Chapter 10
Induced Damage Models - Fire Following Earthquake

10.1 Introduction

Fires following earthquakes can cause severe losses. These losses can sometimes outweigh the total losses from the direct damage caused by the earthquake, such as collapse of buildings and disruption of lifelines. Many factors affect the severity of the fires following an earthquake, including but not limited to: ignition sources, types and density of fuel, weather conditions, functionality of water systems, and the ability of fire fighters to suppress the fires.

It should be recognized that a complete fire following earthquake model requires extensive input with respect to the level of readiness of local fire departments and the types and availability (functionality) of water systems. To reduce the input requirements and to account for simplifications in the lifeline module, the fire following earthquake model presented in this report is also simplified. In addition, while building upon past efforts, the model is still to be considered a technology which is in its maturing process. With better understanding of fires that will be garnered after future earthquakes, there will undoubtedly be room for improvement in our forecasting capability. The methodology, highlighting the Fire Following Earthquake component, is shown in Flowchart 10.1

10.1.1 Scope

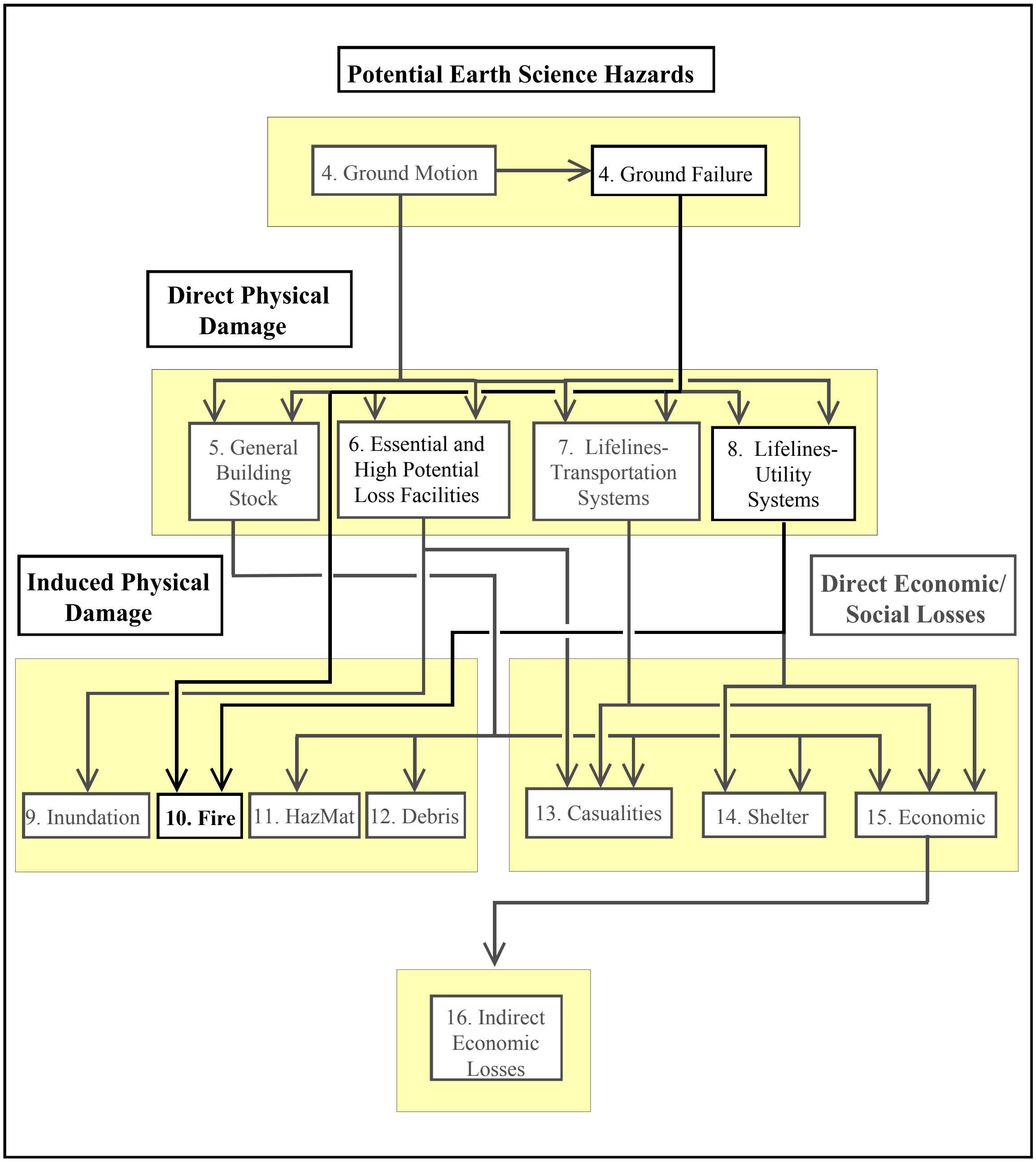
A complete fire following earthquake (FFE) model encompasses the three phases of a fire:

- ignition
- spread
- suppression

This methodology provides the user with the following estimates:

- Number of ignitions
- Total burned area
- Population exposed to the fires
- Building value consumed by the fire

Using Default and User-Supplied Data Analysis information will provide an estimate of the magnitude of the FFE problem, that could be used to plan for and estimate demands on local fire fighting resources.



Flowchart 10.1: Fire Following Earthquake Component Relationship to other Modules in the Earthquake Loss Estimation Methodology

10.1.2 Form of Damage Estimates

The FFE methodology provides the following:

- an estimate of the number of serious fire ignitions that require fire department response after a scenario earthquake
- an estimate of the total burned area
- an estimate of the population and building exposure affected by the fire

By applying the FFE module for several scenario earthquakes, representing different potential earthquakes for the study area, with different recurrence intervals, the user can examine the efficacy of certain pre-earthquake actions that can be used to mitigate the potential losses from fires in future earthquakes. For example, the user could study the effect of building more fire stations; adding more fire apparatus; improving immediate post-earthquake response to detect fires and suppress fires before they spread or seismically upgrading the water system. Since all these activities cost money, the user could study which combination of activities is most effective for their communities.

