SPA Risk LLC

21 March 2008

Mr. Rod Erickson
Applied Technology Group
PBS&J
482 S. Keller Rd.
Orlando, FL, 32810

Re: Fire Following Earthquake, Enhancements in HAZUS-MH
SPA Project No 10010-01-07-01

Dear Rod,

Enclosed please find our report for the subject project. We appreciate the opportunity to work on this project, and look forward to your comments. Please don't hesitate to call or write if you have any questions.

With Best regards,

Charles Scawthorn, Principal

SPA Risk LLC

Enhancements in HAZUS-MH

Fire Following Earthquake

Prepared for

PBS&J

and the

National Institute of Building Sciences

21 March 2008

SPA Project No. 10010-01-07-01

EXECUTIVE SUMMARY

NIBS's objectives are to review and update the fire following module of HAZUS-MH based on newer technology and to correct anomalies indicated by previous validation studies and beta testing.

A review of the current HAZUS-MH fire following earthquake methodology presented in section 2 of this report, and finds that the current methodology was developed more than a decade ago and does not take advantage of data and experience from more recent events, particularly the 1994 Northridge (US), 2001 Nisqually (US), 2003 and San Simeon (US) events. The ignition data is employed in a limited statistical way, with no use of sub-jurisdictional data (e.g., deaggregation of the data by cause of ignition). Derivation of the ignition rate employed an MMI-PGA conversion which may be in conflict with current relations which form the basis for ShakeMap and other tools, with which HAZUS-MH is being linked. Fire spread is modeled using traditional empirical methods based on Japanese data and was not validated against US experience (e.g., the 1991 East Bay Hills fire). Details regarding the simulation and temporal calculation of fire spread are not fully documented and appear to often be based on judgment (e.g., probability of crossing firebreaks). An explicit estimation of suppression requirements is provided, but its linkage with other parts of HAZUS-MH is unclear. There has been no recent validation of the methodology's results, and the validation performed in the late 1990s (which would appear to still apply) found lack of consistency in the estimation of ignitions, and some odd results.

The current state of the art for modeling of fire following earthquake is presented in section 3. Section 4 employs a qualitative benefit-cost analysis to extract from the current state-of-the-art the most appropriate program for improving HAZUS. Section 5 then present a technical scope of work for that program, with section 6 structuring that program into a four year plan for improving the current HAZUS-MH fire following earthquake model, consisting of (Year 1) an enhanced Ignition model using more recent data, considering building damage, and using non-earthquake fire data to more accurately weight or otherwise factor ignition rates; (Year 2) Modeling of the Discovery, Reporting and Response phase to take account of new and emerging technologies in the fire service that are not reflected in the current model. Response modeling is proposed to be enhanced, using approximate or detailed GIS transportation network modeling to estimate fire service response; (Year 3) Fire spread modeling will undergo a major improvement, accomplished by adapting physics based modeling to develop equations similar to Hamada's but used in a new computational framework (e.g., cellular automata), calibrated for US conditions (similar to the work of (Cousins 2003) and reflecting branding and the effects of vegetation; (Year 4) integration of the previous work into a working prototype model, which will be used for final testing and validation. The model development team will have close links to the fire community, from which an eminent Advisory Panel is proposed.

Each year's deliverables will be a stand-alone incremental improvement in the HAZUS-MH fire following earthquake model, validated and documented that year and ready for incorporation in HAZUS at that time. Year 4's work on model integration will address overall model integration and validation, and also numerical simulation/computational aspects in order to achieve acceptable overall accuracy and performance.

The above scope of work is proposed to be performed by **SPA** Risk LLC leading a project team consisting of individuals with specialized knowledge and experience in modeling of fire following earthquake. The proposed scope of work and cost estimate for the development and implementation of the new Fire Following Earthquake Model is detailed in section 6.

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Revision History

Rev.	Date	Comment
0.9	11 Feb 08	Draft for Review
1.0	14 Feb 08	Initial Release
1.1	21 Mar 08	Revised in response to comments, added Proposed Scope of Work, Schedule and Budget, and Project Team

Glossary

ASCE	American Society of Civil Engineers
CA	Cellular Automata
FEMA	Federal Emergency Management Agency
GIS	Geographical Information System
GPS	Geographical Positioning System
NFIRS	National Fire Incident Reporting System (see www.usfa.dhs.gov/**nfirs**/)
NFPA	National Fire Protection Association
NIBS	National Institute of Building Sciences
NIST	National Institute of Standards and Technology
TCLEE	Technical Council of Lifeline Earthquake Engineering (part of ASCE)
UAV	Unmanned Aerial Vehicle
WUI	Wildland Urban Interface

1 INTRODUCTION

1.1 Purpose

NIBS's objectives are to review and update the fire following module of HAZUS-MH based on newer technology and to correct anomalies indicated by previous validation studies and beta testing. In support of those objectives, this report reviews the current HAZUS-MH methodology for fire following earthquake and the current state of the art with regard to fire following earthquake, in order to provide guidance on revision and enhancement of existing HAZUS methodologies, recommend new methodologies be developed to replace existing based on newly available information.

1.2 Organization of the Report

Following this Introduction, the next section reviews the current HAZUS-MH fire following earthquake model, identifying a number of features that are out of date or otherwise in need of improvement. Section 3 then provides a detailed discussion of various possible improvements for the fire following earthquake model. Section 4 qualitatively evaluates these improvements, which forms the basis for a recommended program of enhancements for the current model. Section 5 presents a detailed technical scope of work consistent with the priorities arrived at in Section 4 and HAZUS' needs. Section 6 then presents the schedule and budget for a four year program to perform the technical scope of work. Section 7 presents brief biodata and qualifications for the team we propose to perform the work, and is followed by References and figures.

2 CURRENT HAZUS-MH FIRE FOLLOWING EARTHQUAKE METHODOLOGY

This section reviews the current HAZUS-MH fire following earthquake methodology, as presented in Chapter 10, *Induced Damage Models - Fire Following Earthquake, of the HAZUS-MH MR2 Technical Manual MR3* (FEMA 2003) (excerpts from Chapter 10 are *italicized*).

Based on a review of earlier editions (FEMA 2001a), the fire following earthquake aspects of HAZUS do not appear to have been updated since the late 1990s.

2.1 Overview

The current HAZUS-MH fire following earthquake methodology follows parts of an approach first developed in the late 1970s and presented in 1981 (Scawthorn and Yamada 1981; Scawthorn et al. 1981). That approach treated the fire following earthquake phenomenon for the first time as a stochastic process comprised of the following phases:

1. Occurrence of the earthquake
2. Ignitions due to the earthquake
3. Discovery of fire due to the ignitions
4. Report of the fire to the fire service
5. Response of the fire service
6. Spread of the fires
7. Suppression of the fires by the fire service (or, eventual extinguishment of the fires due to lack of fuel)

Phase 1, Occurrence of the Earthquake, is performed by HAZUS-MH and treated elsewhere in the Technical Manual, and will not be discussed further here.

Specifically, based on ground motions and building inventory, HAZUS-MH treats the fire following earthquake phenomenon in three phases:

- *ignition*
- *spread*
- *suppression*

and provides the user with the following estimates:

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

The goal is *"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"*.

The analysis is based on the following input data:

- *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.

No information is provided with regard to specifics of the simulation – for example what parameters (e.g., ground motion, ignition rate, wind speed, wind direction) are treated as random variables.

2.2 Ignitions

Ignitions as used in HAZUS-MH follows previous usage and "*refers to each individual fire that starts (ignites) after an earthquake that ultimately requires fire department response to suppress*".

Estimation of ignitions in HAZUS-MH follows most previous practice and is empirical, based on 30 data points from ten US events (see Figure 1): San Francisco 1906; Long Beach 1933; San Francisco 1957; Alaska 1964; Santa Rosa 1969; San Fernando 1971; Coalinga 1983; Morgan Hill 1984; Whittier 1987; Loma Prieta 1989.

Three events provide the bulk of the ignition data, Figure 2, with one of these events (1906) having occurred more than 100 years ago. The last event on which the current HAZUS-MH is based occurred in 1989.

Because most of the ignition data used for developing the HAZUS-MH ignition rate relation was available only in MMI, the development of the current HAZUS-MH model converted MMI intensity data to PGA data, using a table as shown in Figure 3. The source of this conversion is not discussed. Several relationships exist to convert from MMI to PGA, among them (Murphy and Obrien 1977; Trifunac and Brady 1975; Wald et al. 1999). Wald et al is the most recent, uses by far the most data, and is the basis for USGS ShakeMaps and other seismic tools. Figure 4 presents the comparison of the MMI-PGA conversion used in HAZUS-MH with those cited above. The HAZUS-MH conversion compares reasonably well at low-moderate intensities, but is significantly lower than (Wald et al. 1999) at higher intensities – at MMI VIII for example, the HAZUS conversion estimates PGA of 0.36g while (Wald et al. 1999) relation corresponds to 0.44g. Using the ignition rate formula of HAZUS-MH (eqn. 10-1), the ignition rates at MMI VIII differ by 33%, Figure 5. Because the HAZUS-MH ignition rate formula is a second order polynomial, the ignition rate at MMI IX (when converted using Wald et al) is lower than at MMI VIII.

About 70% of the estimated ignitions are assumed to occur shortly after the earthquake. However, no information is provided as to the temporal distribution of the remaining 30%.

2.3 Spread

Fire spread in the HAZUS-MH model is based on the Hamada equations, developed based on Japanese data (Hamada 1951). Probability of crossing firebreaks is based on data taken from (Scawthorn 1987), with an assumed pattern of firebreaks (e.g., *the model assumes that every fifth fire break is three times wider than the average city street fire break*).

2.4 Suppression

The suppression phase as employed in HAZUS-MH includes some of the phases as defined above. These phases, and our comments, are:

2.4.1 Discovery Time.

*Elapsed time from the start of the fire until the time of the first discovery which results directly in subsequent suppression action…*85% discovered with 5 minutes, and 100% within 10 minutes.

2.4.2 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.

Five report modes (cell and normal telephone systems, citizen alert, fire service and aircraft) of reporting are assumed, with the mode resulting in the quickest report assumed to function, although no time data for these various reporting modes is presented. In US earthquakes, most reports have been either by self-dispatch of the fire service or still alarm (*citizen alert*).

2.4.3 Arrival Time.

Elapsed time from the report time until the beginning of effective work on a fire.

HAZUS-MH typically assumes fire apparatus respond within 2-12 minutes.

2.4.4 Control Time.

Elapsed time from the beginning of effective work on a fire to when the fire is controlled.

An extended discussion is provided in the HAZUS-MH Technical Manual, involving number of fire engines required to suppress a fire (Figs. 10-3 and 10-4, source not provided), and the corresponding water requirements. The implication is that the control time is derived from this data, although precisely how this is derived is not presented.

2.4.5 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.

No information provided, except that for room and contents fires (i.e., small fires), the engine is held at the location for 10 minutes.

