Estimating Risks from Fire Following Earthquake

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CONTENTS

SUMMARY

Fire is a common consequence of large earthquakes. Sometimes, because fire suppression activities can be compromised after large earthquakes, it develops into conflagration that in turn leads to very serious loss of life and property. A GIS (Geographic Information System) model containing property and valuation data is shown to be a useful platform for modelling the spread of post-earthquake fire in the urban setting. We describe two approaches, one static and one dynamic. The static approach relies on a simple buffering technique to define potential "burn-zones" that are sampled randomly to give estimates of losses. From repeated sampling we are able to assess the probability of exceedance of various levels of loss as a function of the number of ignitions and the spacing between buildings. The dynamic approach uses a cellular automaton technique for determining both the rate and extent of fire spread in response to a wide range of factors including wind, radiation, sparking, branding, and individual separations of buildings. It is more realistic than the simple model but runs much more slowly.

The dynamic model utilises a set of fire spread "rules" that are based on fire physics modified by historical data. Calculations are made of the radiant heat flux from burning areas, and the ignition criteria for nearby buildings take into account cladding materiality. Spread by sparks and flying brands is dependent on wind speed and a user-defined probability. The model can be run in simulated real time for use in real events.

Neither model is yet fully developed. Two important features remaining to be incorporated are the effects of ground slope and vegetation. Bearing this in mind, some conclusions that may be derived from preliminary applications of the models are as follows:

- Losses due to fire following a major earthquake centred on Wellington City are likely to be smaller than losses due to shaking provided the wind at the time is no stronger than a "moderate breeze". However, fire losses are likely to become severe for "near gale" and stronger winds.

- Firebreaks are not an effective way of minimising fire losses when there are multiple (30 or so) ignitions. A better approach is to make buildings resistant to fire-spread.

- For "calm" to "fresh-breeze" conditions the fire loss is roughly proportional to the number of ignitions. Thus minimising the number of ignitions is a good way of mitigating losses due to post-earthquake fires, as is the immediate containment of any fires that do start.

- The cost of not fighting fires is significant even under normal conditions when there is usually only one fire at a time. For a single ignition the 50th percentile loss varies from

about $10 million in calm or light-wind conditions to more than $1 billion for severe wind conditions.

1.0 THE BRIEF

The aim of the work is to develop practical tools for modelling and visualising the spread of post-earthquake fire, and then to use the tools to improve understanding of the hazard affecting major urban areas and to help identify appropriate strategies for reducing consequent losses.

Specific objectives were as follows:

- using a probabilistic approach, to model the occurrence of post-earthquake fires that are capable of spreading,
- to develop GIS-based modelling tools that can provide a quantitative view of how fire can spread in a city after an earthquake,
- to provide a user-friendly interface to the GIS software, and to identify hardware, software, and data requirements for replicating the studies in other cities,
- using Wellington City as an example, to estimate the extent of burn zones (natural zones within which fire will be contained in specified climatic conditions without intervention) to assist city planners in development of a resilient environment, and
- to establish, and recommend practical cost-effective measures to minimise post-earthquake fire and to mitigate the effects if post-earthquake fires occur.

2.0 INTRODUCTION

Fire following earthquake is an extremely variable phenomenon. Losses from such fires can vary from insignificant (e.g. Izmit earthquake 1999, Turkey; ChiChi earthquake 1999, Taiwan) to disastrous (e.g. San Francisco 1906, USA; Tokyo 1923, Japan). New Zealand experience, Table 1, mirrors that seen world-wide. There are two aspects to the variability. One is a high level of variability in the number of ignitions, and the other is a high level of variability in the extent of fire-spread from each ignition. We concentrate on the fire-spread aspect.

Event Name	Date	Magnitude	Locality Affected	Fire Losses
Marlborough	16th Oct 1848	7.8	Wellington [MM8]	none [19]
Wairarapa	23rd Jan 1855	8.1	Wellington [MM9]	none [21,22]
Murchison	16th Jun 1929	7.7	Murchison [MM9]	none [15]
Hawke's Bay	3rd Feb 1931	7.8	Napier [MM10]	conflagration [8,16]
Pahiatua	5th Feb 1934	7.4	Pahiatua [MM8]	none [12]
Wairarapa	24th Jun 1942	7.2	Masterton [MM8]	minor [13]
Inangahua	23rd May 1968	7.2	Inangahau [MM10]	none [17]
Edgecumbe	2nd Mar 1987	6.5	Edgecumbe [MM9]	none [6]

Table 1: New Zealand's experience of fire losses following major earthquakes. In most cases we found no reports of post-earthquake fires. In one case one house was destroyed and there was minor damage to a few others, and in one other case, Hawke's Bay 1931, there was major conflagration that destroyed most of the business district of Napier.

Information on conflagrations in New Zealand is sparse. Historical writings [26,27] reveal that there have been many conflagrations in New Zealand towns in the late 19th and early 20th centuries, fuelled mainly by closely-spaced timber-clad buildings. The main causative factors have been large numbers of ignition sources and a lack of ability to control the fires given poor water supplies and inadequate fire fighting equipment. Because such factors are also likely to be present after large earthquakes, conflagration can be expected in areas of closely spaced wooden buildings that still exist in, for example, the inner suburbs of Wellington.

Wellington City, which we use as an illustration, has many of the risk factors that together give a high probability of post-earthquake conflagration. It straddles one of New Zealand's most active faults and so is likely to experience severe ground shaking. The main access routes and water supply lines cross the fault. Much of the terrain is steep so that many access routes around the city have the potential to be blocked by landslides. Much of the inner suburban area consists of light timber-clad houses, usually of two storeys, that are close to adjoining houses (Figure 1). The central city is reticulated with natural gas. Wellington City thus has many potential ignition sources and, after a large earthquake, fire spread is likely to be rapid. Fire fighting resources, especially water, will be limited. Indeed the first century of European settlement has seen the burnout of one or more blocks of buildings at least eight times [29], with estimated losses up to about $50 million in present day values.

Figure 1: Wellington inner suburb. Note the small separations between the predominantly 2-storied wooden houses.

We have developed two GIS-based models for simulating the spread of post-earthquake fires. One, a static model, uses a simple buffering technique to define potential “burn-zones”, which are then sampled randomly to construct estimates of losses. From repeated sampling we are able to assess the probability of exceedance of various levels of loss as a function of the number of ignitions, the spacing between buildings and the cladding materials. The second is a dynamic model for tracking the rate and extent of fire spread in response to a wide range of factors including wind, radiation, sparking, branding, and separations of buildings. It is more realistic than the simple model, but runs much more slowly.

The static model can be used to scope the fire-spread problem, to assess the effectiveness of large-scale mitigation measures, and to identify those parts of a city where conflagration could occur and where more detailed modelling would be desirable. The dynamic model is intended for detailed investigation of mitigation measures and for response planning during fire emergencies. Both models are still under development but are showing considerable promise.

3.0 UNDERLYING DATABASE

Both models make use of a database of spatial information about the fuel (i.e. the buildings). The main item in the database is the building footprint (Figure 2), and linked to each footprint is information on the number of stories, the floor area, the replacement value, and the cladding materials.