10.1.3 Input Requirements

This section describes the inputs required and output provided by the FFE module.

Input for Analysis:

Provided as general building stock inventory data:

- Square footage of residential single family dwellings (SFD)
- Square footage of residential non-SFD
- Square footage of commercial buildings
- Square footage of industrial buildings

Provided as essential facility inventory data:

- Number of fire stations
- Number of engines at each fire stations
- Geographical location of each station

Provided by the PESH module:

- PGA

Analysis options input by the user:

- Wind speed
- Wind direction
- Speed of the fire engine truck (after earthquake)
- Number of Simulations
- Maximum Simulation Time
- Simulation Time Increment

Multiple estimates for the same scenario earthquake are calculated by simulating fire following earthquakes several times. Hence, the user needs to provide the number of simulations that should be performed in order to come up with average estimates from independent simulations. It is suggested that the user try 6 to 10 simulations. The maximum time after the earthquake for which the simulation should be performed and the time increment for each simulation are also user inputs. For example, a resonable maximum time could be 10,000 minutes when all the fires could possibly be suppressed. It is suggested that a time increment of 1 to 15 minutes be provided for sufficiently accurate simulations.

10.2 Description of Methodology

10.2.1 Ignition

The first step in evaluating the potential losses due to fires following earthquake is to estimate the number of fires that actually occur after the earthquake. The ignition model is based on the number of serious FFEs that have occurred after past earthquakes in the United States.

The term "ignition" refers to each individual fire that starts (ignites) after an earthquake that ultimately requires fire department response to suppress. Thus, a fire that starts after an earthquake but which is put out by the occupants of the building without fire department response is not considered an ignition for purposes of this model. Fires that are put out by building occupants are usually those discovered very early and are put out before they can do substantial damage. These ignitions do not lead to significant losses.

In a fire ignition model previously developed by Scawthorn (1987), the number of FFEs was established by counting the actual FFEs versus the inventory exposed to equal levels of MMI (Modified Mercalli Intensity). The model did not include fire data from more recent and well documented earthquakes, such as the 1989 Loma Prieta event. For this methodology, the model has been re-calibrated. The prediction parameter (MMI) and output parameter (number of ignitions per thousand Single Family Equivalent Dwellings (SFEDs)), have not been carried forward in this project. (One SFED is defined to be 1,500 square feet of floor area.)

The calibration process has been performed in three steps:

- The database of actual earthquake experience was expanded by incorporating new data points representing the fire ignitions from the 1989 Loma Prieta earthquake.
- The ignition per SFED scale was changed to ignitions per 1,000,000 square feet of structure inventory.
- The MMI scale was converted to the PGA scale as shown in Table 10.1.

Table 10.1: MMI to PGA Conversion Table

MMI	VI	VII	VIII	IX	X	XI	XII
PGA	0.12	0.21	0.36	0.53	0.71	0.86	1.15

Table 10.2 provides the results after performing the calibration. This table provides the database of fire ignitions from past United States earthquakes, calibrated to ignitions per 1,000,000 square feet, and as predicted using PGA.

Figure 10.1 is a plot of the information found in Table 10.2. As can be seen from the plot, there is considerable scatter in the empirical evidence. The reasons for this scatter include the following:

- The horizontal axis is based upon historical interpretations of MMI scale value processed through an MMI to PGA conversion. Different investigators will sometimes rate a specific area with different MMI values, sometimes differing by one or two intensities. This introduces large uncertainties. Also, the MMI to PGA conversion process builds in more uncertainty. For example, the same PGA values at rock and at soft soil sites can produce different levels of damage, particularly if liquefaction or landslides occur.

- The quantification of the actual number of fire ignitions in past earthquakes is most often based on conflicting data sources. The usual sources base some estimates on journals and newspaper accounts, which often conflict. More recent efforts have tracked down each fire ignition using fire incident reports from fire departments, and these data are more reliable.

- Fire ignitions are probably not related to a single input parameter, whether it be MMI or PGA. Actual fire ignitions start for a number of reasons, including:
  - Toppling over of unanchored items (this is PGA-related), causing short circuits or fuel spills. This causes fires if an ignition source (spark) is present.
  - Breakage of underground utilities (such as gas lines) which provides a fuel source for the ignition. This is PGD-related.
  - Interstory drift of structures, which may cause short circuits in electrical wiring. This is related to PGA and age of structure / wiring condition.
  - Time of day. During meal times, more electrical and gas appliances are in use. This would allow for more potential for ignitions than if the earthquake occurred during night-time hours. Similarly, time of year is important in that many gas or oil appliances are used in winter for home heating. [Note: time of year is an important factor for fire spread given an ignition, in that fire growth is dependent upon heat.]

A second order fit of the data provides the following ignition model:

$$\text{Ignitions} = -0.025 + (0.592 * \text{PGA}) - (0.289 * \text{PGA}^2) \tag{10-1}$$

Table 10.2 Fires Following United States Earthquakes (1906 - 1989)

City, Year of Earthquake	PGA (g)	Intensity (MMI)	Ignitions	Ignitions per 1,000,000 Sq. Feet
Coalinga 1983	0.36	VIII	1	0.30
Daly City 1989	0.12	VI	3	0.05
Anchorage 1964	0.71	X	7	0.24
Berkeley 1906	0.44	VIII-IX	1	0.16
Berkeley 1989	0.07		1	0.013
Burbank 1971	0.21	VII	7	0.16
Glendale 1971	0.15	VI-VII	9	0.13
Los Angeles 1971	0.15	VI-VII	128	0.09
Los Angeles 1933	0.15	VI-VII	3	0.01
Long Beach 1933	0.53	IX	19	0.26
Marin Co. 1989	0.12	VI	2	0.02
Morgan Hill 1984	0.21	VII	4	0.40
Mountain View 1989	0.21	VII	1	0.02
Norwalk 1933	0.28	VII-VIII	1	0.05
Oakland 1906	0.44	VII-IX	2	0.06
Oakland 1989	0.07		0	0.00
Pasadena 1971	0.21	VII	2	0.04
San Francisco 1989	0.21	VII	27	0.08
San Francisco 1906	0.44	VII-X	52	0.26
San Francisco 1957	0.12	VI	0	0.00
San Fernando 1971	0.53	IX	3	0.37
San Jose 1984	0.36	VIII	5	0.02
San Jose 1906	0.36	VIII	1	0.08
Santa Clara 1906	0.44	VIII-IX	1	0.22
Santa Cruz 1989	0.36	VIII	1	0.04
Santa Cruz Co. 1989	0.28	VII-VIII	24	0.03
San Mateo Co. 1906	0.36	VIII	1	0.14
Santa Rosa 1969	0.36	VIII	1	0.06
Santa Rosa 1906	0.71	X	1	0.18
Whittier 1987	0.28	VII-VIII	6	0.10