2.5 Validation

No information on validation of the HAZUS-MH fire following earthquake methodology is presented in the Technical Manual. However, NIBS sponsored a Validation Study of an early version of the HAZUS Earthquake model (FEMA 2001b), which found:

> *HAZUS did not consistently predict the number of fire ignitions region wide. It may be difficult to determine what should be considered a single ignition. The more important statistic, however, is that HAZUS predicts a high potential dollar loss caused by fires. These predictions are much larger than documented losses. The exception is the Napa earthquake for which HAZUS predicted 386 fires with no dollar loss. It should be noted that HAZUS predicts only the potential for loss, assuming a wind speed, fire engine response time, etc., and that all the buildings in the burned area are a total loss. A more detailed study might explore the actual conditions at the time of the earthquakes with the predicted parameters*

Figure 6 presents a table of comparative analysis in re HAZUS-MH fire following earthquake results, taken from the Validation Study. Whether the fire following earthquake aspects of the current version of HAZUS-MH have been updated or modified since that early version of HAZUS, is unknown.

2.6 Summary Review

The HAZUS-MH fire following earthquake methodology was developed more than a decade ago and does not take advantage of data and experience from more recent events, particularly the 1994 Northridge (US), 2001 Nisqually (US), 2003 and San Simeon (US) events[1]. The ignition data is employed in a limited statistical way, with no use of sub-jurisdictional data (e.g., deaggregation of the data by cause of ignition). Derivation of the ignition rate employed an MMI-PGA conversion which may be in conflict with current relations which form the basis for ShakeMap and other tools, with which HAZUS-MH is being linked. Fire spread is modeled using traditional empirical methods based on Japanese data and was not validated against US experience (e.g., the 1991 East Bay Hills fire). Details regarding the simulation and temporal calculation of fire spread are not fully documented and appear to often be based on judgment (e.g., probability of crossing firebreaks). An explicit estimation of suppression requirements is provided, but its linkage with other parts of HAZUS-MH is unclear. There has been no recent validation of the methodology's results, and the validation performed in the late 1990s (which would appear to still apply) found lack of consistency in the estimation of ignitions, and some odd results.

[1] Additionally, selected foreign events, particularly the 1995 Kobe (Japan), 1999 Chichi (Taiwan), 2004 Niigata Chuetsu (Japan) and 2007 Niigata Chuetsu Oki (Japan) events, which have occurred in modern urban areas, may offer some useful data.

3 FIRE FOLLOWING EARTHQUAKE – THE STATE OF THE ART

This section discusses the state of the art of fire following earthquake analysis today, with comments in re HAZUS at key points. The discussion is structured according to the key phases of the fire following earthquake process noted earlier.

3.1 Ignitions due to the earthquake

Fire following earthquake begins with ignitions so that ignition rates are a key element in the process. Ignition rates were discussed in an American Society of Civil Engineers Technical Council on Lifeline Earthquake Engineering (TCLEE) Monograph on fire following earthquake (Scawthorn et al. 2005), hereafter referred to as "TCLEE Monograph", which treated ignition rates in a similar fashion as treated in HAZUS-MH (i.e., statistically), but also explored them in more detail. For example, detailed data from a NIST-sponsored study of the 1994 Northridge earthquake (Scawthorn et al. 1998), as well as data developed by the Tokyo Fire Department, were used to characterize ignitions and/or ignition rates by:

- Location of the ignition
- Cause of the ignition
- Material first ignited
- Time of day (see for example Figure 7)
- Season (see for example Figure 8)

More detailed estimation of ignition rates taking these factors into account would improve the accuracy of HAZUS-MH estimates.

Other approaches than statistical have been applied to estimate ignition rates. For example (Williamson and Groner 2000) employed a systems approach for the analysis of post-earthquake fire safety, based on the "Fire Safety Concepts Tree" developed by the National Fire Protection Association (NFPA) for fire protection in structures. This was enhanced with Scenario-based Goal Decomposition (SGD) and Influence Diagrams to allow the calculation of probabilities and a general model of fire ignition related to gas and electrical service during earthquakes.

However, most available post-earthquake ignition models are essentially regression models relating some measure of ignition frequency to some measure of earthquake intensity. (Ren and Xie 2004) however also provide a method to estimate the ignition rate in particular buildings within each area unit, based on their relative estimated "fire risk." Because the temporal distribution of ignitions is critical to the fire following earthquake problem, several recent models have estimated the time at which each post-earthquake ignition occurs. (Li and Jiang) assumes that ignitions follow a Poisson distribution in time as well as space; (Zhao et al. 2006) assume ignition times follow a Weibull distribution. A key issue not adequately explored in any of these statistical studies is the general omission of 'zero ignition' data – that is, only instances of ignition are included in the data.

The HAZUS-MH model can be improved by more detailed use of the data for several events – specifically the 1971 San Fernando, 1989 Loma Prieta and 1994 Northridge earthquakes. These three modern events account for 318 ignitions, Table 1, but comprise only 13 data points in the relation underlying the entire HAZUS-MH fire following earthquake model.

Table 1 Selected Ignition Data Summary – 3 US events

Event	No. Ignitions	Data Points in Hazus
1971 San Fernando	149	5
1989 Loma Prieta	59	8
1994 Northridge	110	not considered
Total	**318**	**13**

Most striking perhaps in the development of ignition rates has been the lack of consideration non-earthquake fire data. NFIRS is a repository of literally millions of fires and ignition data, which has not been at all employed for the study of fire following earthquake ignitions[2]. A melding of the two data sets, using a Bayesian framework, will likely produce a much more robust and detailed image of the fire following earthquake ignition distribution.

Furthermore, it should be realized that, prior to HAZUS-MH, a full and integrated building shaking damage and fire following earthquake model were not feasible. However, HAZUS-MH is an integrated model – in some ways, the only one of its kind. Therefore, ignition rates in HAZUS-MH should be based on building damage, or a combination of building damage and shaking intensity, not just on seismic intensity. The first correlations of fire following earthquake were based on building damage, not intensity (Mizuno 1978) in recognition that fires were as much, or more, a function of building damage as seismic intensity. HAZUS-MH permits estimates of ignition to be based on building damage, not simply intensity, and this capacity advantage should be taken of.

Lastly, HAZUS-MH also offers the advantage of modeling of gas and electric utility damage. Integration of utility damage and fire following earthquake models has not previously been possible, but similar to the discussion above regarding building damage, HAZUS-MH provides estimates of the damage to gas lines, and the performance (ie, outage, and restoration) of electricity. Outage of electricity reduces ignition rates, while gas utility damage increases ignition rates. These effects are estimated in HAZUS-MH, albeit often in only an approximate manner, but still omitting this data only impoverishes the HAZUS-MH ignition rate estimates.

In summary, our recommendation is that HAZUS-MH can be significantly enhanced by a more detailed ignition model, based on a combination of (1) use of more detailed recent post-earthquake ignition data, (2) case-by-case use of systems approaches (particularly for industrial fires) for development of ignition models, (3) correlation of ignition rates with HAZUS-MH estimates of building damage, (4) similar correlation with HAZUS-MH utility damage, and (5) use of information from non-earthquake fire data.

Specifically, we recommend that a study be performed to develop a new ignition algorithm for HAZUS-MH. The study would combine the several approaches as follows:

(1) Collect and employ all available post-earthquake ignition data – emphasis would be on recent US events (e.g., including 1994 Northridge as well as 2000 Nisqually and other events) but would also selectively employ data from Japanese, New Zealand and other events. Precisely how non-US data would be employed would be determined once the data is collected and assessed.

[2] NFIRS is a large dataset of 'ordinary' fires, including earthquake-related fires although these are a tiny fraction – most of the data is for non-earthquake related ignitions. However, NFIRS is of great value – for example it can be used to provide information on sources of ignition, on fire spread, and on effectiveness of fire suppression.

(2) For selected cases, such as water heaters in single family dwellings, a systems approach should be employed, similar for example to the approach employed by Williamson and Groner, 2000). Due to the data and other demands for this approach, it can only be employed in a few cases, where the number and similarity of equipment installations justifies the effort. For such cases, typical installations will be reviewed and sample relevant data, such as mass, attachments, fragilities, and failure of fuel lines, will be collected and used to develop a model that can then be used to assess likelihood of fuel release and ignition.

(3) HAZUS-MH estimates of building damage will be employed as an independent variable for estimation of ignition rates, as opposed to ground motion. It is well-known that building damage is probably a better correlate than ground motion (although ground motion is usually employed due to lack of good estimators of building damage).

(4) Similarly, ignitions will be correlation with HAZUS-MH estimates of gas and power utility damage.

(5) Information from non-earthquake fire data, particularly the NFIRS data set, will be employed to enhance the detail of the earthquake related ignition estimates.

(6) All above methods will be combined in an event tree framework, to develop a multi-phased algorithm for estimation of ignition. Care will be taken to avoid double-counting between the overlapping ignition algorithms. The result will be a hybrid multi-phased algorithm for estimation of ignitions (hybrid refers to semi-empirical, and semi-analytical), which will allow estimation of ignitions under existing conditions, and under changed conditions (e.g., bolting of water heaters, or installation of gas seismic shut-off valves).

3.2 Discovery, Report and Response of the fire service

Relatively little work has been done on this aspect of the fire following earthquake problem, so that the current HAZUS-MH fire following earthquake model is typical of the state of the art, which can be characterized as simplistic assumptions regarding discovery, reporting and response. These assumptions should be replaced by distributions of fire growth and reports based on non-earthquake and earthquake-related data, respectively. The 1994 Northridge dataset (Scawthorn et al. 1998) is sufficient for this purpose.

Regarding fire service response, again, travel times (or, travel speeds) are assumed in the current model. Since HAZUS-MH is GIS based and develops estimates of building and transportation damage, internal cross-linking of these capabilities should be taken advantage of. That is, HAZUS-MH estimates of building and transportation damage should be included in estimation of travel times. Ideally, travel times should be calculated using actual GIS transportation network data, not “adjusted straight line” distance. The ArcGIS platform has a network capability, and street data is available, that allows precise calculation of least-distance routes. This approach, combined with some incorporation of census tract damage levels to approximate debris blockage of streets, is the most rational and direct approach, although also the most data- and computationally-intensive approach. Due to data and computational approaches, it may not be feasible to fully implement this approach in the next generation fire following earthquake model, although this should be explored, in collaboration with the HAZUS programming team and perhaps also ESRI. However, even if technically feasible, this approach may not be practical for all users (again, due to data and other demands), so that the more simplified ‘adjusted straight line” approach will need to be retained. However, while retaining the simplified approach for at least Level 1 users, we recommend it be enhanced by incorporating census tract damage levels (in an algorithm that combines damage and building density) to provide an approximation of transportation network impediments. Damage to the transportation system itself should also be incorporated. The final decision as to whether Level 2 uses a full network analysis capability will require further work during initial development.

However, the real future for HAZUS-MH has to do with the impacts the IT revolution is having on emergency responders. Incorporation in HAZUS of new IT developments in the fire service would be of great benefit for the fire service and emergency management community. That is, GIS, GPS, UAV and other developments are now entering the fire service operational mainstream, and will have a major influence on future responses to fires following earthquake, which should be reflected in new HAZUS-MH modeling.