Figure 2: Example of building footprints in the GIS database utilised by the fire-spread models (houses and commercial buildings in the vicinity of Bowen St.).

Data on floor area, number of stories, and cladding materials were derived from a property database that originated from QuotableValue New Zealand (QV). The QV database was chosen because of its extensive coverage, although for our purposes it did have two deficiencies. First, because it was established primarily for taxation purposes, it was organised by legal "property", and there was not always a one-to-one correspondence between a legal "property" and a physical "building". Second, like all large databases, it contained errors, omissions, and ambiguities.

Many of the errors, ambiguities and omissions had previously been corrected [11], and we adopted the following procedures for converting the data from a "property" to a "building" basis. Floor area was estimated by (i) grouping building footprints into city blocks, (ii) using whatever QV data was available to estimate the average number of stories for the block, and (iii) for each footprint multiplying the footprint area by the average number of stories. Buildings were assumed to have the same cladding materials as the parent property. Where there were multiple buildings in a single property all were allocated the same cladding material as the parent property.

The replacement value was calculated as the product of the floor area and an estimated construction cost. Estimated construction costs were assigned mostly according to suburb and use, and ranged from \$650/m^2 for industrial buildings in Grenada North to \$1600/m^2 for commercial buildings in the CBD and \$1800/m^2 for houses in Kelburn. Some significant buildings, e.g. Te Papa and the Newtown Hospital, were given individual values, and small buildings (i.e. area < 10 m^2) were restricted to 1 storey and \$500/m^2. The base costs were derived from published cost estimates for construction in Wellington [20].

Our estimate of the replacement value of all buildings in Wellington City is \$23.4 billion, distributed amongst 75,800 buildings.

4.0 DYNAMIC FIRE-SPREAD MODEL

4.1 Previous Work

Previous post-earthquake fire-spread models have tended to rely on historical data to constrain the rate and extent of fire spread. Due to the relatively small number of post-earthquake conflagrations the amount of data is small, and high quality data is available from only a few events. The available data are difficult to interpret because information relating fire spread rates and minimum firebreak sizes to building sizes and types (including cladding types), and other factors such as wind is not always available. Summaries of previous work are given in Lloydd[25] and Botting[1].

Our dynamic fire-spread model uses a set of “rules” for determining both the rate and extent of fire-spread in response to a wide range of factors including wind, radiation, sparking, branding, building separations and building claddings. The rules are based on fire physics and are guided somewhat by historical data.

4.2 Overview of the Dynamic Fire-Spread Model

The dynamic model uses a “cellular automaton” technique in which the landscape is modelled as a regular lattice of cells with each cell being assigned a set of states and properties representing the physical environment. Spread fire from one cell to another depends on the states, the values and the “rules”. Possibilities considered can include the following:

- state: burning or not, and if burning how fiercely,
- properties: combustible or not, ignitable or not, and
- rules: probability of ignition according to intensity of combustion, distances from burning cells, and biases such as wind and elevation. (Elevation has not been programmed into the present model but is planned for the future.)

An example of the cellular lattice is shown below in Figure 3. A regular grid has been superimposed on the footprint of a building and each cell of the grid has been allocated the properties of what it mostly overlies. Thus if the heavy line denotes the outline of a building then any cell that falls all or mostly within the outline takes the properties of the building, i.e. cladding materials, height, and share of value. The cells that represent the building are shaded. In the present model the cells are 3m squares and so the building in Figure 3 measures about 21m by 36m (7 cells by 12 cells). The rectangular grid overlays all buildings in the area of interest, in our case Wellington City.

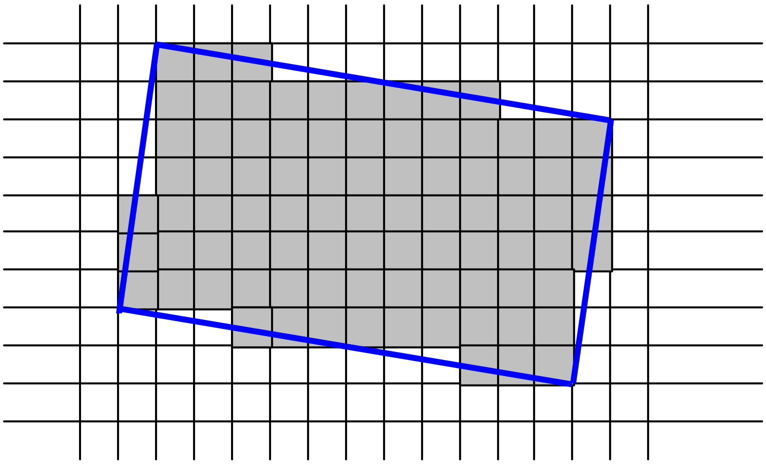

Figure 3: Allocation of properties to cells in the fire-spread model. The shaded cells are the ones allocated properties appropriate to the building denoted by the heavy outline.

The mechanics of the process is that the entire set of cells is scanned repeatedly, cell by cell, in a raster fashion. During the scanning process cells are "activated" one at a time and, whilst activated, a cell's state is changed according to its current state and properties, the states of surrounding cells, and the fire-spread rules.

Because of the repetitive nature of the scanning process there is a built-in time step which makes it straightforward to model time-variant states such as the build-up and decline of a fire. In the fire-spread model we have assigned a time of 2.5 minutes to the interval between scans and the various stages of a fire are set to multiples of 2.5 minutes. Thus the time for a fire in a single cell to progress from ignition to full intensity burning is 7.5 minutes (3 scans), the time of burning at full intensity is 15 minutes (6 scans), and the burn-down time is 12.5 minutes (5 scans).

The cellular model divides the region into 3m squares. The size of 3m corresponds well to a traditional separation between timber houses in the outer suburbs of 10 feet. Building storey-height also is about 3m, and the number of stories could be estimated from the database attached to the GIS model by dividing the gross floor area of each building by the footprint area and rounding off to the nearest whole number. At present in the model, however, the building height is assumed to be 4.5m always.

In selecting the cell size there is a trade-off between detail and run-time. Decreasing the size from 3m to 1m for instance would increase the run time by nearly a factor of ten.

The fire-spread rules govern whether or not fire will spread from one cell to the next. Given the scarcity of historical data a number of assumptions have been required in deriving the rules. Generally an attempt has been made to find minimum and maximum bounds for the input values and then intermediate values have been used for developing the rules.

We assume that buildings with non-combustible cladding can spread fire to other cells when ignited internally, but cannot be ignited by other burning buildings. This assumption is expected to result in an underestimate of losses because fire can sometimes spread to a building with non-combustible claddings through windows or through walls that have been damaged by earthquake shaking, and fire can spread freely through completely collapsed buildings. The possibility of fire spreading to damaged buildings has been assessed in a sensitivity study in which it was assumed that buildings from particular design eras would collapse.

Vegetation is assumed to be non-combustible. This assumption also could result in an underestimate of losses. Wellington is situated on or close to steep hills. Between some suburbs that occupy valleys the hills are clad in native bush, exotic trees or scrub. One introduced species, gorse, is highly flammable when dry. Between buildings, particularly in residential areas, there are trees, shrubs and grass that may be ignited by radiation, sparks or flying brands. Vegetation has varying degrees of flammability depending on climatic conditions and the species. The effect of vegetation on fire spread will be investigated in a future stage of this project.

