread in Urban areas, Scawthorn (1988) introduces a method for computer simulation of fire outbreaks following earthquake. Relations for fire growth in urban areas considering wind speed and direction as well as building density, materials, and time of occurrence have been taken into consideration. Itoigawa and Tsukagoshi (1988) present a stochastic analytical model for fire spread in urban areas based on "fire brand" effects. Mizuno (1987) discusses a method which is based on correlating the building collapse and ignition. These models, however, do not consider the risk of fire following an earthquake for a residential unit due to factors that are specific to interior utility systems and appliances.

The following section presents a description of models that can be used to estimate the risk of fire for a single residential dwelling and discusses techniques that may be used to incorporate factors that contribute to the risk into such models.

2 RISK MODELS

A somewhat generic approach in modeling the sequence of events in a post earthquake fire can only be achieved with certain limitations and approximations. Even with limitations, the modeling cannot be accurately performed for such casual causes as, for example, flammable materials spills, overturning of burning candles, and burning cigarettes discarded by people in the state of panic. For more systematic causes, such as gas leaks and electrical problems in distribution systems, the modeling is more straightforward. In following sections, the sequence of events in the case of gas- and electric-related fires is explained. Event tree models are presented and the likelihood of occurrence of each event in the tree is described and quantified.

2.1 Sequence of events in gas fires

The chain of events that may lead to a gas-related fire is summarized below:

1. Following an earthquake, overstress in the piping system components or overturning or sliding of an appliance (water heater) occurs.
2. Gas leak develops.
3. Leak is undetected; and gas is accumulated in an enclosed area.
4. Gas intensity in the air reaches a ignitible level.
5. An ignition sources is activated.

This chain of events often stops at the fourth or fifth level. In a dwelling equipped with an automatic seismic shut-off valve, the above chain of events can practically stop at the second level. However, if a right condition persists and the above chain of events is followed to the end without any interruption, a fire will develop. The right condition means development of a leak in an area susceptible to gas accumulation and fire. An investigation into the 1987 Whittier Narrows earthquake (Schiff 1988) revealed that about 75% of gas leaks occurred at appliances (primarily at water heaters). Similar results were also noted after the San Fernando earthquake of 1971. Water heaters are normally installed in basements, garages and enclosed areas where potential combustible materials (old furniture, papers, gasoline cans, etc.) are stored. Thus with an ignition source present, the failure of a heater may result in a "right condition" for a fire to occur.

A graphic presentation of the chain of events that may lead to a gas-related fire following a probable earthquake is given in Fig. 1 using the "event tree" scheme (Ang and Tang 1984). The starting event (A) is an earthquake of a given intensity (in terms of MMI or ground acceleration). This is ensued by various levels of "follow-up" events which ultimately lead to a fire. Within each group of follow-up events, two or more mutually exclusive and collectively exhaustive events appear in the tree. Immediately following the earthquake, there may be leaks in the system (Event B). This can be the result of piping system and/or appliance failure (failure means overstress in piping system components or overturning/sliding of an appliance). The next level contains events D and $\bar{D}$ ($\bar{D}$ is the complementary event of D). These events represent leak being detected or remained undetected, respectively. The sequence is continued at next level which contains the event (E) of having an ignition source active in the area. Upon occurrence of E, there will be a fire.

Four types of fires are designated as C_1, C_2, C_3 and C_4 which represent the "consequences" in the tree. The description of each type of fire is explained below:

Type 1: Fire spreads only to the immediate area around its point of origin.

Type 2: Fire catches on a cumbustible material in the room of origin, spreads all over the room; however, it is only confined to the room.

Type 3: Fire catches on a cumbustible material in the room of origin, spreads all over the room and throughout the building.

Type 4: This is Type 3 fire that also spreads to the adjacent buildings.