In many ways, GIS has already entered the fire service mainstream, especially with regard to wildland fires, where it has been used for the last decade for real-time fire growth estimation, for response planning purposes (Figure 10). GPS is also being used, to track fire service apparatus as well as for locational purposes in aerial observation. Heretofore, aerial observation of fires following earthquake has largely been ineffective, due to lack of experience by fire service personnel as well as lack of georeferencing. However, the new frontier for emergency services is unmanned aerial vehicles (UAV) – that is, pilotless drone aircraft with television cameras that relay GPS geo-referenced information on fires, accidents and other incidents to central emergency operations centers, from which emergency responders are dispatched to the scene. This is an emerging technology that will quickly a routine emergency response tool for day-to-day operations, and which should reduce discovery and reporting times for fires following earthquake.

In summary, discovery, reporting and response modeling in HAZUS-MH can be improved via (1) changes that IT advances are making in fire reconnaissance and reporting, and (2) use of HAZUS-MH GIS-generated response data that approximately or realistically reflects actual travel paths and damage to the transportation network.

3.3 Spread (including Suppression)

As noted above, HAZUS-MH without discussion uses the Hamada equations to model urban fire spread. Fire spread is discussed in the TCLEE Monograph where the TOSHO model (Tokyo Fire Department 1997) is presented as an incremental improvement over the Hamada equations. The Monograph also recognizes emerging developments in physics-based modeling of urban fire spread, for example (Himoto and Tanaka 2002; Woycheese et al. 1999), analogous to the work of (Rothermel 1972) and later workers (Weise and Biging 1997) for wildland fires. The current HAZUS-MH model also includes effects of suppression, albeit in a simplified manner.

Fundamentally, the HAZUS-MH model can be improved in the following ways:

3.3.1 Calibration of Empirical Fire Spreading for US conditions

The only corroboration of the Hamada equations for US conditions was by (Scawthorn 1987), which is also presented in the TCLEE Monograph. He compared estimates of fire spreading velocity using the Hamada equations, with US conflagration data, and found general agreement with the exception of spread via branding among wood buildings under high winds. A more detailed examination of the Hamada equations, against empirical US fire spread experience is warranted, particularly the highly relevant data from the 1991 East Bay Hills fire, which destroyed over 3,500 buildings.

3.3.2 Incorporation of Branding and Vegetation

Branding refers to the spread of fire by windborne flaming debris from an existing fire. Branding is a very significant factor in conflagrations, which has been the subject of much research (Cohen 1995; Cousins 2003; Huang et al. 2003; Pagni and Woycheese 2000; Shiraishi et al. 2001; Tran et al. 1992; Woycheese and Pagni 1998; Yoshioka et al. 2003) and which should be included in HAZUS-MH.

Beyond branding, the effects of vegetation, particularly in modeling urban conflagrations in the arid Western US, should be taken into account. This needs to be incorporated in the HAZUS-MH model, not only to permit more accurate modeling at the wildland urban interface (WUI), but also within the urban region itself (LAFD, personal communication).

3.3.3 Physics-Based Approach[3]

The Hamada equations provide an approach that was the only computationally feasible approach until recently. However, cities are much less homogeneous than assumed in the Hamada equations, and more detailed data on fuel variation is available in the GIS-based HAZUS-MH than is currently being used.

A physics-based model that analyzes fire spread to a neighboring building has been developed by (Himoto and Tanaka 2002). Fire spread is modeled as a function of: (1) radiation, if the incident heat flux exceeds a critical value, (2) convection, if the surface temperature of an exterior wooden wall exceeds a critical value, and/or (3) branding, if a brand of sufficiently high energy state contacts the building. The Himoto/Tanaka model requires detailed information about the geometric configuration and material in each building, but relatively few simplifications about the process of fire spread.

A physics-based model has been developed by (Cousins et al. 2002) that simplifies the evolution of a fire within a building so that the progress from unburned to fully burned depends only on elapsed time. Rules of fire spread are developed separately for each type of fire spread (e.g., radiation with piloted ignition, branding) based on simplifications of the physics of those modes and historical experience. The evolution of fire spread is also modeled by (Iwami et al. 2003) based on elapsed time, but state transition times depend on assumed heat generation vs. time curves developed for each building type. The temperature of each building is estimated at each time step based on the estimated heat flux it receives due to radiation from flame and convection. A building is assumed to ignite if a flame touches it or if its temperature exceeds a critical temperature. The ResQ Firesimulator similarly simplifies physical laws to derive rules that address each mode of fire spread separately (Nussle et al. 2004). It has the unique feature of treating each building as a unit of analysis, but then modeling the air as a two-dimensional grid overlain on the buildings. The temperature of each air cell is tracked, and they are allowed to move with respect to the buildings to represent the existence of wind.

Earlier fire spread modeling was at a relatively large scale (e.g., city block, or neighborhood) and assumed that each fire would spread within that unit in the shape of an ellipse. More recent efforts use much smaller scale simulation approaches using cellular automata, based to some extent on Huygens' Principle and the work of (Richards 1988; Turcotte and Malamud 2004). Cousins et al. (2002) and Ohgai et al. (2004) use cellular automata (CA), in which the

[3] This section is based to some extent on S. Lee, R. Davidson, N. Ohnishi and C. Scawthorn, *Fire Following Earthquake – Reviewing the State-of-the-Art of Modeling* (submitted for publication)

landscape is divided into equally-sized grid cells, each of which is in one of a few states (e.g., not burnable, burning, fully burned) at each time step. As time is incremented, the cells change state according to rules, which are based on the current states and other attributes (e.g., building density) of the cell and its neighboring cells. Others using the CA approach include (Lee and Davidson 2006; Tani et al. 2000)

A key benefit that a physics-based model offers for HAZUS-MH is a more detailed modeling that reflects building configurations, material properties, and location. The models are better grounded in theory, so that more accurate estimates of fire spread can be expected. Figure 13 for example shows CA modeling of urban fire growth for a Japanese city, from ignition to 110 minutes, while Figure 14 shows the results of a CA model showing variation of fire spread depending on windspeed and direction. Most importantly, physic-based models can be used to realistically model the effects of suppression. On the other hand, the physics-based approach requires detailed data and computation. As seen from the above discussion, physics based modeling can either be used directly, or employed to develop rules for fire spread analogous to the Hamada equations, but specific to the US urban context.

3.3.4 GIS data

In parallel with the development of data-demanding physics-based models for fire spread, is the rapid emergence of high resolution GIS building inventories and related data. Figure 12 is an example of building footprint data, which can be used in combination with physics based fire spread for detailed fire following earthquake modeling. This kind of data is increasingly becoming widely available, not just in 2D but also in 3D, Figure 15.

In summary, modeling of fire spread in HAZUS-MH can benefit by a fresh approach involving one or more of the following aspects: (1) adaptation or development of equations analogous to the Hamada equations, appropriate for US conditions and based on the wealth of US conflagration data; (2) incorporating effects of branding and vegetation in the fire spread model; (3) employing physics based modeling, either in detail or using a hybrid approach, whereby the physics based modeling is combined with empirical data; (4) using cellular automata, agent-based modeling or similar computational methods; and (5) in concert with the more detailed computational methods, using the rapidly emerging next generation of GIS-based building data.

3.4 Fire Service Involvement

A failing in the development of the HAZUS-MH model was the lack of involvement of fire service personnel. This omission resulted in a failure to properly reflect fire department operations, and emergency response needs. Also as a result, HAZUS-MH has had no champions among the fire service, who are largely unaware of its existence, and the potential utility of its outputs. If the HAZUS-MH model is to be significantly upgraded, the technical development team should include several persons from and/or involved with the fire community, such as one or several fire officers (preferably with IT experience).

3.5 Reporting

HAZUS-MH currently provides the user with the following estimates:

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

For HAZUS-MH to be more useful, fire following earthquake reports should be developed in conjunction with the fire service. Examples of an enhanced report that would be of value includes:

- *an estimate of the number and **mapped distribution** of serious fire ignitions that require fire response after a scenario earthquake*
- ***maps of fire growth with time**, analogous to Figure 13*
- *a **built-in what-if analysis capability**, to examine the effects of various assumptions and conditions*
- ***mapping of evacuation routes** given fires, and other building and transportation damage*
- *a report on **water used for suppression***
- *a report on **apparatus and staffing needs***
- *an estimate of the total burned area*
- *an estimate of the population and building exposure affected by the fire*
- *since simulation is employed for the fire following earthquake modeling, **a probabilistic distribution of losses, or some indication of confidence bounds on the results**.*

3.6 Validation

As noted above, the only validation of the HAZUS-MH fire following earthquake modeling was performed about a decade ago, with a poor showing. A key to enlisting users is demonstrating the accuracy and validity of the model. Any development to improve the HAZUS-MH model should include validation, by comparison of the model with actual fires following earthquake, and the larger non-earthquake fire experience base.

We recommend validation using a modular approach: (a) for ignitions, recent earthquake-related data will be employed as a benchmark; (b) for fire spread, non-earthquake-related data will be employed. (c) similarly for suppression, non-earthquake related data will be employed.

4 RECOMMENDED PROGRAM

This section presents recommendations for enhancing HAZUS-MH based on the previous discussion.

4.1 Comparative Analysis

The various improvements to the HAZUS-MH fire following earthquake model discussed above are summarized in Table 2, which characterizes their Benefits and Costs, and the resulting Benefit / Cost, of each action in terms of High, Medium and Low,. These assessments are qualitative in nature, but provide some guidance as to which improvements may be the most beneficial.

Table 2 Qualitative Benefits / Costs of HAZUS-MH Fire Following Earthquake Model Improvements

Model Phase	Improvement	B	C	B/C
Ignition	Detailed/recent data	H	L	**H**
	Systems approach	M	H	**L**
	Correlate ignition with building damage	H	L	**H**
	Correlate ignition with utility damage	M	H	**L**
	Use non-earthquake fire data	H	L	**H**
Discovery, Reporting and Response	Reflect IT advances	H	L	**H**
	Use GIS modeling for Response	H	M	**L-M**
Fire Spread	Calibrate / Adapt FS Eqns. for US conditions	H	L	**H**
	Model Branding and Vegetation	H	L	**H**
	Correlate spread given water system damage	H	L-M	**M-H**
	Physics Based Modeling	H	M	**M**
Fire Service	GIS Data	H	H	**L**
Reporting	Involve Fire Service personnel	H	L	**H**
Validation	Enhance reports, on advice of fire service	H	L	**H**
	Perform Validation Studies	H	M	**M**

B: Benefit (H,M,L); C: Cost (H,M,L); B/C (H,M,L)

4.2 Recommended Improvements

What emerges from Table 2 is the following outline of a program for improving the current HAZUS-MH fire following earthquake model:

- The ignition model should be updated using more recent data, and some effort should be made to utilize the data in a more detailed fashion, per the discussion regarding Table 1. The correlation should consider building damage, and use non-earthquake fire data to more accurately weight or otherwise factor the ignition rates.
- Modeling of the Discovery, Reporting and Response phase should take into account new technologies adopted by the fire service, or soon to be adopted, that are not reflected in the current model. Some investigation should be made into using GIS transportation network modeling to estimate fire service response, although this may be beyond the scope of the current HAZUS-MH concept.

