# MODELLING EARTHQUAKE-INDUCED FIRE LOSS

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## SUMMARY

Fire loss following earthquake is influenced by three vectors: ignition frequency (number of fires started initially), conflagration potential ("free-field" fire spread), and fire loss suppression (actions of firefighters). Procedures available for modelling each of the three influences are reviewed, and an ignition frequency estimate for typical west coast construction is presented. The key influence is the conflagration potential, and urban areas may fall into three categories. Many have such a low potential that serious loss is unlikely. Other have an intrinsically high potential and nothing short of rezoning can prevent serious fire loss. Finally, there is a middle ground, in which engineering actions may be effective at mitigating loss.

## INTRODUCTION

There is a prevailing belief that fire following earthquake may be a severe indirect loss. This is a result perhaps of our experience in the San Francisco 1906 and the Tokyo 1923 earthquakes. Several loss scenario studies have, roughly, used an extrapolation of the 1906 experience. However, there exist direct contra-indications, such as San Fernando 1971, in which resulting fire loss was minimal even though numerous ignitions were reported. The fire loss is influenced by three vectors, as outlined in the summary above. The serious loss incidents are likely to be predicted by high conflagration potential more than anything else. Upon so decomposing the problem, a more accurate understanding of fire loss can be achieved. In the absence of such an understanding it would be largely fruitless to propose, say, the hardening of water lines. In an urban area with high conflagration potential fire spread will likely occur i) if the fire companies become saturated with initial ignitions, which they almost surely will, and/or ii) if they fail to reach an ignition within a very short period of time. At the other extreme, in an urban area with low conflagration potential little spread will take place, and the hardening would be unjustifiable as an expense.

The overall problem has received considerable attention in Japan, where the research is more advanced than in the United States. Scawthorn has distilled that research and presented some powerful studies of seismic risk analysis incorporating fire loss (Refs. 1 and 2). There is an additional body of Japanese language reports (such as Ref. 3) which have been generated over the years.

## ESTIMATION OF FIRE SPREAD

Fire spread refers to the growth of a fire in an urban area following a specific ignition. It results from house-to-house ignition, from burning vegetation, and (in its most extreme forms) from development of fire storms. The spread type of greatest interest to engineers and planners is the house-to-house ignition, which is generally caused by one of three mechanisms: radiation, firebrands, or flame impingement. Fire spread is essentially a result of the "fuel layout" of the area--the buildings, their materials, their spacing, and so on. It is further influenced by temperature, humidity, and wind conditions. Essentially, it pictures the propensity of an urban area to burn, its conflagration potential.

In our estimation, this is the single most important factor governing fire loss following

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earthquake. Many cities intrinsically have minimal conflagration potential.. Even if numerous ignition were set all would die out shortly with little fire spread. Urban areas with widely spaced dwellings and little brush would fall into this category. A full fire spread model (were it to exist) would demonstrate spread to be nil, as do field observations of actual fires. For instance, the fires following the San Fernando 1971 earthquake produced little damage, primarily because they were not spreading.

On the other hand, some urban areas or neighborhoods experience conflagration very readily and, in real time, quickly. Typically such cities have closely spaced dwellings of highly combustible construction; Japanese urban areas are clear examples. In the United States certain recent fires (older construction in New England or townhouse construction in Texas) also demonstrate the potential for conflagration as determined largely by the fuel layout. Note that fire suppression (firefighters with rapid access and adequate water) is hardly an agent in preventing the development of such conflagrations.

It is our judgement that many urban areas may fall at one extreme or the other, with the following observations:

- In areas with minimal conflagration potential earthquake-induced fire losses are likely to remain low, and it is not likely that engineered improvements for fire suppression would be needed.

- In areas with ;high conflagration potential very high fire losses can be expected, and it is not likely that engineering improvements for fire suppression would reduce those losses. However, those losses could be reduced in the long term by planning (zoning) actions, or by the development of strategies (such as firebreaks) to control the almost-certain conflagration.

Of course, some areas may have an intermediate conflagration potential, at which the presence of fire suppression services may be of marked significance. For such areas the continued performance of water supply may indeed control the resulting loss. Also note that the conflagration potential of certain urban areas may fluctuate seasonally from very low to very high, as a function of humidity, temperature and vegetation.