Initiation of a specific type of fire among the four described above depends on the location of the fire, availability of cumbustible materials in the area where fire starts and fire fighting efforts. Types 3 and 4 are much less expected than Types 1 and 2 mainly due to quick response time by fire departments.

The probability of occurrence of the consequences (i.e., fires) in the tree of Fig. 1 can be obtained using the conditional probability formulation. For a consequence such as C_i ($i=1,2,3,4$), the probability $P(C_i)$ is written as follows:

$$P(C_i)=P(C_i|E)[P(E|D)P(D|B)+P(E|F)P(F|\bar{D})P(\bar{D}|B)]\\ P(B|A)P(A)$$

It is noted that events $\bar{B}$, $\bar{E}$ and $\bar{F}$ do not participate in the sequence of fire development. It is also noted that in the above equation, the fact that there are two possible branches leading to a fire has been included.

The estimation of $P(C_i)$ requires that all probabilities involved in the equation be quantified. Mathematical modeling can be employed to quantify some of these probabilities. For example, an appliance failure probability can be estimated by modeling the motion of the appliance subjected to a known earthquake record and investigating the possibilities for overturning or sliding. For a typical water heater (45-60 gallons capacity), considering the geometry of the heater, its weight, attachment to gas and water pipes, and whether or not it is secured to the wall via straps, this probability was evaluated using a series of simulation analyses. These analyses considered variability in the pipe strength and intensity of the ground shaking. Using the 1989 Loma Prieta, California earthquake record, the probabilities summarized in Table 2 were obtained.

The probability of an earthquake of a given intensity (Event A), can be obtained using one of several available seismic risk analysis models. Table 3 summarizes these probabilities for a site in downtown San Francisco, from Mohammadi and Suen (1992).

When the mathematical modeling is not possible, the needed probability values can be obtained by extrapolating the probabilities known to represent ordinary (i.e., non-earthquake) conditions. For example, the probability of leak development in the piping system under normal operative conditions has been established by Longinow, et al (1989). An earthquake can increase these probabilities in the sense that it will trigger certain parameters that are known to be effective in promoting leaks in a piping system. One such factor is stress generated at joints and fittings in the system. The extrapolation of probability of leak in the system to account for the earthquake effect can be done based on the stress level induced in piping system components. In the study by Longinow et al (1989), the probability of leak in the interior gas piping system in a medium size (four bedroom) dwelling is estimated to be 0.0013 per year. Based on the results of stress analyses of a series of typical interior piping systems, we estimated that this probability will be unchanged at a ground acceleration of 0.05g or less and increase linearly with an increase in the ground acceleration. At 0.5g acceleration, the risk is about 0.013.

2.2 Electric Fires

Current research results indicate that there are many causes for fires initiated in electrical distribution systems and/or electric appliances operating under normal (i.e., non-earthquake) conditions. Potential fire causes are ground fault, improper installation, equipment overload, loose connections, worn-out wires and electrical components, etc. Smith and McCoskrie (1990) report on causes of fires in electrical distribution systems in residential units. An electrical distribution system (EDS) is made up of the following components:

1. Branch circuit wiring
2. Receptacle outlet and switches
3. Cords and plugs
4. Fixtures and lamps
5. Transformers

In the event of an earthquake, the electrical distribution system is especially critical because the ground shaking can trigger displacements of electrical components and friction of wiring and cords against each other or protruding metal edges in their vicinity. Such phenomena will increase the risk of fire. However, a comprehensive modeling for the behavior of an electrical distribution system as a means to estimate the risk of fire is quite challenging. The probability of fire development depends on a variety of factors including the design of the system, the age of the electric components, installation practice, existence of faulty wiring, overloaded components, etc. In this section, the sequence of events that may lead to an electric fire is explained. The risk of fire due to an earthquake is estimated by extrapolating the risk for ordinary (non-seismic) conditions as described earlier.