- Fire spread modeling needs a major improvement, which can be accomplished by adapting physics based modeling to develop equations similar to Hamada's but used in a new computational framework (e.g., cellular automata), calibrated for US conditions (similar to the work of (Cousins 2003) and reflecting branding and the effects of vegetation.
- The development team should include or have close links to the fire community. That community should advise development of better reports.
- At least some effort should be made for validation of the resulting model.

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5 SCOPE OF WORK FOR A NEW FIRE FOLLOWING EARTHQUAKE MODEL

In order to implement the above recommended program, we propose a scope of work consisting of four major tasks:

Year 1. Ignition Modeling

Year 2. Modeling of the Discovery, Reporting and Response Phase

Year 3. Fire Spread Modeling

Year 4. Model Integration

to be performed over a four year period.

5.1 Ignition Modeling

In Year 1, the ignition model will be updated using more recent data, and some effort should be made to utilize the data in a more detailed fashion, per the discussion in section 3.1 and Table 1. The correlation should consider building damage, and use non-earthquake fire data to more accurately weight or otherwise factor the ignition rates. Specifically, we propose to:

(1) **Data Collection**: Collect and employ all available post-earthquake ignition data – emphasis will be on recent US events (e.g., including 1994 Northridge as well as 2000 Nisqually and other events), with a more detailed discretization of data for regression purposes. We also propose to collect and selectively employ data from Japanese, New Zealand and other events. Precisely how non-US data would be employed would be determined once the data is collected and assessed but this data may prove useful in assessing industrial and commercial ignitions, where differences in construction are less. It will also provide additional information on relative sources of ignition, and variation of ignitions with season and time of day. The product of this subtask will be a comprehensive data set on all relevant post-earthquake ignitions.

(2) **Statistical Analysis**: The collected data will be statistically analyzed in several ways. Most basically, it will be employed in empirical regression, with independent variables being ground motion, and/or building damage. The current model does not have building damage as a independent variable, and we believe that building damage is a better correlate than ground motion. For selected events, where building damage is not available for correlation purposes, HAZUS will be used to hindcast building damage. Correlation will not be at the jurisdictional level but rather at the census block group or census track level, including consideration of zero ignition data. In addition to building damage, utility performance (gas, power) will also be examined as an additional independent variable. The product of this subtask will be a set of new equations for estimation of ignitions following earthquakes, as a function of building damage and other parameters.

(3) **Analytical Approach**: For selected cases, such as water heaters in single family dwellings, a systems or analytical approach should be employed, similar for example to the approach employed by Williamson and Groner, 2000). Due to the data and other demands for this approach, it can only be employed in a few cases, where the number and similarity of equipment installations justifies the effort. For such cases, typical installations will be reviewed and sample relevant data, such as mass, attachments, fragilities, and failure of fuel lines, will be collected and used to develop a model that can then be used to assess likelihood of fuel release and ignition. As a test case, we propose

to use this approach for residential water heaters, collecting data on typical residential systems and modeling the water heater system as a physical model that can be subjected to dynamic ground motions in a systems model that permits estimation of gas line leakage. The product of this subtask will be a probability of gas leakage and ignition for residential water heaters.

(4) **Non-Earthquake Ignition Data**: Information from non-earthquake fire data, particularly the NFIRS data set, will be examined for opportunities to enhance the detail of the earthquake related ignition estimates. NFIRS data will be combined with fire following earthquake data in a Bayesian approach. The product of this subtask will be an investigation, and possible enhancement, of the limited fire following earthquake ignition data, with a much larger non-earthquake data set.

(5) **Synthesis and Final *Hybrid* Algorithm:** All above methods will be combined in an event tree framework, to develop a multi-phased algorithm for estimation of ignition. Care will be taken to avoid double-counting between the overlapping ignition algorithms. The result will be a *hybrid* multi-phased algorithm for estimation of ignitions (hybrid refers to semi-empirical, and semi-analytical), which will allow estimation of ignitions under existing conditions, and under changed conditions (e.g., bolting of water heaters, or installation of gas seismic shut-off valves).

The product of this task will be a report documenting the state of the art, all available data, and an examination of several complementary approaches to develop a new hybrid approach for estimation of fire following earthquake ignitions. The hybrid algorithm will be provided in the form of equations and associated tabular or other data, appropriate for programming into HAZUS.

5.2 Modeling of the Discovery, Reporting and Response phase

Year 2 will address the Discovery, Reporting and Response phases of the fire following earthquake process. Because the effort for these tasks is somewhat less than the work required for development of the fire spread model, Year 2 will also initiate data collection efforts for the fire spread model (discussed in section 5.3, however).

Discovery and Reporting: Rapid reporting and response is crucial to control of fires, whether or not in an earthquake. Fire reporting under non-earthquake conditions has changed significantly in the last several decades, and today relies heavily on the telecom system as well as a higher degree of automated reporting. In order to understand how earthquakes may impact current reporting methods, data will be collected on fire reporting statistics. NFIRS and selected sampling with local fire department statistical bureaus (e.g., San Francisco, Los Angeles, smaller departments in other parts of the US as well as California) will provide the basis for this. Statistics will be developed on the various modes of reporting, and each mode will be examined to estimate its effectiveness in the post-earthquake environment. Additionally, all fire following earthquake ignitions will be examined to determine how they were reported. Thirdly, various fire departments will be surveyed as to special operations or capabilities they may currently have, or that are "in the pipeline", that may enhance reporting. Examples include aerial observation (fire department helicopters, UAV, liaison with police or news helicopters), organized citizen response (CERT), cooperation with building security industry, etc. Lastly, fire department dispatch center procedures and command and control procedures will be reviewed with regard to report traffic control – saturation of dispatch centers has been observed in all past earthquakes, and needs to be considered in modeling. The product of this subtask will be an improved algorithm for estimation of temporal distribution of fire report reception.

Response: All else being equal, response of fire apparatus to fires depends on travel routes and speeds, which are a function of the transportation network following the earthquake. Ideally, network analysis of the transport network should be performed for each response, using existing GIS network technology and taking into account reduced travel speeds (and possible need for alternative routes) due to debris and damage. This approach will be explored with the HAZUS programming team, perhaps in consultation with ESRI. However, even if feasible, at least for Level 1 a simpler algorithm similar to the current assumptions may need to be employed. Even so, this algorithm will be enhanced by incorporating building damage along the travel routes, and possibly also by incorporating transportation network damage. The product of this subtask will be an enhancement of the current algorithm, by incorporation of building damage impacts on the transport network, and some incorporation of damage to the transport network itself. An additional product of this subtask will be an investigation and report on the feasibility of using a full transport network analysis approach for modeling of response. For this latter aspect, the investigation may find that the algorithms can be easily developed, in which case they will be. Alternatively, it may conclude that more effort is needed, and will lay out the scope and cost for such effort.

The product of this task will be a set of algorithms for use in HAZUS that reflects modern fire reporting methods, and the impacts of earthquakes thereon. Response algorithms will at a minimum be enhanced from the current state by incorporation of building and transportation damage, and may be completely rewritten to be based on detailed transport network analysis.

5.3 Fire spread modeling

In Year 3 fire spread modeling will be significantly enhanced in the new HAZUS model, to move away from empirical (ie, Hamada) equations to be based on a physics-based model, which will allow modeling of a number of factors not currently considered (fenestration, vegetation, cladding, fire suppression, etc). This will be accomplished by:

(1) **Data Collection**: Data on a variety of urban environments will be collected, from inner city to suburban, commercial to residential, and reviewed against HAZUS default data to develop a taxonomy of ‘fire districts’. While there is wide variety of such neighborhoods, we anticipate the result of this subtask will be approximately 10 to 20 typical ‘fire districts’, which can be correlated against HAZUS default data so that HAZUS data can be automatically used to characterize a census tract as being one of the typical fire districts. Level 2 users will be able to override these default characterizations, as explained next. (this subtask will actually be performed in Year 2).

(2) **Physics modeling**: For each type of fire district, physics based fire modeling will be used to develop a series of fire spreading equations. In actuality, the same equations will be used for all districts, but variables such as building spacing, building age, fenestration, wind, mix of buildings (low-rise contiguous to high-rise, or not), cladding materials, street width, vegetation, effect of branding, etc will differ for each district. The result of this subtask will be a set of fire spread equations for each district. Another result of this subtask will be the methodology for developing customized fire spread algorithms for any unique district. Thus, a small application similar to INCAST might be developed, which would allow a local fire department to tailor HAZUS to its situation.

(3) **Suppression**: Similarly, physics-based modeling will be employed to model the effects of various types of suppression, ranging from interior attack, to ‘surround and drown’, to aerial attack, using water and/or foam or other additives.

(4) **Water System Performance**: Incorporation of a full hydraulic model of the existing water system as impacted by earthquake is highly desirable but may be beyond the scope of HAZUS for the near term. However, various hydraulic models are available, ranging from commercial models (e.g., WaterCad) to open source (EPANET) to academic (GIRAFFE) and selected advanced users may wish to use these models in conjunction with HAZUS. We propose to develop a series of approaches – in Level 1, default algorithms will be used to estimate water system performance based on ground failure (an approach not dissimilar to the current approach, but updated and enhanced). In Level 2, the region of interest will be microzoned by users – such microzoning can be based on system expert judgement, or the output of hydraulic models. The product of this subtask will be a set of algorithms that permits default or user-defined modeling of water system performance, as an input for fire spread.

(5) **Spread**: Currently, HAZUS treats each census tract as being of a homogeneous character. This approach will be critically examined, and possibly retained for Level 1 users. In such case, fire spread can be easily handled using the 'average' fire spread equations as derived above. For Level 2 users, however, detailed building data (e.g., see Figure 12) will be available, and a more detailed and accurate cellular automata approach will be employed.

The product of this task will be a next generation set of algorithms for the modeling of urban fire spread, permitting consideration of a number of variables including suppression techniques, appropriate for incorporation in HAZUS.

5.4 Model Integration

This task will integrate the products of the several tasks above, into a working prototype model, for testing and validation purposes. Following testing and validation, the final working prototype model will be provided to the HAZUS programming team, for their use in developing final code.

5.5 Validation

Validation of the models will be performed in each year, in several ways:

(1) **Hindcast**: The working prototype will be used to estimate selected historical earthquake events (e.g., Northridge, but also perhaps selected foreign events such as Kobe), as well as non-earthquake events (i.e., given ignitions), such as the 1984 Baldwin Hills Fire (LA) or the 1991 East Bay Hills Fire (Oakland and Berkeley).

(2) **Exercises**: The working prototype will be used to develop results for a wide range of scenario events, ranging from modest earthquakes to very large events, under varying wind and other conditions. These results will be reviewed for consistency and reasonableness.

(3) **Expert Panel**: While selected fire service and other experts will be involved in the model development as described below, an independent panel comprised of fire service and fire modeling experts will review the model and scenario results in a structured manner. Individuals indicative of Panel Members we would propose include:

- Chief Don Parker (Chief of Department, Vallejo FD, retired, and current Chair, Seismic Safety Commission, State of California)

- Chief Don Manning (Chief Engineer and General Manager, Los Angeles City Fire Department, retired)
- Chief Frank Blackburn (Asst. Chief, San Francisco Fire Department)
- Chief Frank Borden (Asst. Chief., Los Angeles City Fire Department)
- Prof. Pat Pagni, Univ. California at Berkeley, Professor Emeritus of Fire Safety Engineering Science
- John Hall, Ph.D., Assistant Vice-President, Fire Analysis and Research, National Fire Protection Association.
  NFPA

Final membership in the Panel would be determined in consultation with NIBS and FEMA.