Basically, the items which influence conflagration potential are well defined. An experienced student of fire patterns (and the author is not in that category) can identify those factors, measure them, and come to a reasonable conclusion regarding conflagration potential. While this is perhaps the most appropriate way to examine the problem, there also exist analytical or empirical models for fire spread, as discussed below.

## Earlier Fire Spread Models

The most succinct model available is the Hamada fire spread model (Ref. 4) which is a semi-empirical model derived for a uniform grid of Japanese house construction. The independent variables are the building spacing, the building height, the mix (proportion) of one and two story buildings, and the wind velocity. It predicts a set of three fire front velocities (downwind, upwind, athwart the wind) which spread in an ellipse-like fashion. The burn area (or number of units burnt) therefore increases with time. This model does permit a full picture of fire loss for that particular construction type; unfortunately, we have no counterpart for U.S. construction types. The Hamada model has been employed in many Japanese studies, and in the important work by Scawthorn (Refs. 1 and 2).

In the United States substantive modelling efforts were undertaken in research programs on fire loss following nuclear blast including work at URS, SRI, and IITRI. Those studies include review of analytical models, theories for probabilistic models, and some detailed case studies. However, no existing model has the facility to permit rapid, inexpensive fire spread analysis such as provided by the Hamada model.

## State Transition Models

Fire spread through a grid can also be modelled as a probabilistic transition process, if one knows the probability that an unburnt neighbor will be ignited by a burning building; we will denote that transition probability as PT. Monte-Carlo analysis can be used to trace the history of burns in a grid (Ref. 6). Typically one applies initial ignition with frequency PI, and observes the trend of the final burn frequency PF. Figure 1 shows typical plots of PF versus PI and PT. The author has demonstrated, for an orthogonal grid in which each building has four neighbors, an approximate solution in the form

$$(1-PF) = (1-PI)\ [(1-PF) + PF(1-PT)]^4 \tag{1}$$

While this equation is of some interest, it requires some restrictive assumptions. It is presented for the interest of readers, but is not necessarily recommended for use.

The challenge in applying this method is in identifying the transition probability, PT, which will depend upon the building types and the separation distance. Aoki (Ref. 7) has proposed one model for this process, and estimated the transition probabilities from actual field data of fires for nine different building type pairings. Figure 2 illustrates his results for spread from wooden construction to wooden construction. The transition probability is 0.5 (or greater) for separation distances less than 3.0m; it drops below 0.2 at a separation distance of 5.3m.

A model has also been developed by Berlin and partly developed in the course of this research program. The model predicts the time history of fire growth in a building for several key building types such as mobile home, single family, low rise (ie, townhouse), assembly plant, and so on. Berlin further extended these models to predict spread from building to building in a grid. Figure 3, demonstrating results from that analysis, is introduced in a later section of this paper to illustrate suppression activities.

## ESTIMATION OF INITIAL IGNITION FREQUENCY

In modelling fire loss the analyst must estimate the initial ignition frequency as a function of earthquake intensity. The ignition frequency is clearly influenced by the sources present in the structures prior to the shaking. In modern dwellings likely sources include gas line breaks, electrical shorts, pilots, compressors, flammable liquids, and so on. Given the complexity of the ignition mechanism, it is obvious that field data would very valuable, and a fair amount of such data is available.

## Previous Work

The most copious data have been generated in Japanese experiences. The Tokyo earthquake of 1923 has been the starting point for most studies. Those studies introduced a convention which persists through the present work: the ignition frequency is compared (on a scatterplot) with the damage frequency, or destruction frequency, of the building stock. That is, the damage frequency is taken as a surrogate for earthquake intensity. Initial ignition frequency is also of interest to researchers studying fire following nuclear blast, and workers in that field have already studied the earthquake data. In a 1965 report, McAuliffe and Moll (Ref. 8) review the Japanese data and present the sparse data from several U.S. earthquakes such as San Francisco 1906, Long Beach 1932, Anchorage 1964, and so on. They report that the ignition frequency is smaller than the damage frequency by some two orders of magnitude. They also review the ignition sources; some 52% of the fires were caused by heating/cooking equipment, flammable liquids, gas, and appliances, while some 18% were electrical in nature. A 1981 report by Wilton, Myronuk and Zaccor (Ref. 9) updates the record with data from San Fernando 1971 and other earthquakes. A detailed set of modern studies have been authored in Japan by Mizuno and Horiuchi (Ref's 10 and 11). They review the influence of time-of-day, season, occupancy types, and so on.