Figure 10.1 also shows the best fit curve using equation 10-1. The correlation between PGA and number of ignitions in the fitting is quite low. This confirms that PGA is by itself not a perfect indicator of fire ignitions. This result is not too surprising, given the uncertainties involved in the collection of the empirical data and in the ways fires start.

Timing of Ignitions

The number of ignitions that are predicted using the above ignition model are based on empirical results, and include fires attributed to the earthquake, both starting immediately after the earthquake and starting some time after the earthquake.

Based upon the empirical record, and using judgment, it is estimated that about 70 percent of all fire ignitions start immediately after the earthquake. "Immediately" means that the fire ignition is discovered within a few minutes after the earthquake.

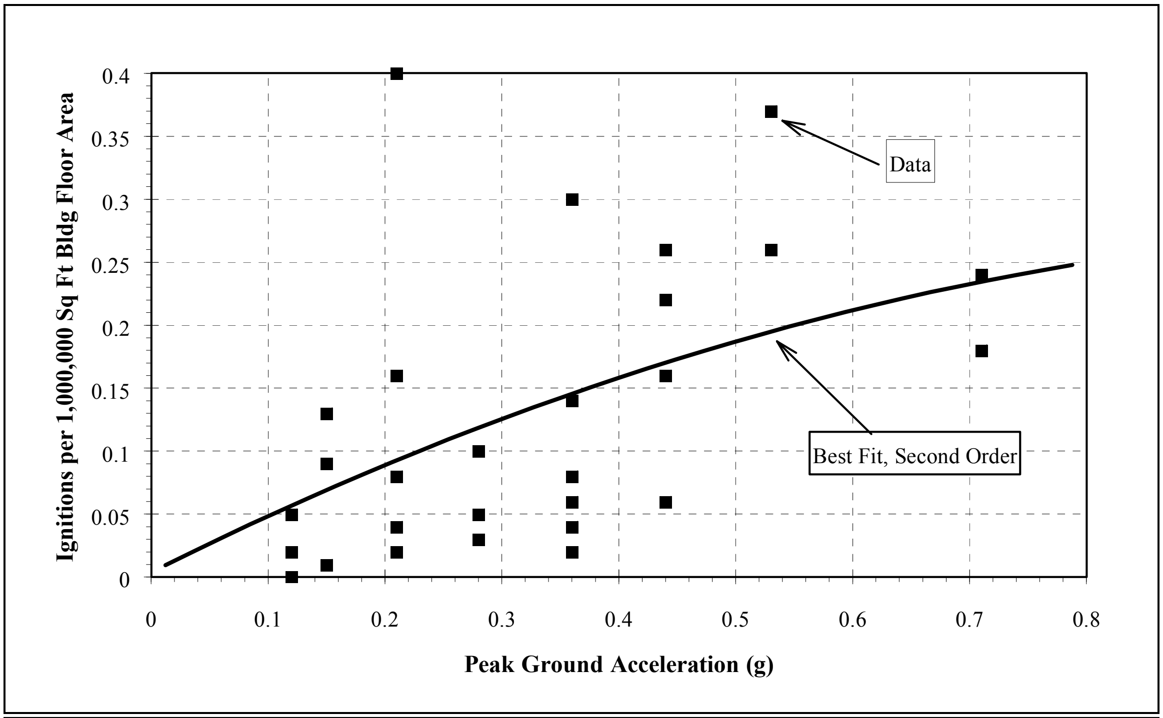


Figure 10.1 Fire Ignitions in United States Earthquakes (1906-1989).

The remaining ignitions start sometime after the earthquake, ranging from an hour to possibly a day or so after the earthquake. A typical cause of these later ignitions is the restoration of electric power. When power is restored, short circuits that occurred due to the earthquake become energized and can ignite fires. Similarly, when power is restored, items which have overturned, fallen onto range tops, etc., can ignite. If no one is present at the time electric power is restored, fire ignitions requiring fire department response can occur.

10.2.2 Spread

The second step in performing the FFE analysis is to estimate the spread of the initial fire ignition. The following description of fire spread in urban areas is based on a model developed by Hamada (1975). Hamada developed a model for fire spreading for urban Japan. His model is described as follows:

$$N_{tV} = \frac{1.5\delta}{a^2} * K_s * \left(K_d + K_u\right) \tag{10-2}$$

where:

$N_{t\,V}$ = Number of structures fully burned
t = time, in minutes after initial ignition
V = wind velocity, in meters per second
δ = "Built-upness" factor, dimensionless, described below
a = average structure plan dimension, in meters
d = average building separation, in meters
K_s = half the width of fire from flank to flank, in meters
K_d = length of fire in downwind direction, from the initial ignition location, in meters
K_u = length of fire in upwind (rear) direction, from the initial ignition location, in meters

$$\delta = \frac{\sum_{i=1}^{n} a_i^2}{\text{Tract Area}} \tag{10-3a}$$

where:

a_i = plan dimension of building i
n = number of structures

$$K_d = \frac{(a+d)}{T_d} * t \tag{10-3b}$$

$$K_s = \left(\frac{a}{2} + d\right) + \frac{(a+d)}{T_s}\left(t - T_s\right) \quad ; \quad K_s \geq 0 \tag{10-3c}$$

$$K_u = \left(\frac{a}{2} + d\right) + \frac{(a+d)}{T_u}\left(t - T_u\right) \quad ; \quad K_u \geq 0 \tag{10-3d}$$

$$T_d = \frac{1}{1.6\left(1 + 0.1V + 0.007V^2\right)}\left[\left(1 - f_b\right)\left(3 + 0.375a + \frac{8d}{25 + 2.5V}\right) + f_b\left(5 + 0.625a + \frac{16d}{25 + 2.5V}\right)\right] \tag{10-3e}$$

$$T_s = \frac{1}{1 + 0.005V^2}\left[\left(1 - f_b\right)\left(3 + 0.375a + \frac{8d}{5 + 0.25V}\right) + f_b\left(5 + 0.625a + \frac{16d}{5 + 0.25V}\right)\right] \tag{10-3f}$$

$$T_u = \frac{1}{1+0.002V^2}\left[\left(1-f_b\right)\left(3+0.375a+\frac{8d}{5+0.2V}\right)+f_b\left(5+0.625a+\frac{16d}{5+0.2V}\right)\right]$$