The sequence of events in an electric fire is shown in the event tree of Fig. 2. The tree is intended to demonstrate the role of key parameters that may accelerate the risk of fire when an earthquake occurs. As seen in Fig. 2, upon occurrence of an earthquake of given intensity (Event A), the first follow-up event is designated as development of a disturbance in the EDS (Event B). The disturbance can be the result of:

1. Excessive friction of electrical wires and cords with one another especially at joints, connections, receptacles and switches.

2. Electrical shorts at connections and joints due to severe structural vibrations.

3. Electrical problems arising from swinging lamps and other suspended fixtures.

4. Electrical problems and overload at extension cords, cables, and receptacles due to overturning and sliding of electric appliances and equipment.

Generally, upon occurrence of one or more of these disturbances, the risk of fire is expected to increase. The extent to which the risk increases depends primarily on the intensity of the earthquake and the design of the electrical distribution system. The risk is also triggered by the follow-up events D_1, D_2, D_3, and E. Events D_1, D_2, and D_3 describe what can occur as a result of partial, full or no electricity cut-off due to either an internal control switch or the area black out. The former has a greater chance to occur. Event E (and its complementary) describes the effect of the duration of the ground shaking. The longer duration has a greater effect on development of an electric fire in the sense that it causes a longer exposure time for wires and cords to engage in friction and for swinging fixtures to get the momentum needed for them to fall or break.

The consequences are again fire types 1-4. The probability of a sequence C_i is obtained trough the following equations:

$$P(C_i)=P(C_i|E)P(E)+P(C_i|\bar{E})P(\bar{E})$$

$$P(E)=\Sigma_{j=1\text{-}3}P(E|D_j)P(D_j)$$

$$P(D_j)=P(D_j|B)P(B|A)P(A) \quad j=1,2,3$$

$$P(\bar{E})=1-P(E)$$

An investigation into electrical distribution system fires for San Francisco for the period 1984-1990 reveals that under normal conditions there is a $4.536\text{x}10^{-4}$ probability that any given dwelling will develop a fire per year. With an earthquake of 0.05g or lower acceleration, this risk is unaffected. However, at higher levels, the risk is increased due to a greater probability that an electrical distribution system component will experience problems that promote fire. Using a series of analyses on typical electrical distribution systems installed on rigid walls, we evaluated severity of earthquakes of various accelerations and durations on elongation and displacements experienced by electrical wires and joints. The wire elongation accelerates local friction of adjacent wires and increases the risk of fire. As a result of these analyses, we concluded that at accelerations above 0.05g, the risk of fire increases by a 1.5/1 ratio.

3 THE LOMA PRIETA EARTHQUAKE FIRES

The earthquake occurred on October 17, 1989 at 5:04 p.m. Pacific Time. The magnitude was measured at 7.1 Richters. The epicenter was located 16 km northeast of Santa Cruz and 30 km south of San Jose, California, in Santa Cruz Mountains (Loma Prieta). The earthquake source was along a section of the San Andreas fault where major earthquakes have also occurred in the past. The earthquake caused damage in San Francisco, San Jose, Santa Cruz and areas in Northern California.

The fire data obtained through local fire departments reveal a total of 41 fires in San Francisco. Of these, 17 (i.e., 42%) occurred on October 17, immediately after the earthquake, 13 (32%) on the next day (October 18), 8 (20%) on October 19, and 3 on October 20, 1989. In terms of severity, using the four types of fires described earlier, all Types 3 and 4 fires occurred immediately after the earthquake. Table 4 presents the umber of fires by causes.

The 41 fires reported after the earthquake in San Francisco were further investigated in terms of their types, the earthquake intensity, and the type of soil and population density at the sites where the fires occurred. The 41 fires were marked on the map of the affected areas along with the measured intensities (see Fig. 3). Using a linear interpolation, the intensity at the site of each fire was calculated. Furthermore, the type of soil in the earthquake-affected areas was obtained from geologic maps and the fire data were investigated in terms of this parameter. Table 5 summarizes the number of fires in terms of accelerations (in g's).