In summation, scatter plots are available from Japanese experience, and isolated data points exist from U.S. experience. All results show an ignition frequency smaller by some two orders of magnitude than the direct damage frequency. One objective of the research program was to present a "best estimate" for ignition frequency for a prototypical west coast neighborhood type. This was performed using elicitation of expert opinion.

## Ignition Frequency Estimation for a West Coast Prototype

Denoting the initial ignition frequency as $\phi$, and the direct damage frequency as $\theta$, Figure 4 reproduces the major portion of the scatterplot from Ref. 11. The data are from Japanese earthquakes in locations where the housing stock was relatively typical. In our estimation, the scatter in Figure 4 can be taken as representative of the ignition process itself, with little scatter from other variables.

A group of fire science researchers were assembled at a FEMA Conference in 1982, and served as experts. They were presented with an information package consisting of:

1. The scatterplot in Figure 4.
2. A brief statement of U.S. experience.
3. An architectural description of the typical Japanese dwelling including its likely ignition sources.
4. A parallel architectural description of the prototypical west coast dwelling including its likely ignition sources.

The thirty experts were told to take Figure 4 as representative of experience for the Japanese dwelling, and were then asked to translate the experience to the west coast prototype. The analysis was performed by Chaloner and Duncan assuming that for an individual expert the uncertainty in $\phi$ at a specific value of $\theta$ can be adequately modelled with a Weibull distribution. The mean estimates were calculated for each expert, with a least squares fit yielding:

$$\log \phi = -3.13 + 0.54 \log \theta \qquad (2)$$

That is, under conditions of full destruction ($\theta = 1$) the ignition frequency is $\phi = 0.00074$. In an earthquake which destroys 10% of the buildings is a neighborhood, the ignition frequency is only $\phi$=0.00021. We consider this result to represent the best current estimate for ignition frequency in U.S. residential construction.

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The standard error of the estimated intercept is 0.16 and of the estimated slope is 0.08. The regression standard deviation is S equals 0.54 and the coefficient of determination is R-squared equals 40.7 percent.

## ESTIMATION OF FIRE LOSS SUPPRESSION

Fire loss suppression refers to the control of fires by actions of the fire department once a fire develops. Lifeline engineers have expressed some concern over the fire losses which may develop if water supplies are cut off, or if transportation is slowed or halted. Please note that water supply is only one component of fire loss suppression, one which may well never be the governing factor. Some fundamental common-sense arguments should establish that.

### Saturation and Limitations of Service

An urban area will have a finite number of fire companies. For instance, in 1974 Denver had 46 fire companies (27 engines, 17 ladders, 2 rescue) for some 500,000 population, which equated to more than 100,000 buildings. The common dispatching procedure is to send 3 engines and 2 ladders to each alarm. If this is followed, there is available one full team for every 10,000 dwellings. If an earthquake damages 10% of all buildings, equation (2) predicts an ignition frequency of 0.00021, or more than two ignitions for each full team. Even though the ignition frequency is low, it will readily saturate fire department services in any damaging earthquake.

This observation holds even more strongly when numerous real aspects of the earthquake aftermath are considered. It is not clear that fire fighters would even be dispatched to fight fires when they may be needed to protect lives in other actions such as rescue.

There are also limits to the suppression that can be achieved. Fire department operations are usually predicated upon reaching a fire as soon as possible and fighting it can still be contained. Once a fire exceeds a certain size, the firefighters basically have to let it burn out while they minimize the danger of spread. While one can propose alternate strategies for firefighting (self-help teams, alternate dispatch procedures to prevent saturation, etc.) they are beyond the scope of this paper, and they have the danger of compromising fire safety under non-earthquake conditions. In summary, the possibility of saturation seems very high.

### Modelling of Fire Suppression

The effect of fire suppression would enter the analysis process within the fire spread model. A dynamic spread model is required, and there must be an algorithm for "assignment" (in O-R terms) of fire suppression activities. Finally, there must be an explicit mathematical statement of the suppression activity influence. These elements do not exist, and a large-scale suppression analysis was not carried out.