(10-3g)

where:

$$f_b = \frac{\text{Number of fire resistant buildings}}{\text{All buildings}}$$

A discussion of the Hamada model follows.

- It is assumed that an urban area is represented by a series of equal square (plan area) structures, with equal spacing between structures. The plan dimension of the average structure is denoted "a", and hence the plan area is a^2.

- It is assumed that the spaces between structures in a subdivision can be represented by an average separation distance, d. For purposes of this model, the separation distance represents the typical distance between structures within a single block. This distance accounts for side yards, backyards and front yards, but does not include streets and sidewalks.

- The "built-upness", or building density ratio δ is defined by equation 10-3a. To put this building density ratio in context, a value of 0.35 represents a densely built area, and a value of 0.10 represents an area which is not very densely built.

- Figure 10.2 shows the fire spread in terms of ovals, which is the usual case of fires burning through an evenly distributed fuel load, with constant wind velocity. In the actual urban conflagrations, fires exhibit this trend initially, but the final shape of the fire spread differs, as different fuel loads are experienced, as wind shifts, and as different fire suppression actions take place. The fire burn area is approximated as the product of the downwind fire spread plus the upwind fire spread (K_d + K_u) times the width of the fire spread ($2K_s$).

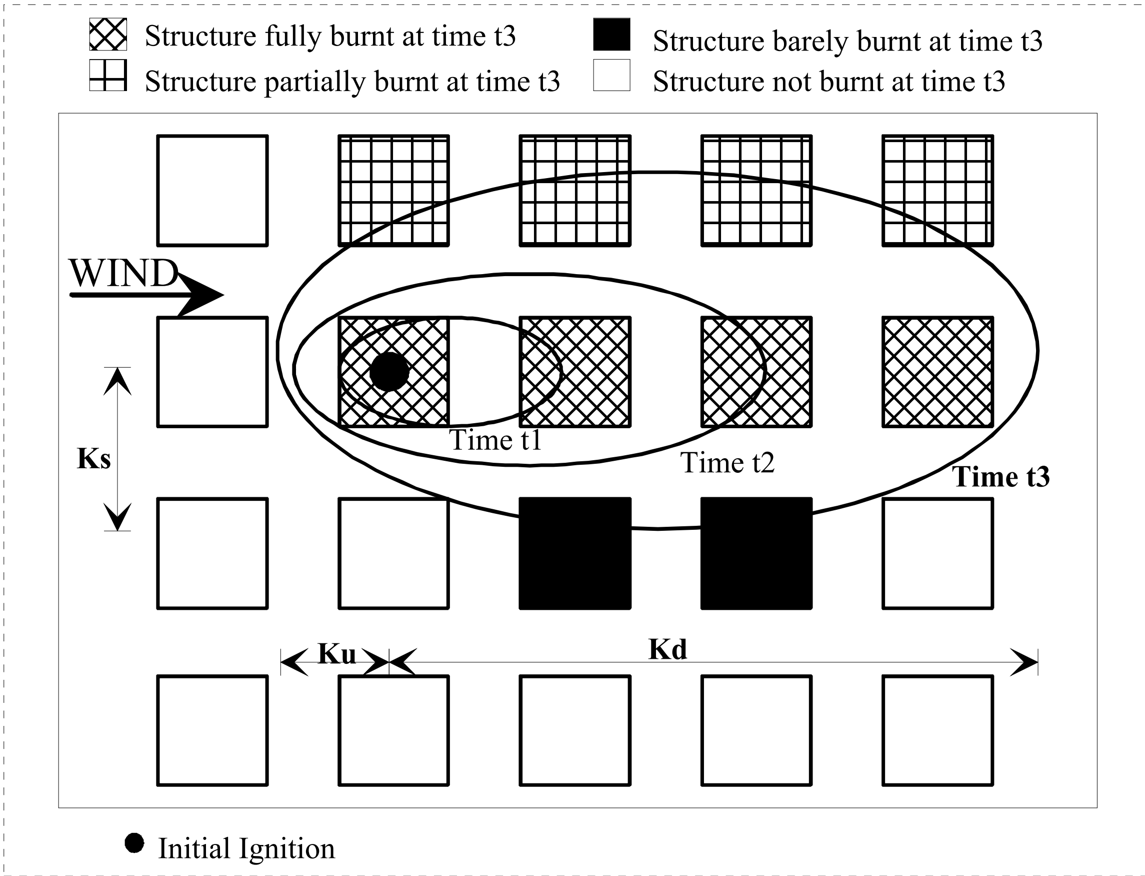


Figure 10.2 Fire Spread Process.

- The fire spread model accounts for the speed of advance of the fire considering the following variables:

  - **Direction of spread**. The speed of advance of the fire is highest in the downwind direction, slower in the side wind direction, and slowest in the upwind direction.
  - **Wind velocity**. The speed of advance of the fire increases as the square of the wind velocity.
  - **Fire resistance of structures**. The speed of advance through wood structures is about twice the speed of advance through fire resistant structures.