The results are displayed as images of burnt and burning areas at specified time intervals, and the model takes into account individual building separations, cladding combustibility, and wind speed and direction. Losses are accumulated for burned areas and can be exported from the GIS system as lists of areas or values as required.

4.2.1 Empty and occupied cells

Any cell which is more than 50% filled with a part of a building is deemed a building cell and all other cells are deemed empty. Hence, as shown in Figure 4 in which the outlined buildings have been allocated the shaded cells, the separations between “buildings” in the model often differ in detail from reality. As a result the upper left and lower “buildings” of the model are adjacent and the upper right building is spaced one cell (3.0m) from the other two.

The same process is followed when the buildings are not aligned with the grid. Buildings 1 and 2 (Figure 5) are each allocated four cells. In the model, building 1 is deemed to be adjacent to the dark shaded cell and building 2 is deemed to be 1 grid or 3.0m away. In reality the distances between the buildings and the dark shaded cell are about 1.4m for building 1 and 2.5m for building 2.

As will be shown later, neither of the above changes to spacing is expected to have a significant effect on the likelihood of fire spread between buildings.

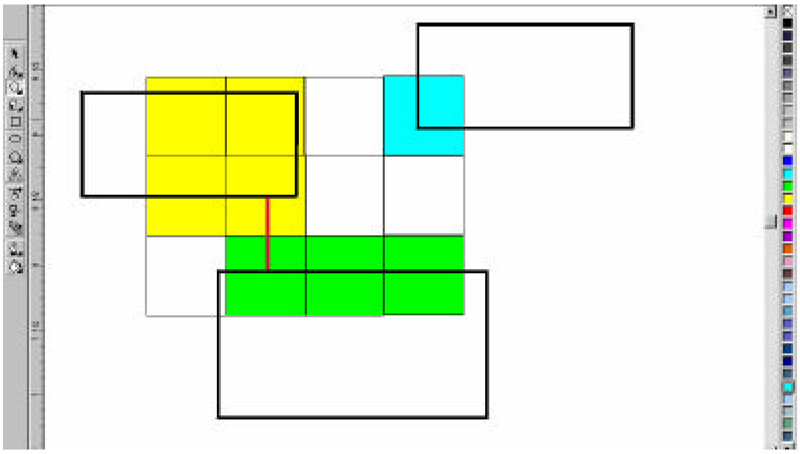

Figure 4: Allocation of buildings to cells, and resultant changes in separations.

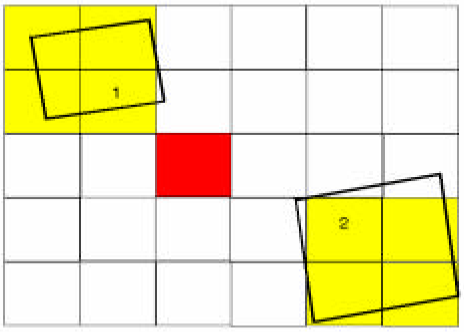

Figure 5. Allocation of buildings to cells, effect of irregular alignment with grid.

4.3 Modes of Fire-Spread

We consider four modes of fire spread, as follows:

- direct spread to a contiguous cell,
- radiation to a nearby cell with spontaneous ignition of the cladding,
- radiation to a nearby cell with piloted ignition of the cladding (sparking), and
- ignition by airborne flaming material (branding).

Both sparking and branding are assigned a probability thus allowing the model to be easily modified to allow for different building types, for example the use of timber shingle roofs in buildings in California.

4.3.1 Spread to contiguous cells

Fire is assumed always to spread from a burning cell to any combustible cell in contact with it. The adjoining cell may be either in the same building or in an adjoining building with combustible claddings. The only parameter is the time taken for fire spread, set at 2.5 minutes for fire to spread from one cell to the next. This value is based on anecdotal evidence of fire-spread rates throughout a typical New Zealand dwelling.

4.3.2 Selection of radiation parameters

The temperature of the radiator has a significant effect on the level of radiant heat flux, because the heat flux varies with the fourth power of absolute temperature. The *deemed to satisfy* provisions of the New Zealand Building Code [4] use varying values for temperature depending on the fuel load equivalent density. Each level of fuel load is assumed to correspond to a time and hence to a corresponding temperature on the standard ISO-834 time-temperature curve, which is typically lower in temperature than compartment fires. Values of between 800 and 1200ºC are expected in compartment fires [5], but in a small compartment that has reached flashover temperatures of 1000-1100°C are likely [3]. We have assumed a temperature of 1000°C for radiating cells in the fire-spread model, because it is a temperature that most compartment fires are expected to reach [3].

Reported emissivity values for fires in the open cover a wide range from 0.5 to 1.12 [18]. Most reports focus on compartment fires or furnaces, where the emissivity values are a combination of the emissivity and the absorptivity of the bounding surfaces. Others [2] focus on design methods, where the aim is to prevent fire spread and hence a conservative value of 1.0 is used. We assume a radiator emissivity of 0.9 for the fire-spread model.

4.3.3 Criteria for spontaneous and piloted ignition

The ignition of a heated building cell depends on whether or not the cladding material is heated sufficiently to cause either spontaneous ignition or piloted ignition. In each case the criterion is that the received radiation exceeds a critical level. This is a simplification, because the level of radiation heat flux required for ignition does reduce somewhat with time.

Critical values reported for spontaneous ignition of timber range from 28 kW/m^2 [18] to 33.5 kW/m^2[5]. The value adopted for the fire-spread model is 30 kW/m^2, which also is the value used in the *deemed to satisfy* provisions of the New Zealand Building code [4].

Similarly critical the value for piloted ignition varies from 10.0 kW/m^2 (long duration exposure as the critical heat flux for timber specimens in a cone calorimeter [33]) to 18.0 kW/m^2 (30 minute exposure in the open as used to calculate tables of window sizes and boundary distances in the *deemed to satisfy* provisions of the New Zealand Building code [4]). The value adopted in the fire-spread model is 12.5 kW/m^2.

With a 3m cell size, the sensitivity to the choice of radiator temperature and the critical values of heat flux is possibly somewhat less than would be expected for a model using actual separation distances and radiator dimensions.

Radiation from projecting flames has been ignored. Flames cool rapidly with height and so flames above a burning building will not contribute significantly to the level of radiation.

Give the above assumptions regarding the temperature and emissivity of the radiator, the dimensions of the radiator, and a separation distance, the incident radiation on a target cell can be calculated. The results of the calculation are shown in Table 2.