An examination of the soil types reveals that the affected areas are mainly made of four major types. These are: (i) stable bedrock, (ii) unstable bedrock, (iii) unconsolidated soil, and (iv) mud and fill. The earthquake shock transmitted to the areas with unconsolidated soil and mud and fill is expected to be strongly increased; whereas, the shock in stable bedrock is not increased and in unstable bedrock is only slightly increased. Accordingly, because of the greater potential for building damage in areas with unconsolidated soil or mud and fill, more number of fires are expected in these areas. An investigation of the 41 fires indicated that most fires (33 out of 41) occurred at sites on unconsolidated soil, 5 at sites on mud and fill and the rest at sites on stable rock. It is emphasized that the population density also plays an important role in the number of fires. Regarding the large number of fires reported at sites on unconsolidated soil, the vastness of coverage of this soil type versus the other types may also be a factor. Areas along the San Francisco Bay (east of San Francisco) are mainly on mud and fill soil. However only a few fires were reported in theses areas. This is attributed to the relatively less concentration of housing units in this area. Figure 4 shows the number of fires along with the type of soil in the area.

The city of San Francisco, excluding Presidio, has been divided into ten fire battalion districts by the San Francisco Fire Department. Using these districts as the basis for the geographical breakdown of the city, district, population density (see Fig. 5) and the number of fires in each district are summarized in Table 6. The statistics in Table 6 reveals that over 51% of fires occurred in districts 1, 2, 4 and 5 which have the largest population concentrations.

4 SUMMARY AND CONCLUSIONS

This paper presents an overview of fire risks following earthquakes. A review of past earthquake hazards reveal that destructive fires have been initiated after nearly all major California earthquakes of modern times. The paper presents a brief review of current models available for estimating the risk of earthquake-generated fires. Numerous factors can contribute to a post-earthquake fire. Thus development of a systematic formulation to estimate the risk associated with all types of fires (in terms of their causes) is difficult. The paper describes that the risk of fires caused by gas piping and gas appliance failure and by electrical distribution systems in single family dwellings can be modeled using an event tree analysis. The starting event in the tree is an earthquake of specific intensity. The subsequent events are those describing the possibilities for a system and components failure that may ultimately lead to a fire. The consequences are fires of different types.

A summary of findings on fires following the Loma Prieta earthquake of October, 17, 1989 is also presented. The data on the causes of the 41 fires occurred after this earthquake was acquired from fire departments. The attempt was to find any correlation between the ground intensity and the number of fires. However, there are other factors including the population density and the type of soil at the site of the damaged buildings that may influence this correlation.

Table 1 Earthquake-Related Fires in US

Event/Magnitude	No. of Fires
1906 San Francisco/8.3	58
1925 Santa Barbara/6.2	1
1933 Long Beach/6.3	13
1957 San Francisco/5.3	1
1965 Puget Sound/6.5	1
1969 Santa Rosa/5.6	1
1971 San Fernando/6.6	109
1983 Coalinga/6.7	1
1984 Morgan Hill/6.2	6
1987 Whittier-Narrows/5.9	26
1989 Loma Prieta*	41

Table 2 Appliance Failure Probability

Accel.	W/O Strap	With Strap
0.10g	0.081	0
0.20g	0.949	0.001
0.30g	0.999	0.004
0.40g	≈1.0	0.009
0.50g	≈1.0	0.020

Table 3 Estimates of P(A)

Intensity	P(E)/year
0.1g	0.1100
0.2g	0.0220
0.3g	0.0054
0.4g	0.0020
0.5g	0.0010

Table 4 Loma Prieta Earthquake Fires

No. of Fires	Cause
6	Electric Wiring
8	Electric Equipment
11	Stove, Electric/Gas
8	
2	Water Heater
2	Gas Appliances
4	Miscellaneous