It should be noted that the Hamada model results in different fire spreading rates in the downwind, sidewind, and upwind directions even for zero wind speed. To correct this problem, a linear interpolation function is introduced which forces the fire spreading rates to be equal in all directions as the wind speed approaches zero. For wind speeds less than 10 m/sec, the adjusted fire spreading rates (K_d', K_u' and K_s') are given as follows:

$$K_d' = K_d\left(\frac{V}{10}\right) + \sqrt{\left(\frac{K_d + K_u}{2}\right)K_s}\left(1 - \frac{V}{10}\right) \quad (10\text{-}4a)$$

$$K_u^{'} = K_u\left(\frac{V}{10}\right) + \sqrt{\left(\frac{K_d + K_u}{2}\right)K_s}\left(1 - \frac{V}{10}\right) \quad (10\text{-}4b)$$

$$K_s^{'} = K_s\left(\frac{V}{10}\right) + \sqrt{\left(\frac{K_d + K_u}{2}\right)K_s}\left(1 - \frac{V}{10}\right) \quad (10\text{-}4c)$$

10.2.3 Suppression

The term suppression is defined as all the work of extinguishing a fire, beginning with its discovery. The steps in the suppression activity are defined as follows:

- **Discovery Time**. Elapsed time from the start of the fire until the time of the first discovery which results directly in subsequent suppression action.
- **Report Time**. Elapsed time from discovery of a fire until it is reported to a fire agency that will respond with personnel, supplies and equipment to the fire.
- **Arrival Time**. Elapsed time from the report time until the beginning of effective work on a fire.
- **Control Time**. Elapsed time from the beginning of effective work on a fire to when the fire is controlled.
- **Mop-up Time**. Elapsed time from completion of the controlling process until enough mop-up has been done to ensure that the fire will not break out and the structure is safe to re-occupy.

10.2.3.1 Discovery Time

The time to discover a fire is usually on the order of a few minutes if anyone is present to observe the fire. In modern urban areas, many structures have smoke detectors, and these will alert occupants or perhaps people nearby the structure that a fire has ignited. The following discovery model is used:

- 85 percent of structures are occupied at the time of the earthquake. In these structures, fires are discovered randomly between 0 and 5 minutes.
- 15 percent of structures are not occupied at the time of the earthquake. In these structures, fires are discovered randomly between 3 and 10 minutes.

10.2.3.2 Report Time

The time to report a fire is usually less than one minute under non-earthquake conditions. Most people report a fire directly to the fire department or call 911. The 911 dispatchers determines the degree of the emergency and notify the fire department.

After an earthquake, this usual method to report fires will be hampered, either due to phone system overload (inability to get a dial tone) or due to physical damage to various parts of the phone system. In theory, the fire model could account for the various levels of phone system damage from outputs from the communications module. However, for simplification the report time aspects are based on the following methods.

Five different methods are considered in determining how the fire will actually be reported to the fire department after an earthquake.

- **Cellular phone**: The model assumes that 15 percent of all fires can be reported by cellular phone taking 1 minute.
- **Regular phone**: The model assumes that 25 percent of all fires can be reported by regular phone taking 1 minute; 50 percent of all fires can be reported by regular phone, taking anywhere from 1 to 5 minutes; and 25 percent of all fires cannot be reported by regular phone.
- **Citizen alert**: In all fires, one option to report fires is for the resident to walk or drive to the nearest fire station and report the fire. This method of reporting is available for all fire ignitions. The time to report such a fire is anywhere from 1 to 11 minutes.
- **Roving Fire Vehicle**: A fire department practice for fire response after earthquakes is to immediately get fire apparatus onto the streets, looking for fires. The model assumes that a roving vehicle can detect a fire somewhere between 3 and 14 minutes after the earthquake.
- **Aircraft**: In many post-earthquake responses, helicopters and other aircraft will be flying over the affected areas. Often by the time a fire is spotted at height, it has already grown to significant proportions. The model assumes that fires can be detected by aircraft anywhere from 6 minutes to 20 minutes after the earthquake.

The model considers all five methods to report fires. The method which results in the earliest detection is the one which is used in the subsequent analysis.

10.2.3.3 Arrival Time

The arrival time is the time it takes after the fire is reported for the first fire suppression personnel and apparatus to arrive at a fire ignition. Under non-earthquake conditions, fire engines respond to fires by driving at about 30 miles per hour on average. After an earthquake, it is expected that fire engines will have a somewhat more difficult time in arriving at a fire due to damage to the road network, debris in the streets due to fallen power poles or damaged structures, traffic jam caused by signal outages, and the like.

The model accounts for this slowdown in arrival time as follows:

- If the fire was detected by a roving fire engine, arrival time is 0 minutes (the engine is already at the fire).
- If the fire is called in or reported by citizens, the time for the first engine from a local fire department to arrive at the fire is between 2 and 12 minutes. (Under

non-earthquake conditions, arrival time is usually about 1 - 6 minutes, so the model assumes that the fire engines drive at 50 percent of normal speed).

10.2.3.4 Control Time

The time and resources needed to control the fire will depend upon the status of the fire at first arrival of the first fire engine. The model accounts for different control times considering the status of the fire. Since the status of a fire can vary over time, the model continues to check fire status every minute.

10.2.3.4.1 Room and Contents Fires

If the total time from ignition to arrival is short, then the fire may be still a "room and contents" fire. These fires are small, and most fire engines carry enough water in the truck to control them. (Typical water carried in a pumper truck is 500 gallons to 1000 gallons). If this is the case, the model assumes that the first responding fire engine can control the fire. The engine is held at the location of the fire for 10 minutes. Thereafter, the engine is released for response to other fires that may be ongoing.

10.2.3.4.2 Structure Fires - Engines Needed

If the fire has spread to beyond a room and contents fire, then suppression activities require two resources: an adequate number of fire apparatus (engine trucks, ladder trucks, hose trucks) and personnel, and an adequate amount of water.

Most fire apparatus today are engine trucks, and the model does not differentiate between the capabilities of a ladder truck and an engine truck. (The user should input to the model the sum of fire department apparatus which can pump water at a rate of about 1,000 gpm to 2,000 gpm. Hose tenders without pumps, search and rescue trucks, and automobiles are not counted as available apparatus in the model).