Radiator width (m)		3	6	9	12	15	21	24	36	39	72	75	Infinite
Distance (m)	Within (m)												
1.5	3	85.1	104.6	109.0	110.4	110.9	111.3	111.4	111.5	111.5	111.5	111.6	111.6
4.5	6	23.0	39.2	48.4	53.2	55.8	58.2	60.0	59.5	59.6	59.9	59.9	60.0
7.5	9	9.4	17.6	23.9	28.3	31.4	34.8	38.5	37.5	37.7	38.4	38.4	38.5
10.5	12	5.0	9.6	13.6	16.9	19.5	22.9	28.1	26.4	26.7	27.8	27.8	28.1
13.5	15	3.1	6.0	8.7	11.0	13.0	16.0	22.0	19.7	20.1	21.6	21.7	22.0
16.5	18	2.1	4.1	6.0	7.7	9.2	11.7	18.1	15.3	15.7	17.5	17.6	18.1
19.5	21	1.5	3.0	4.4	5.7	6.9	8.9	15.4	12.2	12.6	14.6	14.7	15.4
22.5	24	1.1	2.2	3.3	4.3	5.3	7.0	13.3	9.9	10.3	12.4	12.5	13.3
25.5	27	0.9	1.7	2.6	3.4	4.2	5.6	11.8	8.1	8.5	10.7	10.8	11.8
28.5	30	0.7	1.4	2.1	2.7	3.4	4.5	10.6	6.8	7.2	9.3	9.4	10.6

Table 2: Incident radiation in kW/m^2 on external surfaces of exposed buildings at increasing separation distances for varying widths of a 4.5m high radiator. The darker and lighter shaded areas show combinations where the radiation required for spontaneous (30 kW/m^2) and piloted (12.5 kW/m^2) ignition respectively occurs.

4.3.4 Spread by spontaneous ignition

Whenever the radiation incident on a combustible cell exceeds 30kW/m^2 the cell is assumed to ignite spontaneously. Wind is assumed to have no effect.

As described above, the way buildings are allocated to cells may result in two buildings just under 3.0m apart being allocated to adjoining cells in the model. This has no affect on the possibility of fire spread between such buildings. When a radiator 3.0m (one cell) wide and 3.0m high is 3.0m away from a receiver of radiation, then the incident radiation on the receiver is 32.5 kW/m^2 which is sufficient to cause spontaneous ignition of combustible claddings. Hence making the buildings adjacent instead of up to 3.0m apart does not increase the probability of ignition.

4.3.5 Spread by piloted ignition

In the model it is assumed that burning cells will produce sparks from 7.5 to 22.5 minutes after ignition. Fire spread by the sparks is dependent on the distance that they can travel and on having a minimum level of incident radiation of 12.5 kW/m^2. It is assumed that the sparks will spread in all directions with the spread downwind only being enhanced by wind as indicated in Table 3.

Wind strength (and approximate speed)	Calm	Moderate Breeze (20 km/h)	Fresh Breeze (30 km/h)	Near Gale (50 km/h)
Spread distance downwind (m)	12	15	21	45
Spread distance cross and upwind (m)	12	12	12	12

Table 3: Spark spread distances as a function of wind strength.

The distances in Table 3 were derived from the areas of loss compared with wind speed reported by Scawthorn [31]. The derivation was performed on a trial and error basis by running the fire-spread model with various distance values and comparing the total burnt out area with Figure 11 of Scawthorn's report [31]. In the process we excluded some of Scawthorn's data, i.e. some apparently abnormally low burned areas for wind speeds between 10 and 30 km/hr. The excluded data was from the San Francisco 1906 post-earthquake fire, and at the locations in question it appeared that wind had no effect on the speed of fire spread. This may have been due to several factors such as low local wind speeds (wind speeds may have been measured elsewhere) and lack of spark production. Incorporating the low values would have resulted in a counter-intuitive prediction that spread rates would increase with wind speed to a wind speed of 20 km/hr, then reduce between 20 and 30 km/hr, and then increase again after 30 km/hr.

The critical distance value for spark spread in "near gale" winds is set the same as that for spread by flying brands. If a flaming brand, which is larger than a spark, can spread 45m then a spark must also be able to travel at least that distance. During post-earthquake fires in Kobe in 1995, a "wide" street was able to stop fire-spread when the wind speed was 20 km/hr [23]. Assuming that a wide street is 20m across we have estimated that sparks will spread 15m in a moderate breeze [32].

4.3.6 Spread by flying brands

Spread by flying brands is assumed to commence when the wind strength reaches "near gale", after which point fire spread and losses increase rapidly [34]. Some branding occurred in Kobe after the Great Hanshin-Awaji earthquake in 20 km/hr winds [23], but this has not been observed after other earthquakes.

The model is tested for brand propagation from a burning cell between 12.5 and 22.5 minutes after ignition. Brands are assumed to propagate in a 45° arc downwind and may spread up to 45m. This is slightly more than the 38m that fire spread across Van Nees Avenue after the 1906 San Francisco Earthquake when the wind speed was about 42 km/hr [32]. The likelihood of brands being a means of rapid fire-spread is less in Wellington than in regions such as southern California, because the majority of roofs in Wellington are corrugated steel and flat roofs are relatively uncommon. A brand is most likely to cause ignition if it lands on a combustible surface such as timber roof shingles, whereas on a sloped iron roof it is most likely to simply fall off. There is, however, the possibility of ignition of plant material adjacent to buildings and that which has accumulated in roof gutters.

4.4 The "Rules" governing Fire-Spread

When the above information is combined, a set of "rules" is determined for radiant exposure, as follows (Table 4):

Rule No.	Rule	Wind Strength
1	1 or more burning cells within 3.0m causes spontaneous ignition of a target cell	Calm
2	2 or more burning cells within 6.0m causes spontaneous ignition 1 or more burning cells within 6.0m can cause spark (piloted) ignition	
3	5 or more burning cells within 9.0m causes spontaneous ignition 2 or more burning cells within 9.0m can cause spark ignition	
4	no spontaneous ignition at 12.0m 3 or more burning cells within 12.0m can cause spark ignition	
5	no spontaneous ignition at 15.0m 5 or more burning cells within 15.0m can cause spark ignition	Moderate Breeze
6	no spontaneous ignition at 18.0m 8 or more burning cells within 18.0m can cause spark ignition	Fresh Breeze
7	no spontaneous ignition at 21.0m 13 or more burning cells within 21.0m can cause spark ignition	
8	no spontaneous ignition at 24.0m 25 or more burning cells within 24.0m can cause spark ignition	Near Gale
9	no spontaneous ignition at 27.0m no spark ignition at 27.0m	

Table 4: Basic fire-spread rules based on fire physics. Spontaneous ignition is independent of wind, and the spark ignition cases are for downwind spread.

Wind is taken into account by varying the distance sparks can spread from the burning cell. For piloted ignition to occur, the level of radiation at the target cell must be high enough (i.e. greater than 12.5 kW/m^2) and the target cell must be within the spark spread distance for that wind speed as given in Table 3. In high winds, branding ignition can also occur at distances of up to 45m from a burning cell.

4.5 Sensitivity of the Model to Various Assumptions and Parameters

In deriving the above “rules” we have made a number of assumptions and selected values for four parameters. In all cases there are uncertainties involved. We now assess the effect that those uncertainties might have on the fire-spread model.

In the radiation calculation there are four parameters for which there is uncertainty in the input value. They are the flame emissivity, the flame temperature and the critical levels of radiation for (a) spontaneous and (b) piloted ignition. The arrangement of multiple burning cells also can vary, from aligned to scattered. We have used a standard height of 4.5m for radiating cells, and have ignored radiation from flames projecting above the burning cells.