However, the trends can be readily demonstrated in smaller scale fire spread analyses. Figure 3 plots the fire spread history, as programmed by Berlin. There was "one fire service" local to the grid region, with a programmed response. Basically, two ignitions were set, and the grid (because of its close 2m spacing) was predicted to have a 24% burn after 5 hours in the absence of any suppression. However, the one fire service was capable of arresting some fires, and brings the burn history nearer to that experienced following a single ignition. Similar results (not shown) show the influence of grid spacing, of local versus distant fire series (increasing the travel time) and of wind conditions.

## CONCLUSIONS

The elements governing fire loss have been reviewed, and some sample modelling procedures have been described. We do not have, at present, a model which would yield a meaningful analysis for any urban area. However, the most important determinations can be made without a precise analytical model. Our recommendation is that an urban area first be evaluated for conflagration potential, as judged by an experienced fire scientist. The following actions are the recommended:

- Areas with high conflagration potential: These areas face high loss if struck by a damaging earthquake. Estimation of ignition frequency (Eq. 2) would be a sufficient scenario to convince most experienced fire safety professionals. The remedies include rezoning, emergency response plans (as in wartime to combat incendiary bombing raids), or other strategic planning.

- Areas with low conflagration potential: It is likely that fire loss will not be high, and is probably not a top priority for seismic safety planning. However, circumstances which may alter the conflagration potential should be carefully monitored.

- Other areas: Planners should try to identify which elements are on the "critical path" for loss reduction. While water supply comes to mind for most engineers there are several other effects (saturation, dispatch and transportation delays, etc.) which may govern instead.

## ACKNOWLEDGEMENTS

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This research effort was further made possible by sincere interest and generous assistance from many, many researchers in the fire science and earthquake engineering communities. Dr. Charles Scawthorn shared with us his background and experience on the whole problem of fire following earthquake. Jim Kerr, of FEMA, invited us into the community of researchers studying fire following nuclear blast, welcoming our participation in three annual workshops held at Asilomar. Numerous researchers within this country (Stan Martin, Chuck Wilton, and many others) and abroad (Dr. Kobayashi and others) shared their perspectives and skills with us unstintingly. Their kindness was exemplary, and I remain in their debt.

## REFERENCES

1. Scawthorn, C., "Lifeline Effects on Post-Earthquake Fire Risk", ASCE TCLEE Conference, Oakland, CA, August 1981.

2. Scawthorn, C., Yamada, Y., and Iemura, H., "A Model for Urban Post-Earthquake Fire Hazard," DISASTERS

3. Horiuchi, S., "Research for the Forecasting of the Damage due to the Fire after a Large Earthquake in Kyoto City," see note.

4. Horiuchi, S., "The Speed of Fire Spreading in a Section of a Town Consisting of Wooden Buildings," Kenchiko Bouka. see note.

5. Hahl, R., "DCPA Fire Research Bibliography," DCPA-RE-24, January, 1976 (Summarizes DCPA research from FY 1962 to 1975 and lists the reports.)

6 Schmidt. L., "Parametric Study of Probabilistic Fire Effects." Institute for Defense Analysis, IDA P-1372, Arlington, VA, September 1979.

7. Aoki, Y., "A Stochastic Model for Fire Spread in an Urban Area," see note.

8. McAuliffe, J., and Moll, K., "Secondary Ignitions in Nuclear Attack," OCD 2534A, SRI, 1965.

9. Wilton, C., Myronuk, D. and Zaccor, J., "Secondary Fire Analysis," Work Unit 2564I, Scientific Service, Inc., Redwood City, CA, 1981.

10. Mizuno, H., and Horiuchi, S., "On the Prediction of Fire Outbreaks Caused by the Earthquakes," see note.

11. Mizuno, H., and Horiuchi, S., "The Relationship Between the Rate of Fire Outbreak and the Rate of Complete House Destruction Following an Earthquake," see note.

Note: Unedited translations of these reports are available, at cost, from the author of this paper.