The model determines the number of required trucks as follows:

- Single Family Residential Fires. Figure 10.3 shows the number of fire trucks needed to suppress a fire, versus the number of structures already burned.
- Other Fires. Figure 10.4 shows the number of fire trucks needed to suppress a fire, versus the number of structures already burned, for the case when the original ignition was at a structure other than a single family building. These ignitions include fires at apartment, commercial, wholesale and industrial structures. From Figure 10.4, it is shown that a minimum of two trucks are needed if the burnt structures range from zero to four. Since only one truck is sent to each fire, this leads to all fires becoming a conflagration, regardless of size. A modification is introduced by modifying the requirement to:

    - One truck is needed if the burnt structures are less than 2.
    - Two trucks are needed if the burnt structures are between 2 and 4.

This modification will reduce the total burnt area since all fires close to the fire stations will be controlled and putout by only one engine.

10.2.3.4.3 Structure Fires - Water Needed

Except in the case of room and content fires, urban fire suppression usually requires large quantities of water in order to gain control. (The issue of firebreaks in urban areas is described later). The amount of water needed is usually expressed in two terms:

- **Required Flow**: This is the amount of water needed to fight a fire from one or more fire hydrants, usually expressed in gallons per minute, gpm.
- **Required duration**: This is the length of time the fire flow is needed, in hours (or minutes).

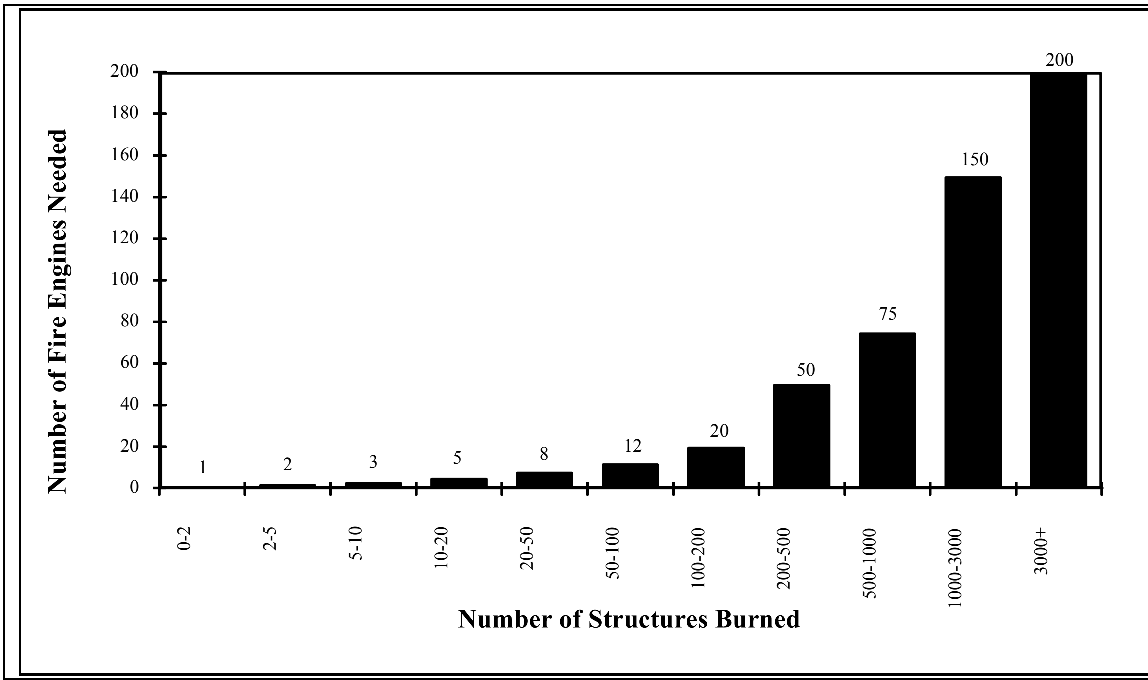


Figure 10.3 Ignitions That Start in Single Family Structures.

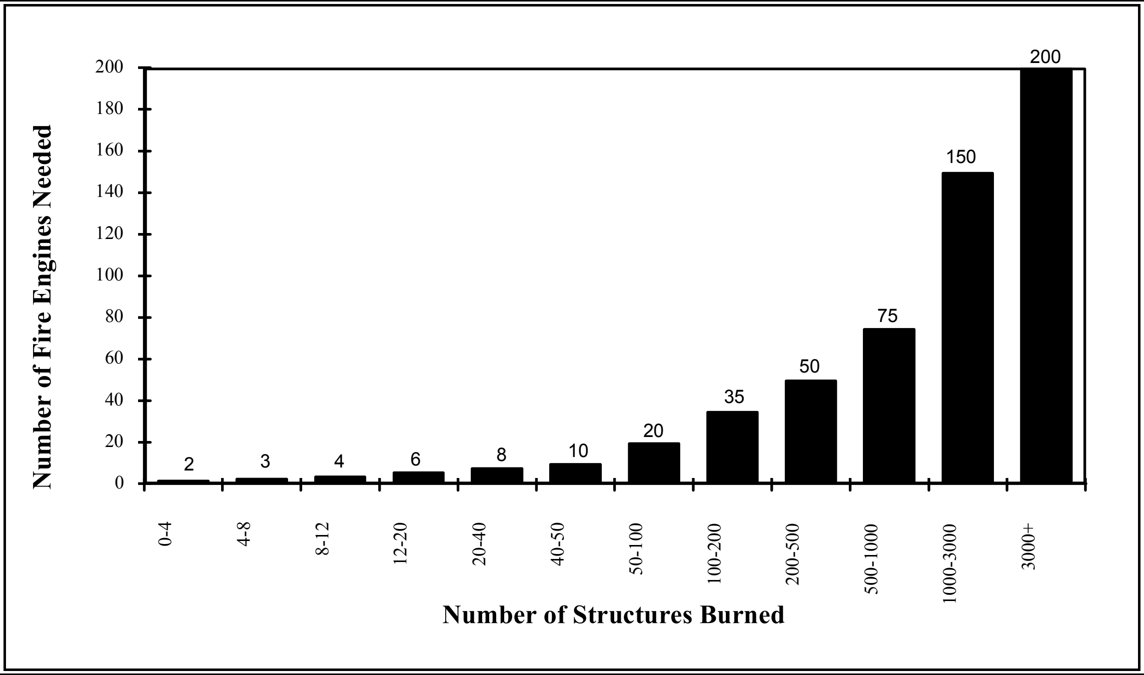


Figure 10.4 Ignitions That Start in Non-Single Family Structures.