5.6 Documentation

Each year's work, and the entire model, including data and validation, will be documented in a technical report suitable for incorporation in HAZUS' Technical Manual.

6 PROJECT MANAGEMENT, SCHEDULE AND BUDGET

This section presents the plans to perform the recommended scope of work over a four year period. We propose that **SPA** Risk LLC manage the project and technical development of the model according to the recommended scope. **SPA** is a limited liability company organized in the State of California, and has performed similar work for a USGS, FEMA-sponsored projects and private industry. Validation and documentation occur in each Year, for the phase of the work performed that year.

6.1 Year 1 Ignition Modeling

Table 4 presents the schedule and budget for Year 1, which focuses on Ignition Modeling as described in section 5.1. Validation would occur via two mechanisms – the ignition algorithms would be tested against historical events, and would also be presented to an expert panel drawn from the fire service. The product of Year 1 would be a written report presenting new ignition algorithms, their background and guidance in their use, suitable for inclusion in the HAZUS Technical Manual and appropriate for implementation by the HAZUS programming team.

6.2 Year 2 Modeling of the Discovery, Reporting and Response Phase

Table 5 presents the schedule and budget for Year 2, which focuses on the fire discovery, reporting and response phase as described in section 5.2. Since this aspect requires less work than is needed for modeling of fire spread, the data collection aspects of fire spread modeling are also performed in Year 2.

6.3 Year 3 Modeling Fire Spread

Table 6 presents the schedule and budget for Year 3, which focuses on modeling of fire spread as described in section 5.3. The data collection aspects of fire spread modeling are performed in Year 2, with analysis, validation and documentation in Year 3.

6.4 Year 4 Model Integration

Table 7 presents the schedule and budget for Year 4, which integrates the prior three years' work. A working prototype is developed during this year, which is used for overall model validation and testing. Numerical aspects of simulation and computational efficiency are also addressed in this year, to achieve acceptable accuracy and performance.

In the following pages, each table details schedule and budget. In summary, the four years require the following effort:

Table 3 Summary Four Year Program

Year	Aspect	Effort (person-days)	Cost ($ thous)
1	Ignition Modeling	110	$125
2	Fire Discovery, Reporting and Response Phases	111	$126
3	Fire Spread	178	$191
4	Model Integration	208	$228
	Total effort	**607**	**$670**

Table 4 Year 1 – Ignition Modeling

Task	1	2	3	4	5	6	7	8	9	10	11	12	Sr.	Proj Engr	Panel
						Month (hrs / month)								Personnel (days)	
1 Ignition Modeling															
1.1 Data Collection															
Senior Personnel	2	2	1	1									6		
Project Engineer/Analyst	4	4	4	3										15	
1.2 Statistical Analysis															
Senior Personnel				1	3	1							5		
Project Engineer/Analyst				3	6	3								12	
1.3 Analytical Approach															
Senior Personnel						1	2						3		
Project Engineer/Analyst						4	6							10	
1.4 Non-Earthquake Ignition Data															
Senior Personnel						1	2	1					4		
Project Engineer/Analyst						4	6	4						14	
1.5 Synthesis and Final Hybrid Algorithm															
Senior Personnel								1	3	1			5		
Project Engineer/Analyst								3	8	3				14	
1.6 Validation (including Fire Service Expert Panel)															
Senior Personnel										2	2		4		
Project Engineer/Analyst										4	4			8	
Fire Service Expert Panel (4 Members)											4				4
1.7 Report															
Senior Personnel											2		2		
Project Engineer/Analyst											4			4	
Total Personnel (days)													29	77	4
Rate ($/day)													$ 1,200	$ 800	$ 800
Labor ($ th)													$ 34.8	$ 61.6	$ 3.2
Project Management (5%)													$ 5.0		
Total Labor ($th)															**$ 105**

Expenses			
Project meetings	1		
panel members	4		
Project staff/meeting	2		
air travel + per diem ($th) / person	$1		
(assume Calif venue)		Total Project Meetings	$6
		Communications and other Travel ($th)	$8
Total Expenses ($th)			**$ 14**
		Overhead (5%)	$6
Total Labor + Expenses ($th)			**$ 125**

Table 5 Year 2 – Modeling of the Discovery, Reporting and Response Phase (and initiation of data collection for Fire Spread)

							Month (hrs / month)							Personnel (days)		
Task		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**Sr.**	**Proj Engr**	**Panel**
2 Discovery, Reporting and Response Phase (and initial work on Fire Spread)																
2.1 Discovery and Reporting																
Senior Personnel		2	1	1										4		
Project Engineer/Analyst		4	4	3											11	
2.2 Response																
Senior Personnel				1	3	3	1							8		
Project Engineer/Analyst				3	6	6	3								18	
3.1 Fire Spread Data Collection (part of Yr 3)																
Senior Personnel								4	4	4				12		
Project Engineer/Analyst								12	12	12					36	
2.3 Validation (including Fire Service Expert Panel)																
Senior Personnel											2	2		4		
Project Engineer/Analyst											4	4			8	
Fire Service Expert Panel (4 Members)												4				4
2.4 Report (Discovery, Reporting and Response Phase)																
Senior Personnel												2		2		
Project Engineer/Analyst												4			4	
Total Personnel (days)														30	77	4
Rate ($/day)														$ 1,200	$ 800	$ 800
Labor ($ th)														$ 36.0	$ 61.6	$ 3.2
Project Management (5%)														$ 5.0		
Total Labor ($th)																**$ 106**
Expenses																
Project meetings	1															
panel members	4															
Project staff/meeting	2															
air travel + per diem ($th) / person	$1															
(assume Calif venue)																
Total Project Meetings																$6
Communications and other Travel ($th)																$8
Total Expenses ($th)																**$ 14**
Overhead (5%)																$6
Total Labor + Expenses ($th)																**$ 126**

Table 6 Year 3 – Fire Spread Model

	Task	1	2	3	4	5	6	7	8	9	10	11	12	Sr.	Proj Engr	Panel
		Month (hrs / month)												Personnel (days)		
3	**Fire spread modeling**															
3.1	Data Collection															
	Senior Personnel		performed in Year 2											0		
	Project Engineer/Analyst														0	
3.2	Physics modeling															
	Senior Personnel			4	4	4	4							16		
	Project Engineer/Analyst			12	12	12	12								48	
3.3	Suppression															
	Senior Personnel						2	2	2					6		
	Project Engineer/Analyst						6	6	6						18	
3.4	Water System Performance															
	Senior Personnel							2	2					4		
	Project Engineer/Analyst							6	6						12	
3.5	Spread															
	Senior Personnel							3	3	3	3			12		
	Project Engineer/Analyst							10	10	10	10				40	
3.6	Validation (including Fire Service Expert Panel)															
	Senior Personnel										2	2		4		
	Project Engineer/Analyst										4	4			8	
	Fire Service Expert Panel (4 Members)											4				4
3.7	Report															
	Senior Personnel											2		2		
	Project Engineer/Analyst											4			4	
	Total Personnel (days)													44	130	4
	Rate ($/day)													$ 1,200	$ 800	$ 800
	Labor ($ th)													$ 52.8	$ 104.0	$ 3.2
	Project Management (5%)													$ 8.0		
	Total Labor ($th)															**$ 168**

Expenses			
Project meetings	1		
panel members	4		
Project staff/meeting	2		
air travel + per diem ($th) / person	$1		
(assume Calif venue)		Total Project Meetings	$6
		Communications and other Travel ($th)	$8
Total Expenses ($th)			**$ 14**
		Overhead (5%)	$9
Total Labor + Expenses ($th)			**$ 191**

Table 7 Year 4 – Model Integration

	Task	1	2	3	4	5	6	7	8	9	10	11	12	Sr.	Proj Engr	Panel
						Month (hrs / month)								Personnel (days)		
4	**Model Integration**															
4.1	Model Integration															
	Senior Personnel	5	5	5	5									20		
	Project Engineer/Analyst	20	20	20	20										80	
4.2	Review and Revision of Simulation Methodology					5	5	5						15		
						20	20	20							60	
4.3	Validation (including Fire Service Expert Panel)															
	Senior Personnel								3	3	3	2		11		
	Project Engineer/Analyst								6	6	6	4			22	
	Fire Service Expert Panel (4 Members)											4				4
4.4	Report															
	Senior Personnel											2		2		
	Project Engineer/Analyst											4			4	
	Total Personnel (days)													48	166	4
	Rate ($/day)													$ 1,200	$ 800	$ 800
	Labor ($ th)													$ 57.6	$ 132.8	$ 3.2
	Project Management (5%)													$ 9.7		
	Total Labor ($th)															**$ 203**

Expenses			
Project meetings	1		
panel members	4		
Project staff/meeting	2		
air travel + per diem ($th) / person	$1		
(assume Calif venue)		Total Project Meetings	$6
		Communications and other Travel ($th)	$8
Total Expenses ($th)			**$ 14**
		Overhead (5%)	$11
Total Labor + Expenses ($th)			**$ 228**

7 PERSONNEL AND PROJECT MANAGEMENT

In order to implement the above recommended program, we propose a team involving the following personnel:

- Project Manager and Technical Director: Dr. Charles Scawthorn
- Project Engineers: Dr. Mohammad Javanbarg; Ms. Selina Lee
- Senior Advisor: Prof. Rachel Davidson
- Quality Assurance: Dr. Keith Porter

In brief:

- Dr. Charles Scawthorn will serve as Project Manager and Technical Director for the project. He is widely recognized for his work since the 1970s in fire following earthquake. Most recently, he had supervised research in regard to fire following earthquake modeling in Japan, while serving as a Professor at Kyoto University, as well as developing fire following earthquake models for the insurance industry. He is the chief Editor and major contributor to a monograph on the topic published by the American Society of Civil Engineers (Scawthorn et al, 2005), and recently provided the fire following earthquake modeling inputs for a major exercise by the state of California.
- Dr. Mohammad Javanbarg will serve as a Project Engineer for the project. He recently received his doctorate from Kobe University, Japan, for research related to "Integrated GIS-Based Seismic Performance Assessment of Water Supply Systems".
- Ms. Selina Lee will serve as a Project Engineer. She is currently a doctoral candidate at Cornell University, working on research related to modeling of following earthquake using cellular automata, under the supervision of Prof. Rachel Davidson. She is co-author with Prof. Davidson and Dr. Scawthorn of a review article on the topic of fire following earthquake.
- Prof. Rachel Davidson (Univ. of Delaware) will serve as a senior advisor to the project. Prof. Davidson has conducted research into fire following earthquake ignitions.
- Dr. Keith Porter will be responsible for quality assurance aspects of the project, by providing an independent review of methods, and results. Dr. Porter is a well-known expert on the topic of earthquake loss simulation, and has worked on modeling of fire following earthquake since the 1990s.

Detailed curriculum vitae are available for these individuals.