Table 5 Fires vs Acceleration, g

	No. of Fires by Types				
Accel.	1	2	3	4	Total
.05-.10	7		3		10
.10-.15	8	5	2	2	17
.16-.20	4		1		5
.21-.30	1		2	5	9

Table 6 Population vs No. of Fires

Dist.	Population Density*	No of Fires
1	0.894	6
2	0.863	3
3	0.311	1
4	1.065	10
5	0.889	6
6	0.745	1
7	0.527	5
8	0.331	5
9	0.337	2
10	0.344	2

* Per 1000 Square Feet

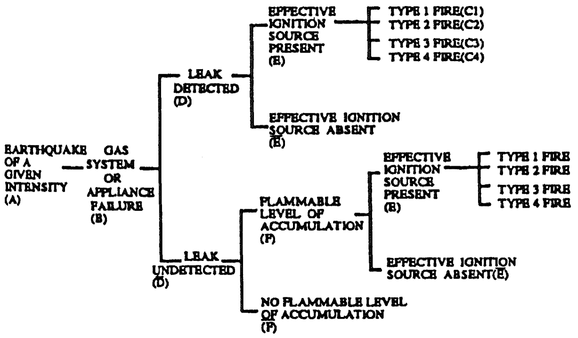

Fig. 1 Sequence of events for a gas fire

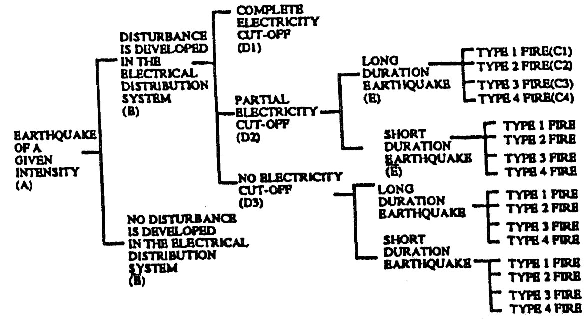

Fig. 2 Sequence of events for an electric fire

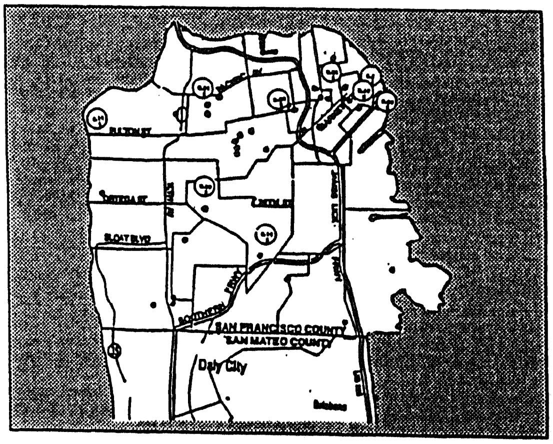

Fig. 3 Location of fires and earthquake intensities following the Loma Prieta Earthquake of October 17, 1989.

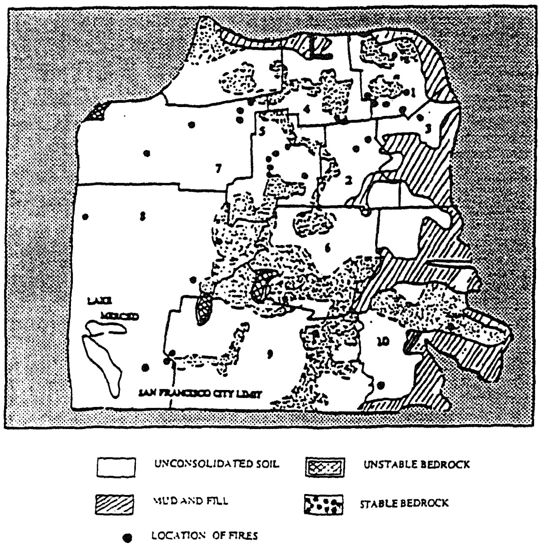

Fig. 4 Type of soil and location of fires in San Fransisco following the Loma Prieta Earthquake