A term often used in describing water needs is pressure. In the usual fire fighting terminology, the fire flows are required at the hydrant outlet at a minimum of 20 psi residual pressure while the hydrant is flowing.

Most cities use a water distribution system that delivers water for customer needs (drinking, sanitary, and other uses) and water for fire flow needs through a single set of pipes. Water pressures are usually kept in the mains at around 40 psi - 60 psi to meet normal customer needs. When a hydrant is opened, flows through the water mains increase. In areas of the city where mains are not highly interconnected (such as in hillside communities) or where mains have small diameters (2", 4" and some 6" pipes), the high velocities of water needed to deliver the water to the fire hydrant cause significant pressure drops. If the water pressure drops below about 20 psi, then fire engines have a difficult time drafting the water out of the hydrant.

The water needed to fight a fire at any given time t (W_t in gallons), depends upon the extent of the fire. The following equations are used to calculate the water needed:

$$W_t = 1250(N_{tV})^{0.4} \quad ; \quad 0 < N_{tV} \leq 3000 \qquad (10\text{-}5)$$

where N_{tV} = Number of structures burned at time t, at wind velocity V

Equation (10-5) is based upon the Uniform Fire Code (1991) for single structure fires (N_{tV} = 1) and modified for large conflagration fires.

For apartment fires, the amount of water needed is somewhat higher than the water needed for a single family residence, and is expressed in equations 10-6 and 10-7:

$$W_t = 1500(N_{tV})^{0.5} \quad ; \quad 0 < N_{tV} \le 4 \qquad (10\text{-}6)$$

or,

$$W_t = 3000 + 1250(N_{tV} - 4)^{0.4} \quad ; \quad 4 < N_{tV} \le 3000 \qquad (10\text{-}7)$$

For commercial, wholesale and industrial fires, the amount of water needed is higher than the water needed for a small apartment building, and is expressed in equations 10-8 and 10-9:

$$W_t = 2500(N_{tV})^{0.5} \quad ; \quad 0 < N_{tV} \le 4 \qquad (10\text{-}8)$$

or,

$$W_t = 5000 + 1250(N_{tV} - 4)^{0.4} \quad ; \quad 4 < N_{tV} \le 3000 \qquad (10\text{-}9)$$

For petroleum fires, the amount of water needed is higher than the water needed for other types of fires, and is expressed in equations 10-10 and 10-11:

$$W_t = 4000(N_{tV})^{0.5} \quad ; \quad 0 < N_{tV} \le 4 \qquad (10\text{-}10)$$

or,

$$W_t = 8000 + 1250(N_{tV} - 4)^{0.4} \quad ; \quad 4 < N_{tV} \le 3000 \qquad (10\text{-}11)$$

For all types of fires, the duration of flow is determined by equation 10-12:

$$D = 0.5 * (\text{engines needed})^{0.4} \qquad (10\text{-}12)$$

where D = duration of flow needed, in hours
(engines needed) = taken from Figure 10.3 or 10.4

10.2.3.4.4 Engines Available

The number of fire apparatus (engines and ladders) available in the study area is supplied by the user as input to the model. The following information is needed:

- The number of pumper apparatus engines in every jurisdiction within the study area. The user must select the level of refinement of the jurisdiction within the study area. A jurisdiction can be set at either the fire station level, the battalion level, or the city level.
  - Jurisdictions can be set as a city if the city has population of about 400,000 people or less.

- Jurisdictions should be set as a battalion (or more refined) if the city has population greater than about 400,000.

- The number of pumper apparatus available from mutual aid, from jurisdictions outside the study area. Mutual aid jurisdictions can usually be set in terms of the number of pumper apparatus available within a county. The geographic extent of the earthquake should be considered to decide what proportion of mutual aid that can be normally counted on will be delivered.

The model tracks the order of detection of the fires. Fire engines will serve fires which have been discovered first and are nearest to the fire stations. An insufficient number of fire trucks will result in the fire spreading faster which will be addressed later.

10.2.3.4.5 Water Available

The water available to fight a fire depends upon the capacity of the water distribution system, taking into account the level of damage to the system. Parameters that determine the amount of water available in a cell to suppress fires include:

- Available water flow
- Duration of water flow for pumped water system

10.2.3.4.6 Fire Spread with Partially Effective Suppression

For each fire, at each time step of the analysis, the model checks to see what is the available flow for fire suppression activities and what number of fire trucks are at the scene of the fire. Based upon the size of the fire at that time, the model calculates the number of fire trucks needed and the amount of water normally needed to control the fire. From these values, two ratios are calculated:

$$R_{truck} = \frac{\text{trucks at fire}}{\text{trucks needed at fire}}, \qquad \text{but } R_{truck} \text{ should not exceed 1.0}$$

$$R_{water} = \frac{\text{available flow at fire}}{\text{flow needed}}, \qquad \text{but } R_{water} \text{ should not exceed 1.0}$$

where,

available flow = (reduction factor) * (typical discharge from hydrant) * (number of hydrants to fight fire)

The reduction factor is set to the serviceability index obtained from Chapter 8. The typical discharge from a hydrant is around 1750 gallons/min. Finally, the number of hydrants available at the scene of the fire is estimated as follows:

No. of Hydrants = 1.5 * (K_d+K_u)(2K_s)/(100*100)

Where K_d, K_u, and K_s are previously defined. Note that 100 is the average spacing in meters between fire hydrants (typically, the spacing is in the range 60 m to 150 m). The coefficient 1.5 reflects the assumption of 50% of additional fire hydrants from adjacent blocks or equivalent will be available to fight the fire.

Based on the calculated values of R_{truck} and R_{water}, the fire suppression effectiveness is:

$$P_{\text{effective}} = \left(R_{\text{truck}} * R_{\text{water}}\right)^{0.7} \geq 0.33R_{\text{truck}} \tag{10-13}$$

This equation reflects the following logic. If the available trucks and water are much less than required, then there is good chance that the fire will spread. Conversely, if most of the trucks and water needed are available, then the fire suppression effectiveness is much better.