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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 1 Ignition data employed in HAZUS-MH

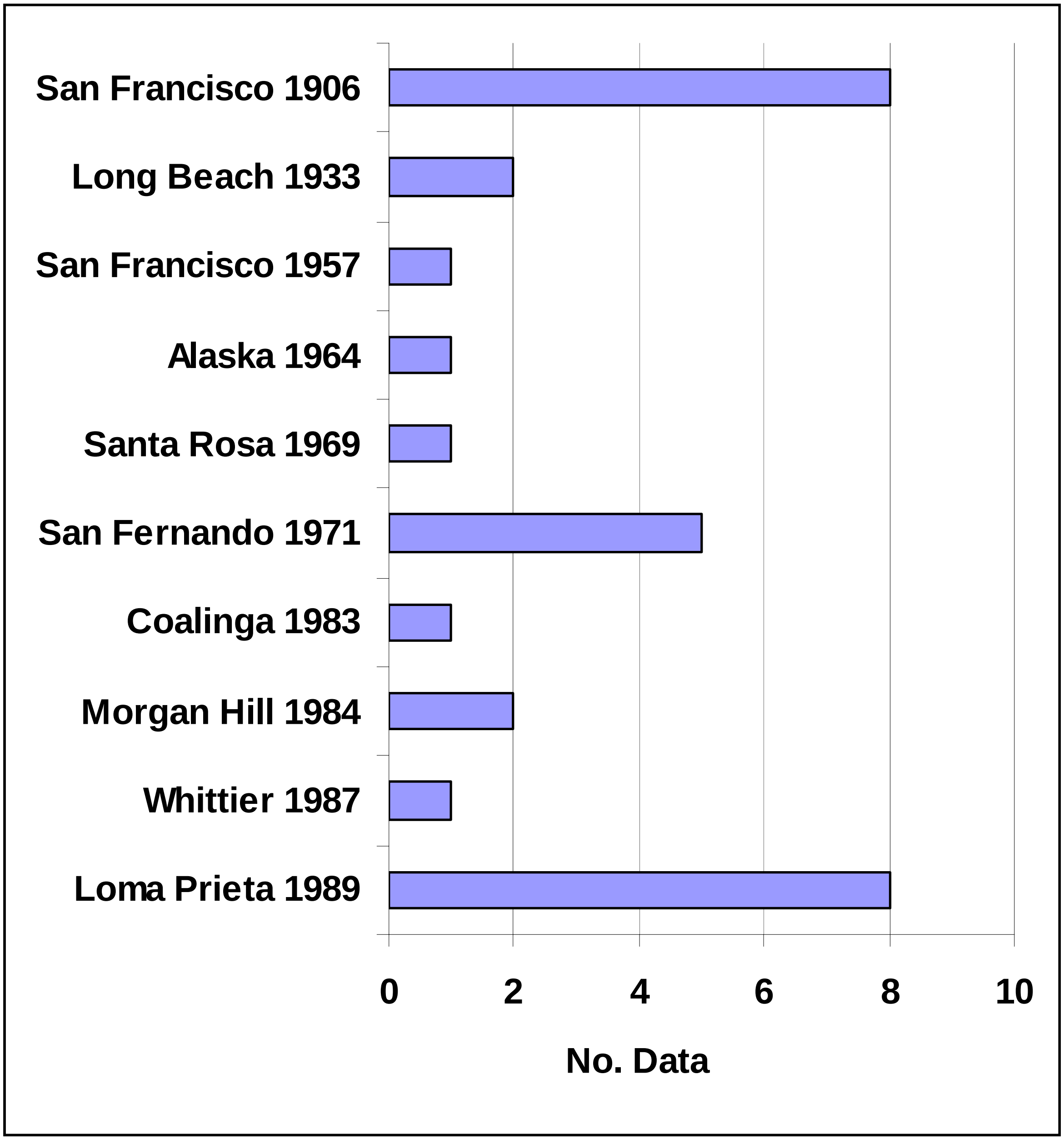


Figure 2 Histogram of Ignition Data used in HAZUS-MH

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

Figure 3 HAZUS-MH MMI-PGA Conversion

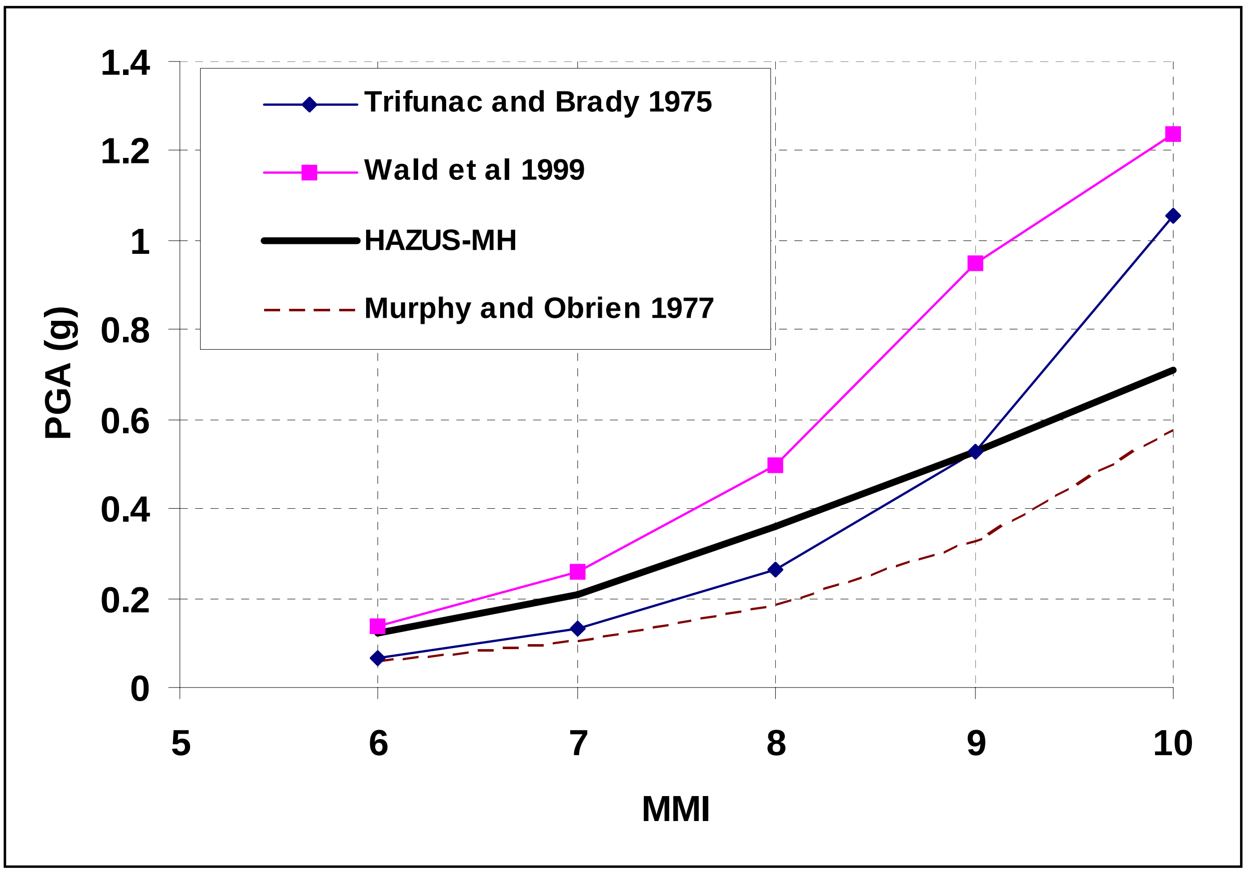


Figure 4 MMI-PGA comparison

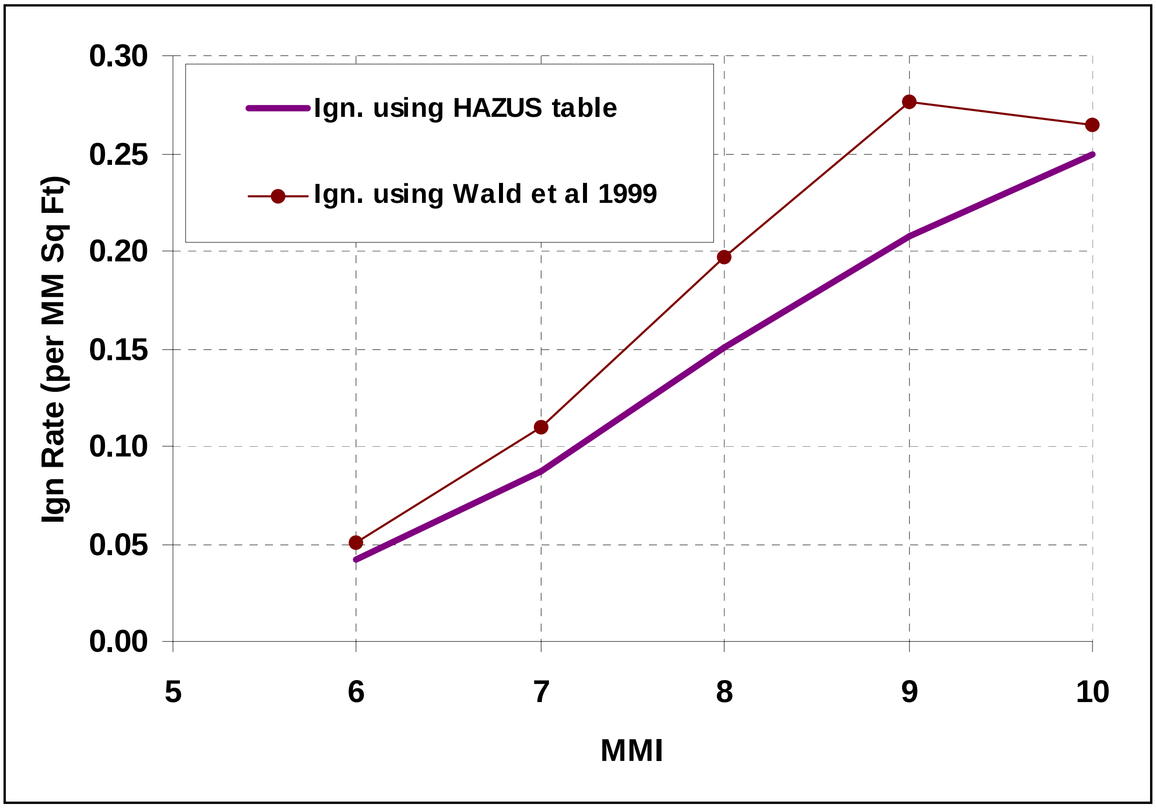
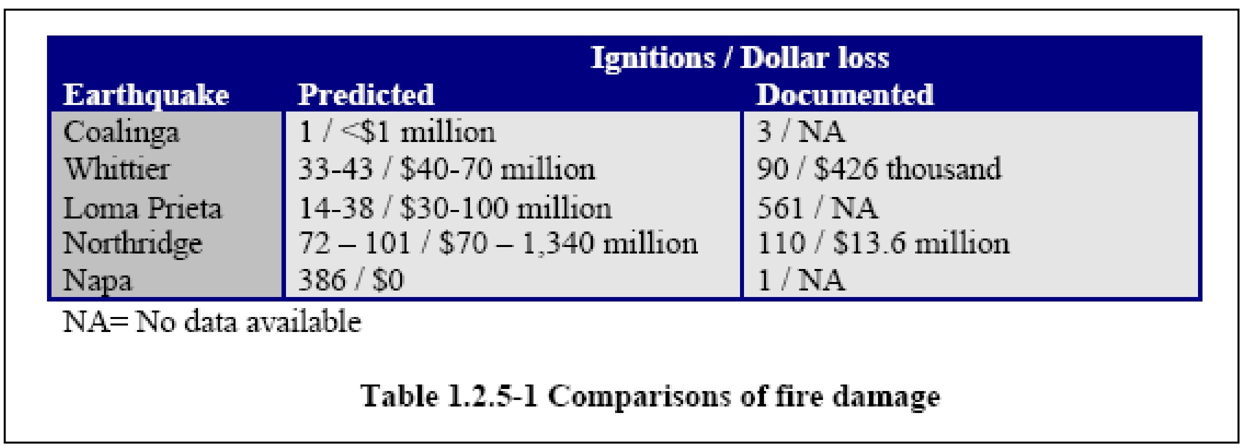