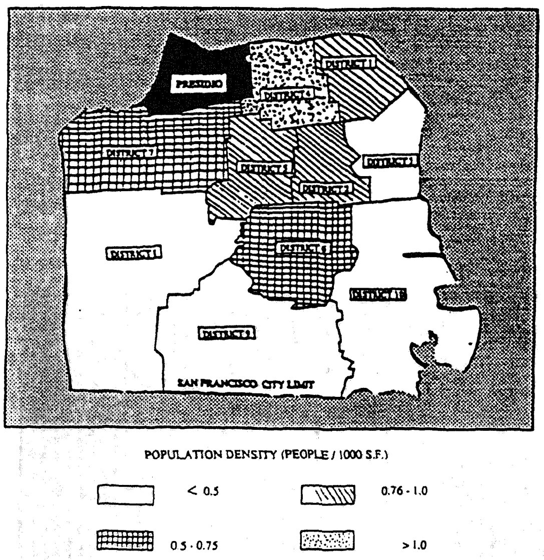

Fig. 5 Population densities of fire battalion Districts in San Fransisco

5 ACKNOWLEDGMENT

Support for this research is provided partially by the NSF/USGS Grant BCS-9003557. Drs. William Anderson from NSF and Elaine R. Padovani from USGS are the cognizant officials for this grant.

REFERENCES

Ang, A. H.-S. and Tang, W. H. 1984. *Probability concepts in engineering planning and design, Volume II.* New York: John Wiley and Sons.

Itoigawa, E. and Tsukagoshi, I 1988. Stochastic model for fire spread in urban areas based on fire brands effect. *Proc., 2nd Japan-US Workshop on Urban Earthquake Hazard Reduction*: 223-233, Earthquake Eng. Research Institute (USA).

Longinow, A., Mohammadi, J. and Williams, T. 1989. Risk associated with interior gas distribution systems. *Topical Rept.* Chicago: Gas Res. Inst.

Longinow, A. et al 1990. Load and environmental effects on interior gas piping systems. *Final Technical Report #GRI-90/0132*: 4.1-1.4. Chicago: Gas Research Institute.

Mizuno, H. 1987. *On outbreak of fires in earthquakes.* Dissertation, Dept. of Arch. Kyoto University.

Mohammadi, J. 1990. Earthquakes and earthquake-resistant design. *Cost Engineering* 32: 12-17.

Mohammadi, J., Bak, D.N. and Alyasin, S. 1991. Risk of fire following earthquakes," *Proc., System Safety Conference*: 2.1/4/1-2.1/4/12 Sterling, Virginia: System Safety Society.

Mohammadi, J., Longinow, A. and Williams, T. 1991. System reliability using expert opinions. *Structural Safety* 9:227-241.

Mohammadi, J. and Suen, S.-J. 1992. An investigation of the effect of source parameters in seismic hazard analysis," *European Earthquake Engrng.*

Scawthorn, C.G. 1986. Simulation modeling of fire following earthquake," *Proc., 3rd US National Conf. on Earthquake Engineering*, Vol. III.

Scawthorn, C.G. 1988. Fire and hazardous materials following earthquake: US perspectives. *Proc., 2nd Japan-United States Workshop on Urban Earthquake Hazard Reduction*: 234-243. Earthquake Eng. Res. Inst., USA.

Schiff, A.J. 1988. The Whittier-Narrows, California earthquake of October 1, 1987. *Earthquake Spectra* 4:339-366.

Smith, L.E., and McCoskrie, D. 1990. What causes wiring fires in residences. *Fire Journal*, January/February: 19-24.

URS Corporation 1988. Risk of earthquake-induced gas fires in residential housing. *Rept. to Southern California Gas Co.*, San Francisco: URS Corp.