4.5.1 Standardised height of radiator

Each cell radiates heat flux across the gap between itself and nearby cells. The level of radiant heat flux incident on a nearby cell depends on the radiator temperature and the radiation view factor. The view factor in the model depends on the number of contiguous cells that are alight and their arrangement. Both width and height are important.

The building height parameter, 4.5m, is a weighted average value for a mixture of 1 and 2 storey residential buildings. Buildings of this type have floor-to-ceiling (stud) heights ranging from 2.4m to 3.6m. Stud heights of more than 3.0m are uncommon and modern homes mostly have stud heights near the lower end of the range (although the more expensive modern homes tend to have higher stud heights). A reasonable mean value for stud height is 2.7m. Allowing 0.3m for the depth of a floor/ceiling combination gives 3.0m as a mean inter-storey height and 4.5m as the 1½-storey height.

The effect of varying the height of the radiator between 3.0 and 6.0m is shown in Figure 6 for a 12.0m wide radiator. The effect is not significant (less than 10% change) at small separations, but is more significant at wider separations. At the critical value of 30 kw/m^2 for spontaneous ignition, the 3.0m and 4.5m high radiators will cause spontaneous ignition of a cell within 6.0m, but not at 9.0m, whereas the 6.0m high radiator will cause spontaneous ignition within 9.0m. At the critical value of 12.5 kW/m^2 for piloted ignition, the 3.0m, 4.5m and 6.0m high radiators will cause spontaneous ignition of a cell within 9.0m, 12.0m and 15m respectively. This effect is less marked for wider radiators but not at 9.0m, whereas the 6.0m high radiator will cause spontaneous ignition within 9.0m.

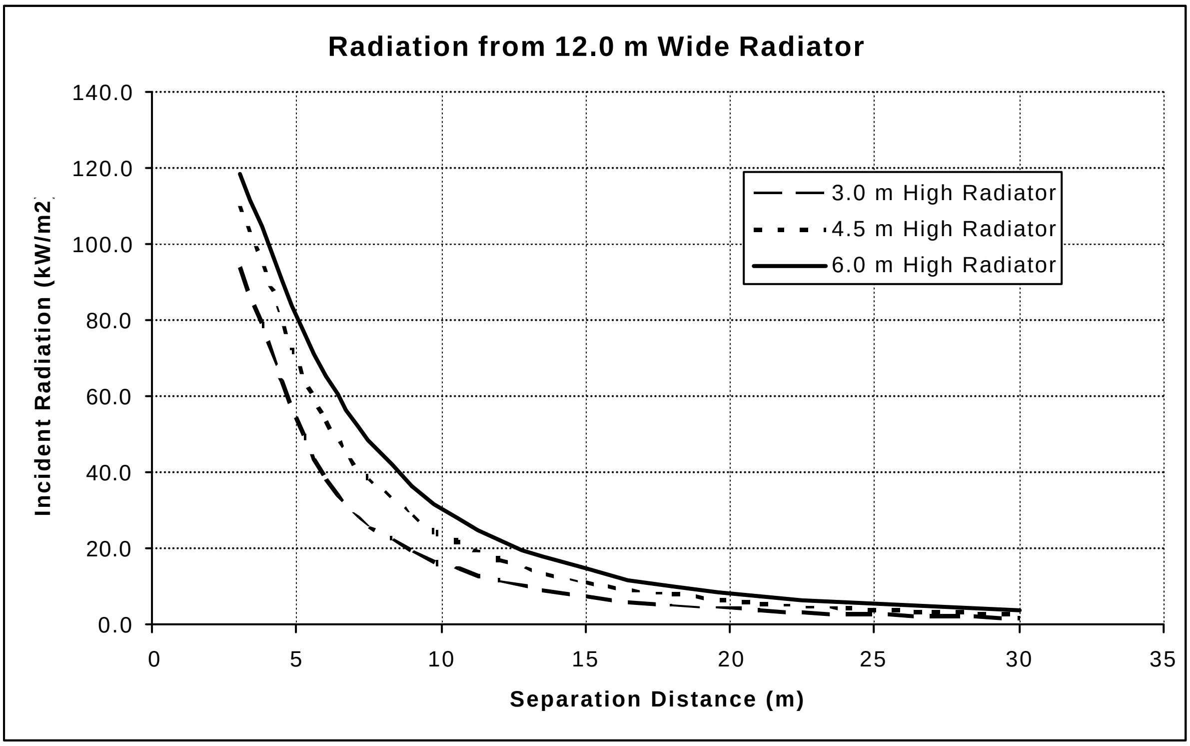

Figure 6. Radiation levels from radiators of various heights

4.5.2 Radiation from projecting flames

In a building fire the flames will often extend above the roof, especially if the roof collapses. However the projecting flames are at a lower temperature than the burning compartment and the increase in incident radiation from the projected flame is not significant. This is because emitted radiation is proportional to the temperature raised to the power of 4.

Consider the example of a burning building 12m long by 4.5m high, and radiating heat at 1000ºC. The incident radiation 12m away, perpendicular to the centre of the radiator, is 13.5 kW/m^2. Such a situation is shown on the diagram on the left-hand side of Figure 7. The flame projection has a temperature of 600ºC and may be a triangle 12.0m wide and 6.0m high. This can be converted to a rectangle 12.0m wide and 3.0m high, giving a level of incident radiation 12m away of 2.0 kW/m^2 perpendicular to the centre bottom of the radiator. The rectangular radiator 12.0 by 4.5m high produces 12.7 kW/m^2 of incident radiation 12.0m away from the centre top of the radiator as shown on the right hand diagram in Figure 7. The total received radiation is 14.7 kW/m^2, an increase of 1.2 kW/m^2 or 9%. Perpendicular to the centre of the building the received radiation is 15.3 kW/m^2, an increase of 13%. Given the accuracy of the modelling and the number of other assumptions, this difference is not significant. This is consistent with tests on the radiation from windows and flame projections reported by Carlsson [7].

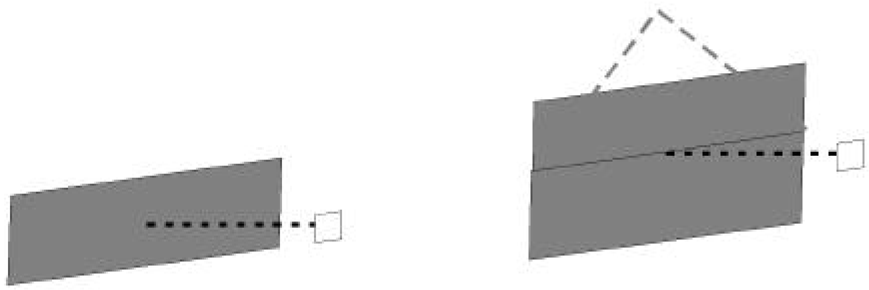

Figure 7. Orientation of radiator and emitter, excluding and including flame projection.