Figure 5 Ignition Rates using two different MMI-PGA conversions



	Ignitions / Dollar loss	
Earthquake	**Predicted**	**Documented**
Coalinga	1 / <$1 million	3 / NA
Whittier	33-43 / $40-70 million	90 / $426 thousand
Loma Prieta	14-38 / $30-100 million	561 / NA
Northridge	72 – 101 / $70 – 1,340 million	110 / $13.6 million
Napa	386 / $0	1 / NA

NA= No data available

Table 1.2.5-1 Comparisons of fire damage

Figure 6 Table of Comparative analysis, NIBS Validation Study (FEMA, 2001b)

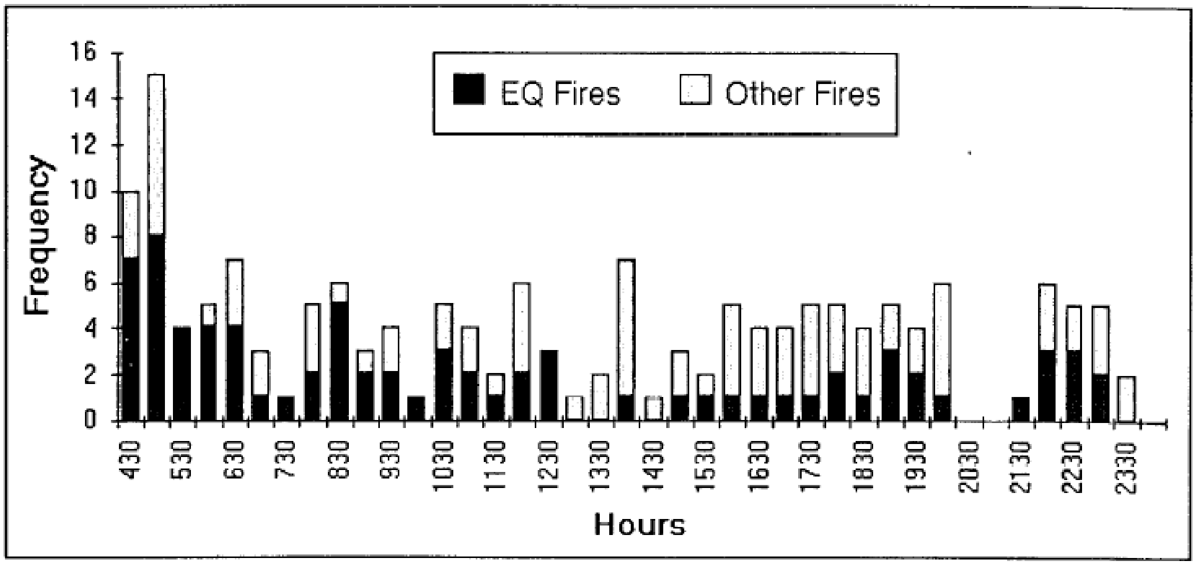


Figure 7 LAFD Fires, Jan 17, 1994 Northridge Earthquake (Scawthorn et al. 1998)

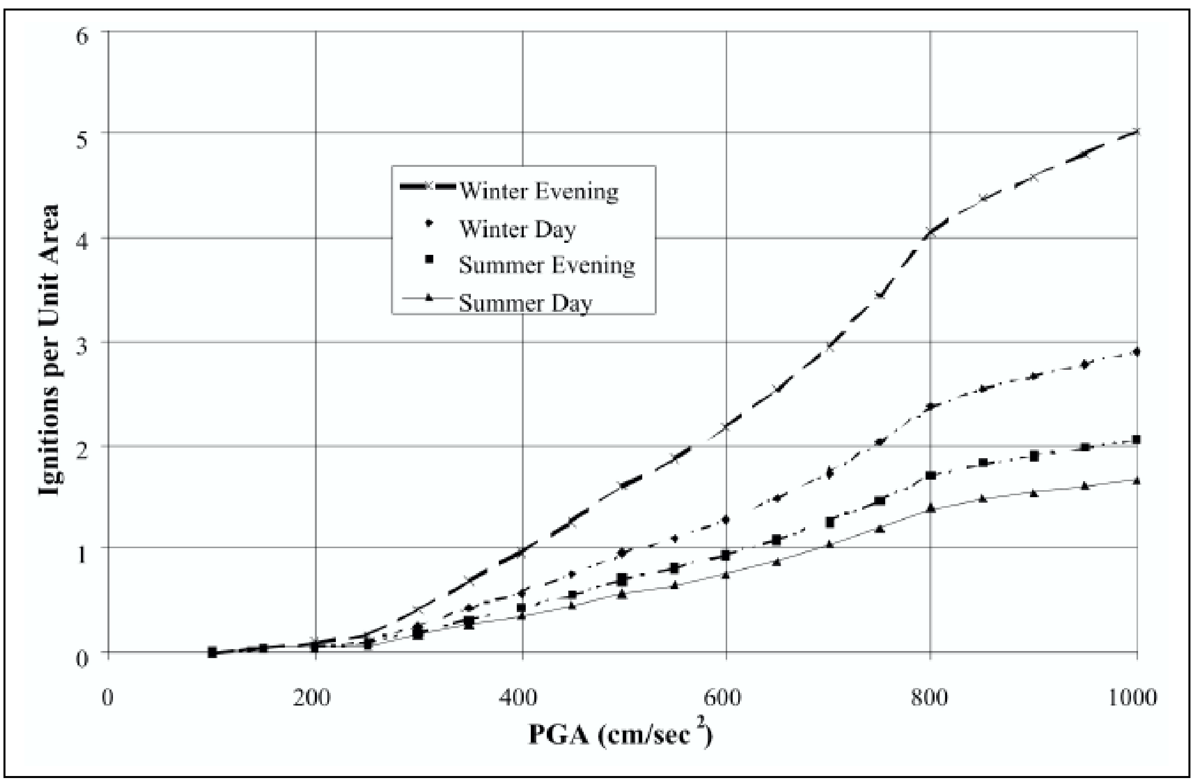


Figure 8 Fire Ignition rate as a Function of Season and Time of Day
(Tokyo Fire Department 1997)

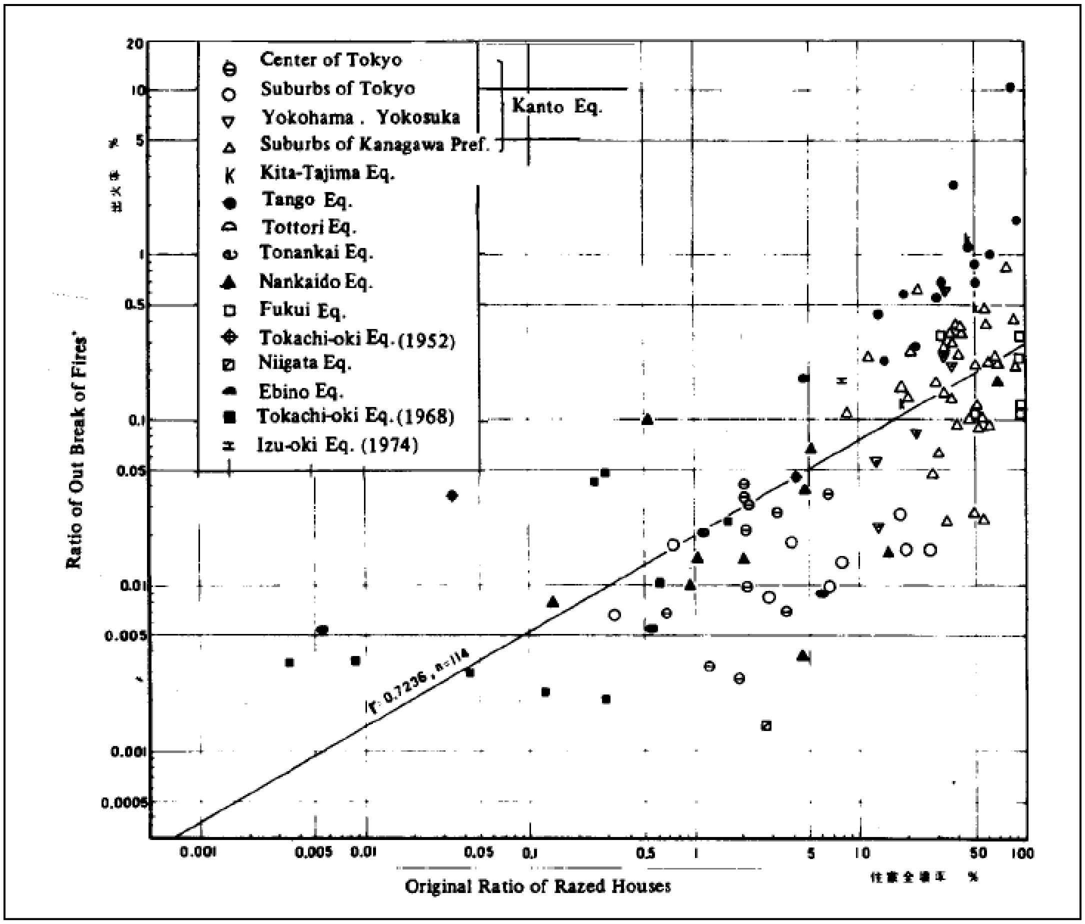


Figure 9 Correlation of ignition rate with ratio of razed (ie, collapsed) houses (Mizuno 1978)