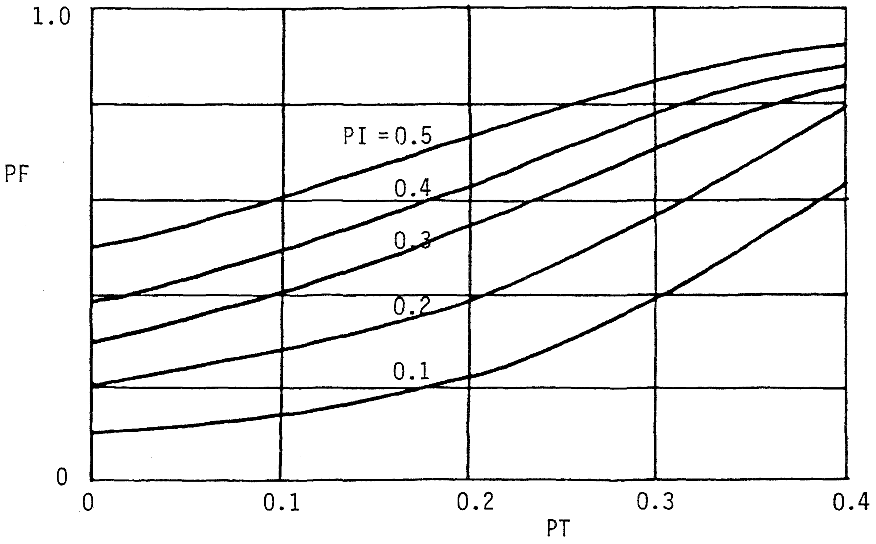

Figure 1. Average Final Burn Frequency, from Ref. 6.

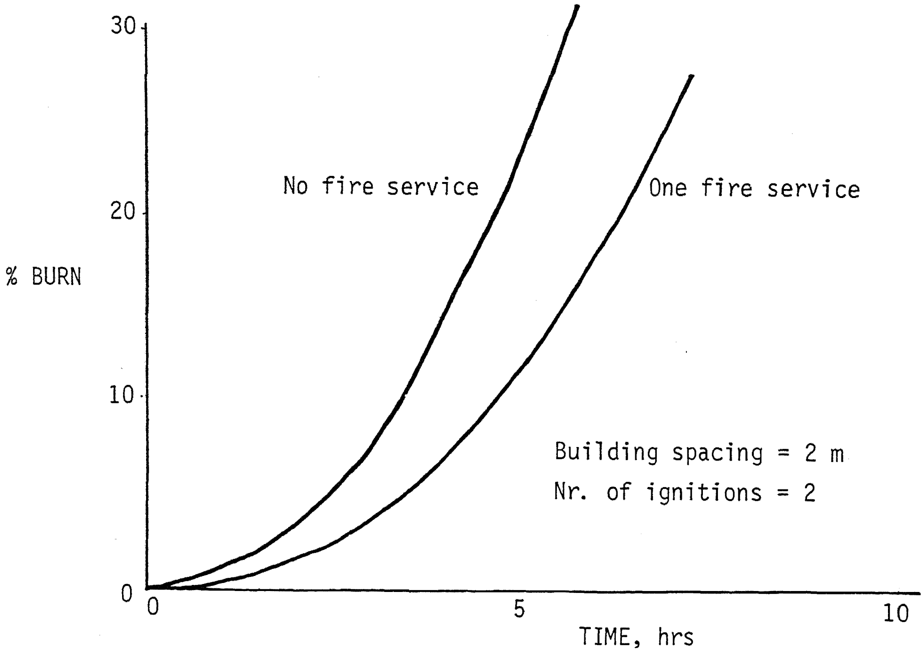

Figure 3. Typical Time History of Fire Spread

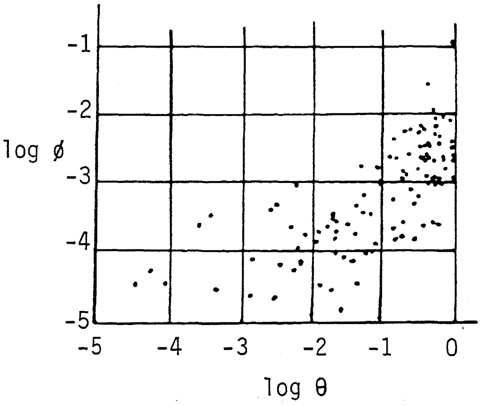

Figure 2. Ignition Frequency (Ref. 11.)

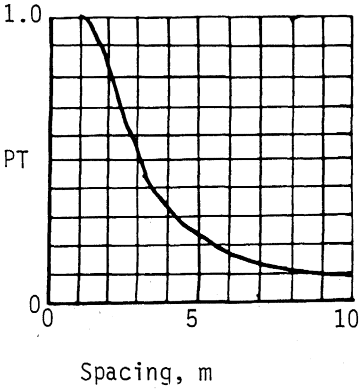

Figure 4. PT (Ref. 7.)