4.5.3 Configuration of radiating cells

In order to minimise computation time in the fire-spread model, we do not check that the burning cells of a radiator are aligned. Instead the numbers of burning cells that are within certain distances of the target cell are determined. The effect of this approach was investigated by calculating the radiation incident on a target cell for the various combinations of burning cells that complied with the each of the rules for piloted ignition. The probability of a given number of burning cells causing piloted ignition of the target cell, assuming an equal likelihood of any possible valid configuration of the burning cells, is given in Table 5.

It is also assumed for the model that if two radiating cells are lined up behind one another in relation to a target cell, then the front radiating cell is transparent so that radiation from the cell behind can pass through it. This assumption has also been checked by the process of calculating total radiation for various combinations of burning cells. If cells are aligned one behind another, then there is also the possibility of another of the rules governing, which further reduces the effect of this assumption. For example, if two cells are within 9.0m of and directly in line with a target cell, then one of the cells must be within 6.0m of the target so that rule 2 governs rather than rule 3. Given that most buildings are more than 6.0m in width, particularly along side boundaries, the possibility of having only one or two burning cells radiating to a target cell is low, reducing the effect of the lower probability of fire spread determined by rules 2 and 3.

Rule No.	Rule	Probability of Ignition
2	1 or more cell within 6.0m	0.50
3	2 or more cells within 9.0m	0.81
4	3 or more cells within 12.0m	0.86
5	5 or more cells within 15.0m	1.0
6	8 or more cells within 18.0m	1.0
7	13 or more cells within 21.0m	1.0
8	25 or more cells within 24.0m	1.0
9	No spontaneous ignition at 27.0m	0.0

Table 5: Validity of radiating cell location assumption

4.5.4 Flame emissivity

An emissivity of 0.9 was adopted for the fire-spread model. The effect of uncertainty in emissivity was assessed by varying it from 0.7 to 1.0 and for each value calculating the number of burning cells within a certain distance required to meet the radiation criteria for piloted ignition at the target cell (Table 6). It is apparent that a 0.1 change in emissivity has little effect up to a separation distance of 12.0m. This change will therefore have little effect in calm conditions or low wind speeds when sparks can not travel more than 12.0m.

Distance (m)	Within (m)	Number of burning cells required			
		= 0.7	= 0.8	**= 0.9**	= 1.0
1.5	3	1	1	1	1
4.5	6	1	1	1	1
7.5	9	2	2	2	2
10.5	12	4	4	3	3
13.5	15	7	6	5	5
16.5	18	13	10	8	7
19.5	21	N/A	19	13	11
22.5	24	N/A	N/A	25	17
25.5	27	N/A	N/A	N/A	32
28.5	30	N/A	N/A	N/A	N/A

Table 6: Effect of varying radiator emissivity on the number of burning cells (within a given distance) required to meet the radiation criteria for piloted ignition at the target cell. The value used for the fire-spread model was = 0.9 (bold).

4.5.5 Flame temperature

The second parameter to be varied was the flame temperature. The effect of the variation is summarised by Table 7 that gives the number of burning cells (within a given distance) required to meet the radiation criteria for piloted ignition at the target cell.

Distance (m)	Within (m)	Number of burning cells required			
		T=800ºC	T=900ºC	**T=1000ºC**	T=1100ºC
1.5	3	1	1	1	1
4.5	6	2	1	1	1
7.5	9	4	2	2	1
10.5	12	9	4	3	2
13.5	15	N/A	6	5	4
16.5	18	N/A	10	8	5
19.5	21	N/A	19	13	8
22.5	24	N/A	N/A	25	11
25.5	27	N/A	N/A	N/A	12
28.5	30	N/A	N/A	N/A	23
28.5	30	N/A	N/A	N/A	44
28.5	30	N/A	N/A	N/A	N/A

Table 7: Effect of radiator temperature on the number of burning cells (within a given distance) required to meet the radiation criteria for piloted ignition at the target cell. The value used for the fire-spread model was T=1000ºC.

The temperature was varied from 800 to 1100ºC. A change in temperature of only 100ºC has a very significant effect. This is to be expected, because the incident radiation is proportional to the absolute temperature raised to the fourth power. A change in temperature of the radiator from 900ºC to 1000ºC increases the level of radiation by 28%, and from 1000ºC to 1100ºC by 35%, whereas a change in emissivity of 0.1 results in a change of only 11% in the level of radiation.

4.5.6 Radiation needed for piloted ignition

The other important assumption is the critical level of radiation for piloted ignition to occur. This value was varied from 10.0 to 18.0 kW/m^2. The effect of the variation is summarised by Table 8, which gives the number of burning cells (within a given distance) required to meet the radiation criteria for piloted ignition at the target cell.

The effect of this change is insignificant at small separations and more significant at larger separations. It is not as significant as a change in temperature.

Distance (m)	Within (m)	Number of burning cells required			
		CR = 10	**CR = 12.5**	CR = 15	CR = 18
1.5	3	1	1	1	1
4.5	6	1	1	1	1
7.5	9	2	2	2	3
10.5	12	3	3	4	5
13.5	15	4	5	7	9
16.5	18	6	8	12	39
19.5	21	9	13	31	N/A
22.5	24	13	25	N/A	N/A
25.5	27	19	N/A	N/A	N/A
28.5	30	N/A	N/A	N/A	N/A

Table 8: Effect of critical radiation level (CR, kW/m^2) on the number of burning cells (within a given distance) required to meet the radiation criteria for piloted ignition at the target cell. The value used for the fire-spread model was CR = 12.5.

5.0 SOME APPLICATIONS OF THE DYNAMIC FIRE-SPREAD MODEL

5.1 Visual display of fire-spread with and without wind

One potential application of the dynamic fire-spread model is real-time simulation of fires with the results being displayed as images of burnt and burning areas at specified time intervals. Four images from each of two such simulations are shown in Figure 8. The colour coding is as follows:

- white building with combustible cladding,
- green building with non-combustible cladding,
- pink building recently ignited,
- yellow fire in build-up state, neither sparking nor branding occurs,
- red fire burning at maximum intensity, sparking and branding possible,
- orange fire burning down, neither sparking nor branding occurs, and
- black burnt-out building.

The left-hand set shows the growth and extinction of a single fire in calm conditions. The fire starts in a house at the corner of a block (top image), spreads in both directions (second image from top) and then proceeds to burn out all buildings with combustible claddings in the block (bottom two images). It does not spread beyond the initial block. The right-hand set shows the effect of a moderate southerly wind. The fire is able, at one point, to cross a road on its down-wind side (third image from top) and is in the process of consuming a second block in the final image.