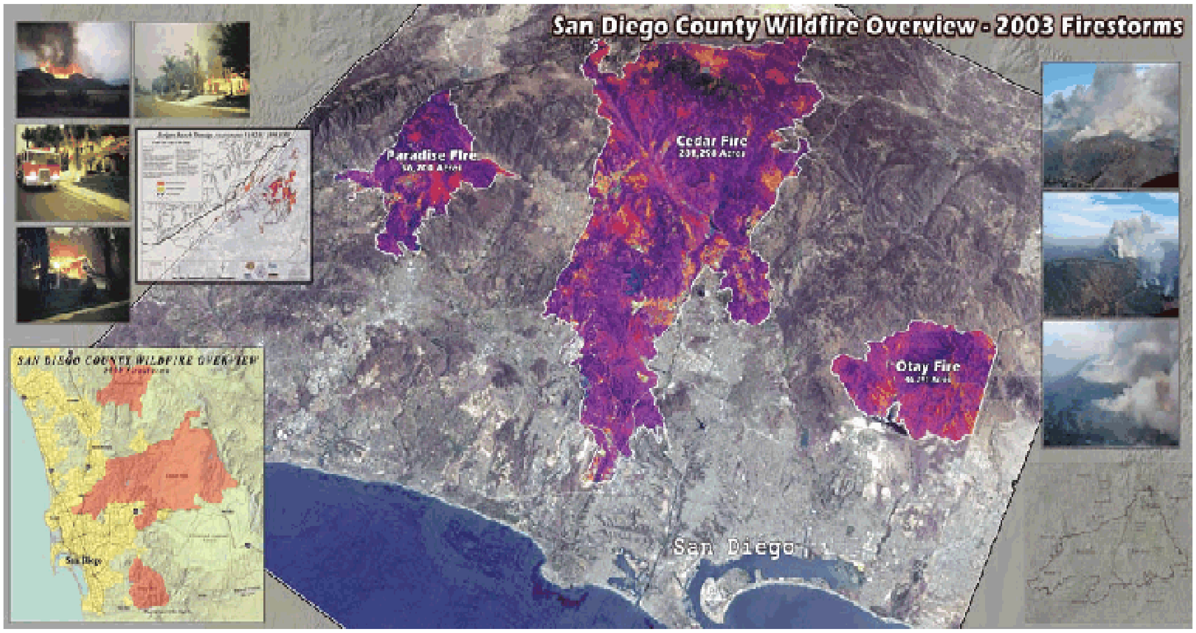
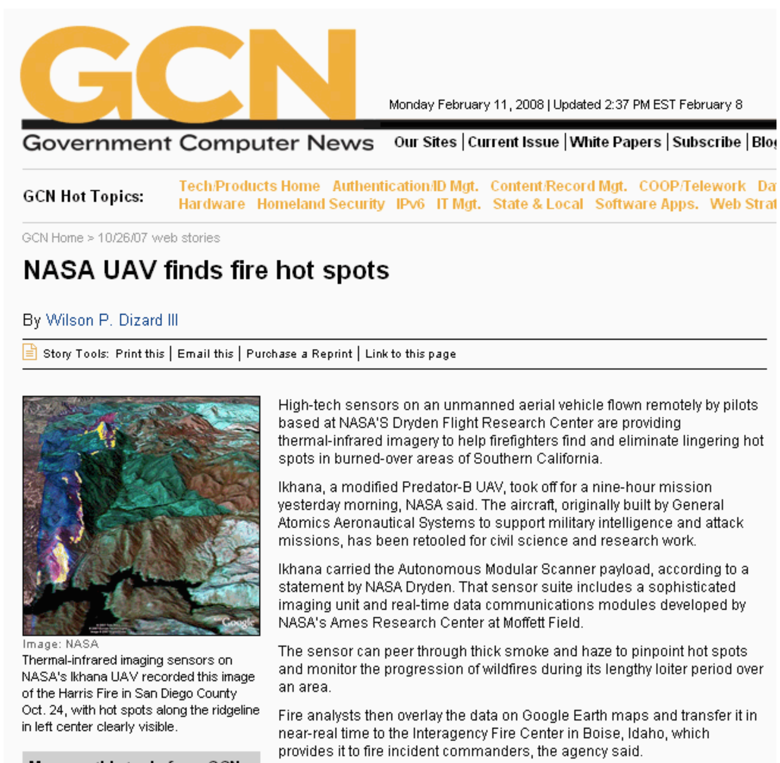


Figure 10 GIS use for wildland fires
(http://www.esri.com/news/arcnews/winter0304articles/winter0304gifs/p22p1-lg.jpg)



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NASA UAV finds fire hot spots

By Wilson P. Dizard III

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Image: NASA
Thermal-infrared imaging sensors on NASA's Ikhana UAV recorded this image of the Harris Fire in San Diego County Oct. 24, with hot spots along the ridgeline in left center clearly visible.

High-tech sensors on an unmanned aerial vehicle flown remotely by pilots based at NASA'S Dryden Flight Research Center are providing thermal-infrared imagery to help firefighters find and eliminate lingering hot spots in burned-over areas of Southern California.

Ikhana, a modified Predator-B UAV, took off for a nine-hour mission yesterday morning, NASA said. The aircraft, originally built by General Atomics Aeronautical Systems to support military intelligence and attack missions, has been retooled for civil science and research work.

Ikhana carried the Autonomous Modular Scanner payload, according to a statement by NASA Dryden. That sensor suite includes a sophisticated imaging unit and real-time data communications modules developed by NASA's Ames Research Center at Moffett Field.

The sensor can peer through thick smoke and haze to pinpoint hot spots and monitor the progression of wildfires during its lengthy loiter period over an area.

Fire analysts then overlay the data on Google Earth maps and transfer it in near-real time to the Interagency Fire Center in Boise, Idaho, which provides it to fire incident commanders, the agency said.

Figure 11 UAV application in re fire
(http://www.gcn.com/online/vol1_no1/45305-1.html)

Figure 12 Clark County OH building footprint data

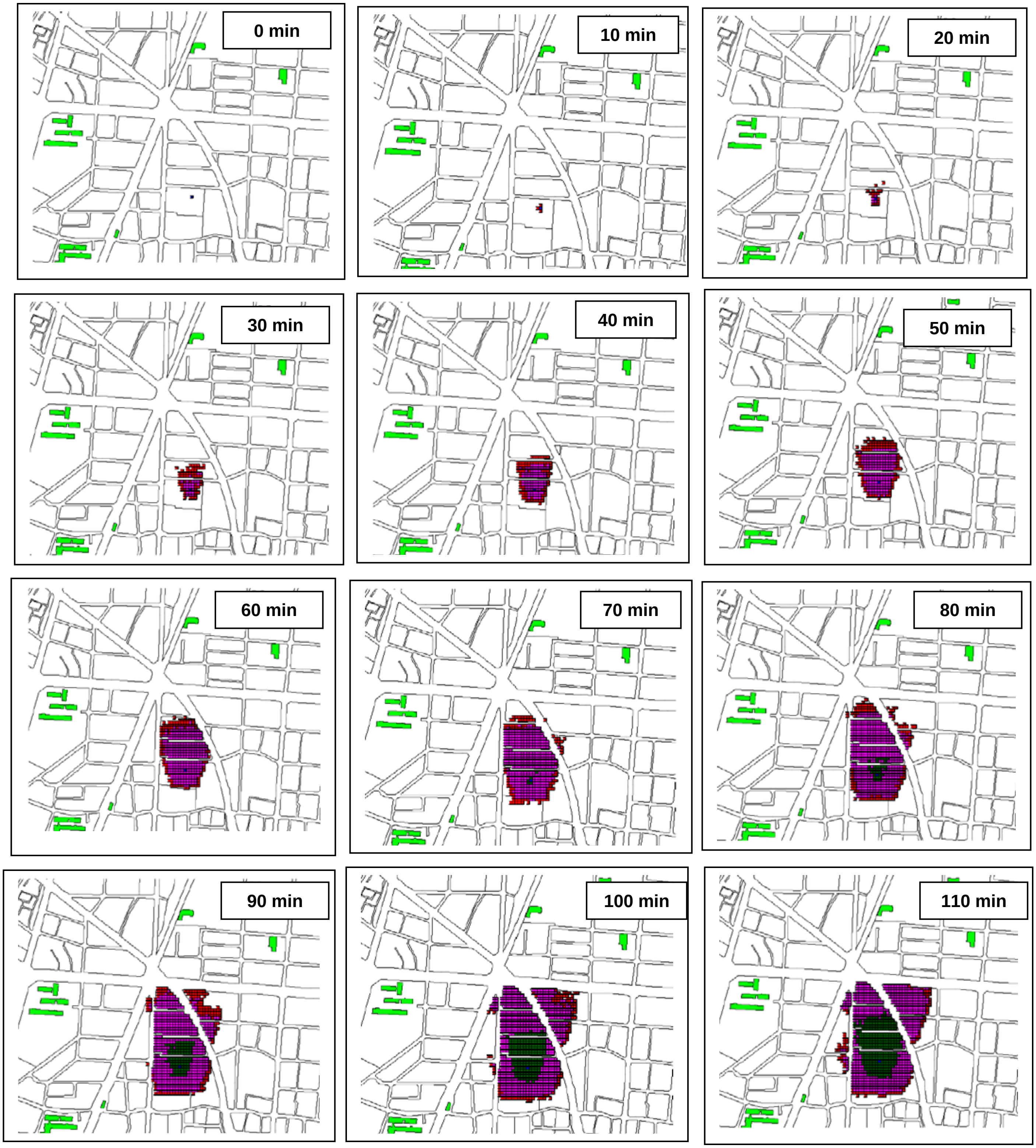
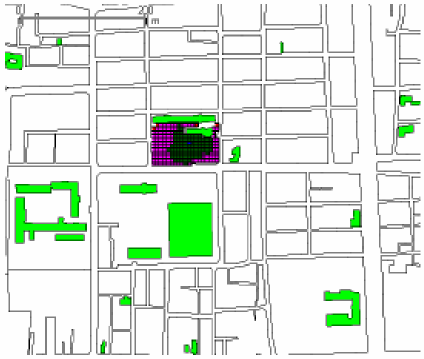
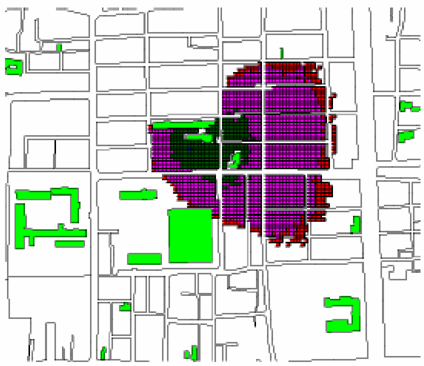


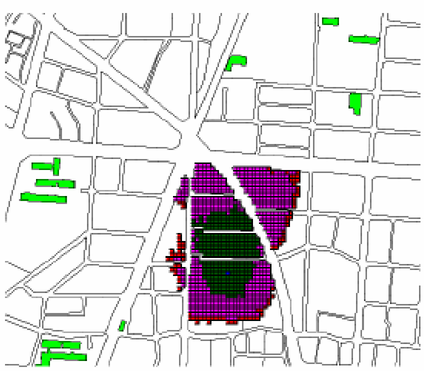
Figure 13 Cellular Automata model for Urban fire growth
– case of Japanese City, wind from south at 5 m/s (Kubo et al. 2008)



Case-1 $(v = 0)$[m/s] / after 110 minutes



Case-2 $(v = 5$[m/s] for East) / after 110 minutes



Case-3 $(v = 5$[m/s] for North) / after 110 minutes

Figure 14 Cellular Automata model for Urban fire growth
– Sensitivity of fire growth to wind speed and direction, Japanese City, (Kubo et al. 2008)

Figure 15 3D building data – K Street and Vermont Ave, looking toward L Street, Washington DC