Due to fire suppression, the rate of fire spread will be slowed down and the reduced rate will be

$$\text{Spread Rate} = \text{Spread}_{\text{non-suppressed}} \cdot \left(1 - P_{\text{effective}}^{0.7}\right) \tag{10-14}$$

The Spread Rate is the key variable used in determining the spread of the fire. Equations 10-13 and 10-14 together provide the prediction as to the effectiveness of partial fire suppression in stopping urban conflagration.

10.2.3.4.7 Fire Spread at Natural Fire Breaks

Fire breaks are one of the ways to stop fires from spreading. Fire breaks abound in an urban area and include streets, highways, parks, and lakes. The model accounts for fire breaks as follows:

- Fires can spread within a city block following equation 10-3 as modified by equation 10-14. The model keeps track of the spread.

- The average city block is assumed to have two rows of houses, and there are 15 houses down a single side of a block. The average length of a city block is taken as the average of the width and length of the block. If the user does not supply the average width of a city block street, including sidewalks, then the model will use default width of 25 meters.

- The model assumes that every fifth fire break is three times wider than the average city street fire break. These wide fire breaks account for the presence of wide boulevards, interstate highways, parks and lakes.

- If the fire spread just reaches a fire break, then there is a probability that the fire break will control the fire, even with no active suppression or partial suppression ongoing. The probability of the fire jumping the fire break increases with the wind velocity, decreases with the width of the fire break, and decreases if there is active fire suppression as shown in Figure 10.5. Figure 10.5 is adapted from Dames and Moore, 1987, and combined with judgment.

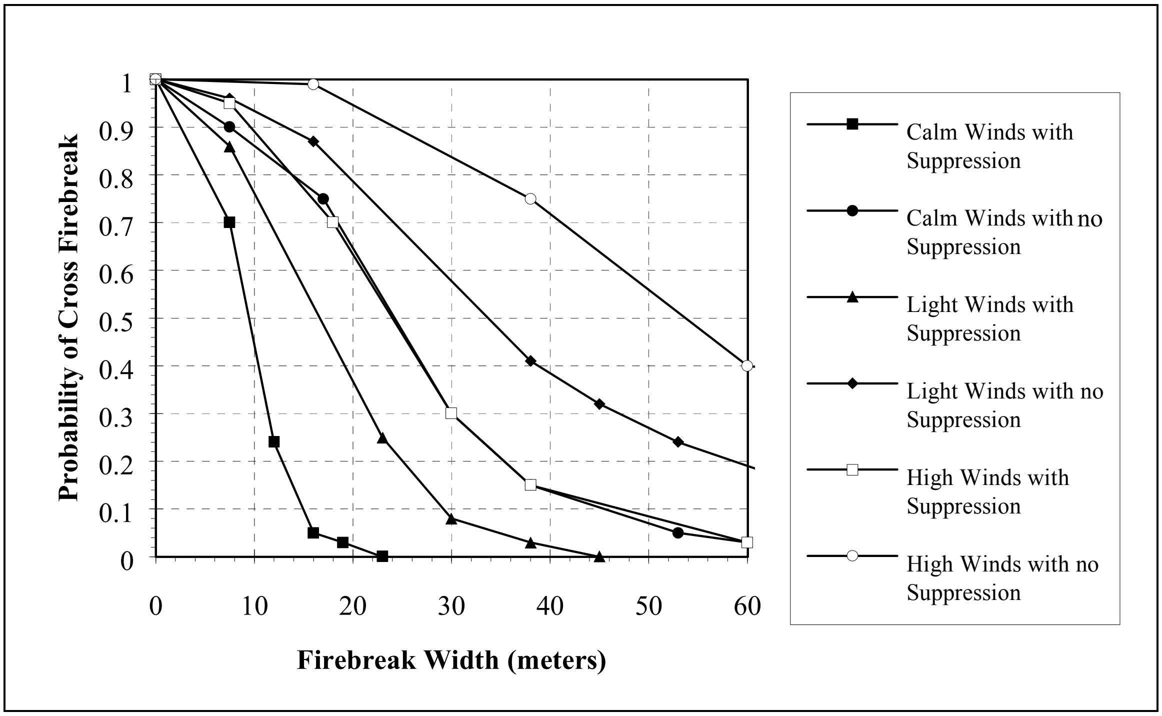


Figure 10.5 Probability of Crossing Firebreak.

10.3 Guidance for Expert-Generated Estimates

As described in Section 10.2, the FFE model makes several simplifying assumptions about the study area. Any or all of these assumptions can be relaxed, and the resulting FFE model will be more refined. The reader may adjust the model by relaxing the following assumptions:

- Analyze the actual water system, for each pressure zone. Many water systems are made up of dozens of pressure zones, many interdependent upon each other. With zone-by-zone information, the analysis can much better identify which parts of the study area are most prone to conflagration.

- Adjust the model for urban intermix fuels, if these conditions are applicable to the study area. Fire spreads are much higher in these areas than in urban areas. The analysis will have to digitize in the fuel mix for each cell of the model, and adjust the fire spread model accordingly.

- Add high flow water system boundaries to the model. In some areas of the city, the water system may be designed to provide very high flows: 24" diameter (or larger) transmission pipes (with hydrants) which carry flows on the order of 20,000 gpm or higher. If there are adequate fire department resources available, then almost any fire can be stopped at these locations, even under relatively high winds. Of course, the Water System Lifeline module will have to also be analyzed to determine if these pipes break under the earthquake.

10.4 References

Dames and Moore Report, March 1987. "Fire Following Earthquake, Estimates of the Conflagration Risk to Insured Property in Greater Los Angeles and San Francisco," Report to All-Industry Research Advisory Council, C. Scawthorn.

G&E Engineering Systems Inc., 1994. "Earthquake Loss Estimation, Technical Manual, Fire Following Earthquake", Prepared for the National Institute of Building Sciences, Principal Investigator: John M. Eidinger.

Hamada, M., 1975. "Architectural Fire Resistant Themes", No 21., Kenchikugaku Taikei, Shokokusha, Tokyo.

International Conference of Building Officials, Uniform Fire Code, 1991.