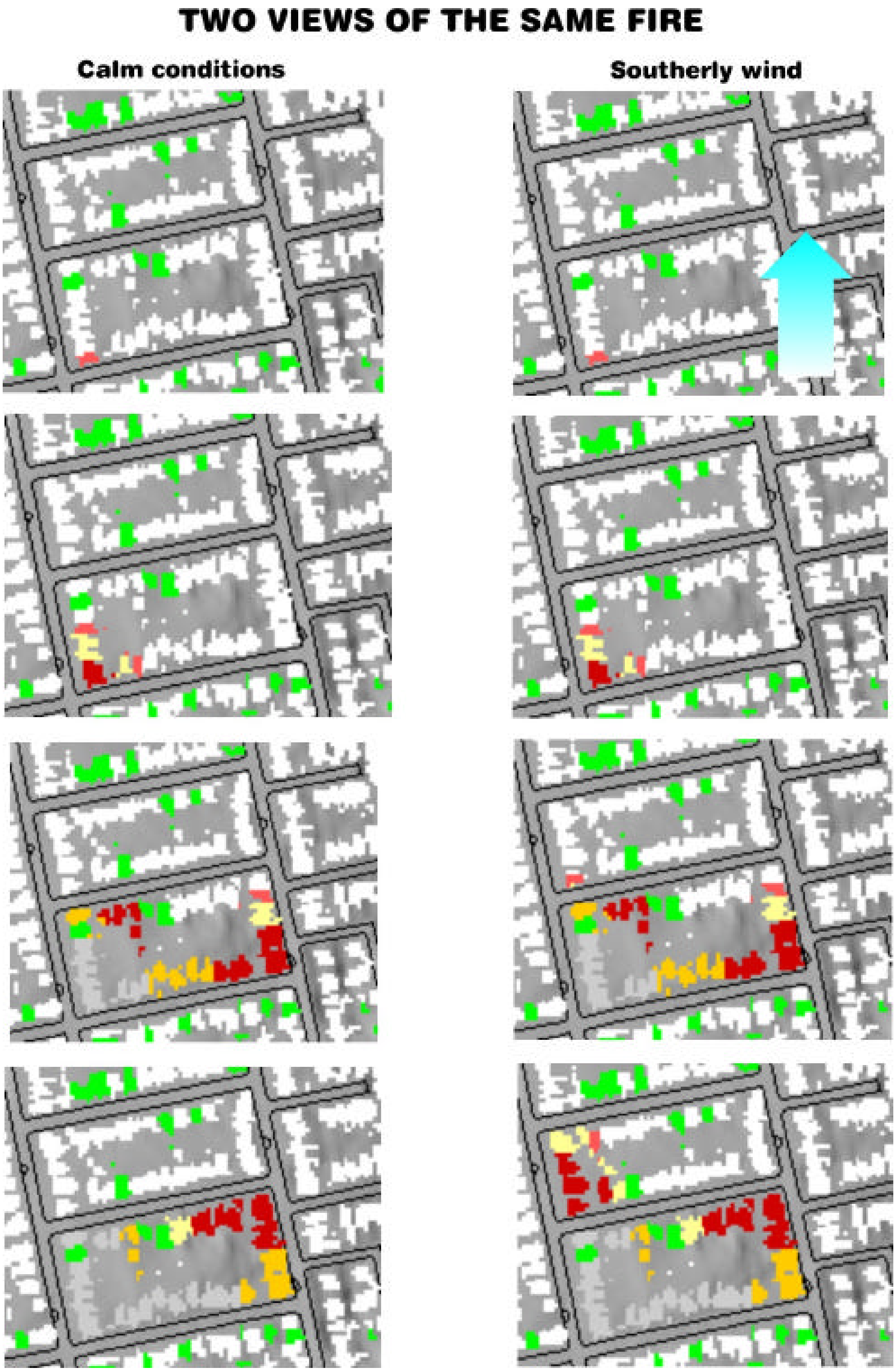

Figure 8: Example of visual display from the dynamic fire-spread model. The left-hand sequence shows the spread of a fire in calm wind conditions. The right-hand sequence shows a southerly wind causing the fire to spread across a road (third image from top).

5.2 Effect of Wind

As an illustration, the model has been run for Wellington City with 27 randomly located ignition points. Twenty-seven is the mean number of expected ignitions based on historical data [25]. There were four runs each with a different wind speed but using the same set of ignition points. The estimated losses (Table 9) varied from 0.4 to 1.3% of the exposure of $23.4 billion in Wellington City. The losses are significantly smaller than the 2% estimated for calm to moderate wind speeds in a previous study [9,10,14], but the previous study permitted fire to spread between some buildings with non-combustible claddings and was based on 40 ignitions for Wellington City. Also, given the highly variable nature of the post-earthquake phenomenon, the probability that any two trials will give the same result is highly unlikely. At least several hundreds of trials would be needed to give a reasonably reliable mean loss.

Wind speed	Calm	Moderate Breeze	Fresh Breeze	Near Gale
Number of buildings burned	358	362	409	1503
Area burnt (1000 m^2)	46	47	50	140
Loss ($millions)	87	89	100	310
Loss (percent of exposure)	0.37	0.38	0.43	1.3

Table 9: Results from the four wind scenarios, showing the number of buildings burned, floor area lost and the replacement value of the buildings lost.

The relatively small increase in total loss from the “calm” to the “fresh breeze” scenarios indicates that the effect of allowing for piloted (spark) ignition of buildings in the downwind direction is apparently not very great. In contrast the combined effect of sparking and branding at a wind speed of “near gale” is quite large. The low level of loss in “calm” to “fresh breeze” conditions can probably be attributed to the relatively large road widths in Wellington [28]. In the outer suburbs road reserves are of the order of 20m wide, with town planning requirements prohibiting building within 3m of the front boundary. This creates an “across-road” gap of 26m between buildings. In the inner suburbs the road reserves are smaller, but timber buildings (mostly dwellings) tend to be built back from the boundaries and the separation distances across streets are rarely less than 15m, which in the model prevents spread except in the downwind direction.

Note, however, that all of the wind-affected results depend very much on the probabilities of ignition assigned to the sparking and branding modes of fire-spread. In our model we assume that branding occurs only at wind speeds greater than “fresh breeze”. In Kobe 20 instances of branding were reported, even though the wind speeds did not exceed “moderate breeze” [23]. More development and calibration of the model are clearly needed in this area.

5.3 Variation in Loss for Single Ignition

The natural variability of the fire-spread problem was investigated by carrying out a large number of trials, 435, each with a single randomly located ignition and "fresh-breeze" level of wind. Fire was assumed not to spread to buildings with non-combustible claddings, and the probabilities of spark ignition and brand ignition were set at 1 and 0 respectively.

The estimated losses ranged from $12,000 to $145 million (implying a factor of 12,000 from minimum to maximum) with a mean of $6.7 million.

5.4 Impact of Earthquake Damage to Non-Combustible Claddings

One of the underlying assumptions in the fire-spread model is that fire cannot spread to buildings with non-combustible cladding. In an earthquake, however, building claddings can be sufficiently damaged that such spread becomes possible. In New Zealand there were two significant milestones in the evolution of building codes and hence in the design and construction of buildings. The first was a minimum earthquake design standard implemented after the Hawke's Bay earthquake of 1931, and the second was a substantial increase in the design earthquake loads for buildings in the 1976 loadings code. The buildings database in our model contains building ages by decades, hence we were not able to match precisely the dates of the code changes. As an approximation, we carried out an analysis assuming firstly that all buildings built prior to 1940 would be damaged to such an extent that fire could spread to and through them and secondly that the same would occur for all buildings built prior to1980. This analysis was carried out for 1 wind speed, a "moderate breeze".

The assumption that fire could spread to (as well as from) all pre-1940 buildings with non-combustible claddings resulted in an increase of 30% in the total loss over the base case of no spread to such buildings. Assuming that fire could spread to all pre-1980 buildings with non-combustible claddings resulted in an increase of 120% over the base loss case.

Using the same wind speed, another analysis carried out with the assumption that fire could spread to all buildings with non-combustible claddings within 3m of another (burning) building. This was to simulate the spread of fire through windows and other openings, or by mechanisms such as from non-fire rated roofs to windows on adjacent higher buildings. In this analysis the expected loss increased by 160% over the base case.

Note that fire-spread should not occur via windows at a 3m separation if both of the buildings comply with the New Zealand Building Code or NZS1900: Chapter 5.

6.0 STATIC BURN-ZONE MODEL

6.1 Background

The static "burn-zone" model has two main features. One is the specification of a "critical separation", which is the maximum distance that a fire can jump from one building to another, and the other is the exclusion of all biasing factors such as wind, ground slope or active suppression. The reasons for not allowing any biasing factors are that the critical separation is then independent of the direction of fire-spread and, consequently, the size and shape of a burn-zone do not depend on which building within the zone is ignited first. In other words, the burn-zones can be defined uniquely by the critical separation alone. Once the critical separation has been selected, the burn-zones are generated within the GIS and summary data are extracted for statistical modelling. The generation of the burn-zones may take some hours of computer processing time for each value of critical separation, but the summary data, once available, can be used to carry out many thousands of fire simulations.

The static burn-zone model is potentially useful for

- statistical investigations of losses due to uncontrolled fire,
- determining the overall significance of post-earthquake fire,
- assessing the value of fire fighting,
- highlighting parts of the city where high losses can be expected,
- highlighting natural firebreaks, and
- assessment of some mitigation measures.

6.2 Generation of Burn Zones for Wellington

Within the GIS database are the footprints of all buildings in Wellington City. To define the burn-zones we draw buffers with width equal to half the critical separation around each building's footprint, and then group together those buildings whose buffers touch or overlap. Regardless of which building within a group (i.e. within a burn-zone) is ignited first, it is assumed that the fire will propagate from building to building until all within the group have been consumed. Figure 9 is an illustration of burn-zones in the Newtown suburb of Wellington as defined by a critical separation of 12m. The labels "1", "2" and "3" respectively show burn-zones comprising a single building, four buildings, and a block of about 27 buildings.

Figure 9: Examples of burn-zones for a mixed residential/commercial area of Wellington as defined by a critical separation of 12m. Fire is allowed to spread from one building to another when the separation is 12m or less, i.e. whenever there is contact between the 6m-wide buffer zones around adjacent buildings.

Note that we have implicitly assumed (i) that all buildings are combustible and (ii) that fire can spread to and from all buildings. Hence the basic model represents a type of worst-case scenario, though not necessarily the worst possible case because vegetation is presently not included in the model.

For each size of critical separation, the buffering process defines a unique set of burn-zones for the entire city. The value of each burn-zone, and hence the loss that occurs if it is burned, is obtained by summing the values of the buildings contained within it.

Our estimate of the replacement value of all buildings in Wellington City is $23.4 billion, distributed amongst 75,800 buildings. Table 10 gives the distribution of that value amongst the various sizes of burn-zone as delineated by critical separations ranging from 10 to 48m. When the critical separation is 12m there are 5310 burn-zones. Most of them, 2739, have values below $1 million and probably represent small groups of houses. The largest has a value close to $1 billion (actual value: $898 million, number of buildings: 92) and is the block of buildings bounded by Lambton Quay, Bowen St., The Terrace, Willis St. and Boulcott St. The bulk of the value of Wellington, about 60% or $14 billion, resides within burn-zones having values within the range $5 million to $50 million (Figure 10). More of the value lies within much larger burn-zones when the critical separation is increased to 20m (Figure 11).

Value of Burn-Zone $millions	Number of Burn-Zones for given Critical Separations (m)								
	10	12	14	16	18	20	24	30	48
0 to 1	4456	2739	1882	1353	1050	821	557	371	170
1.1 to 2	1000	630	426	276	198	152	78	46	24
2.1 to 5	1165	828	558	390	266	177	82	40	22
5.1 to 10	596	534	436	315	216	139	54	28	14
10.1 to 20	342	365	331	239	157	97	43	15	7
20.1 to 50	132	173	180	161	116	66	25	13	9
50.1 to 100	21	28	44	31	37	27	13	5	2
100.1 to 200	7	8	9	18	13	8	3	2	1
200.1 to 500	2	4	5	8	14	13	1	1	0
500.1 to 1000	1	1	1	1	3	4	4	2	0
1000.1 to 2000	0	0	1	0	0	2	3	4	2
2000.1 to 5000	0	0	0	1	1	0	0	0	1
5000.1 to 10,000	0	0	0	0	0	1	0	0	0
10,000.1 to 20,000	0	0	0	0	0	0	1	1	1
All	7722	5310	3873	2793	2071	1507	864	528	253

Table 10: Distribution of the replacement value of Wellington City's buildings amongst burn-zones defined by critical separations between buildings of 10 to 48m.

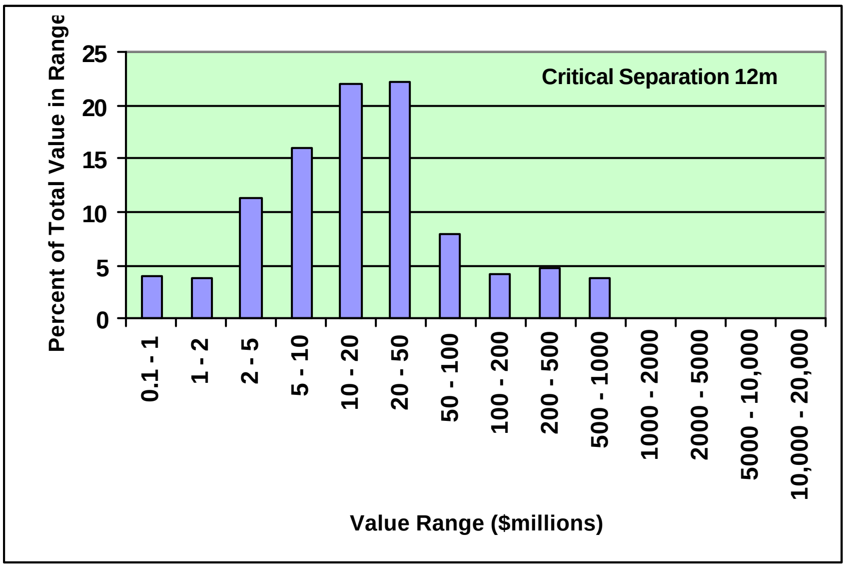

Figure 10: Distribution of the replacement value of Wellington City's buildings amongst the various sizes of burn-zone defined by a critical separation between buildings of 12m, assuming that all buildings are combustible. Sixty percent of the value of Wellington's buildings, $14 billion, lies within burn-zones of $5 million to $50 million in value.

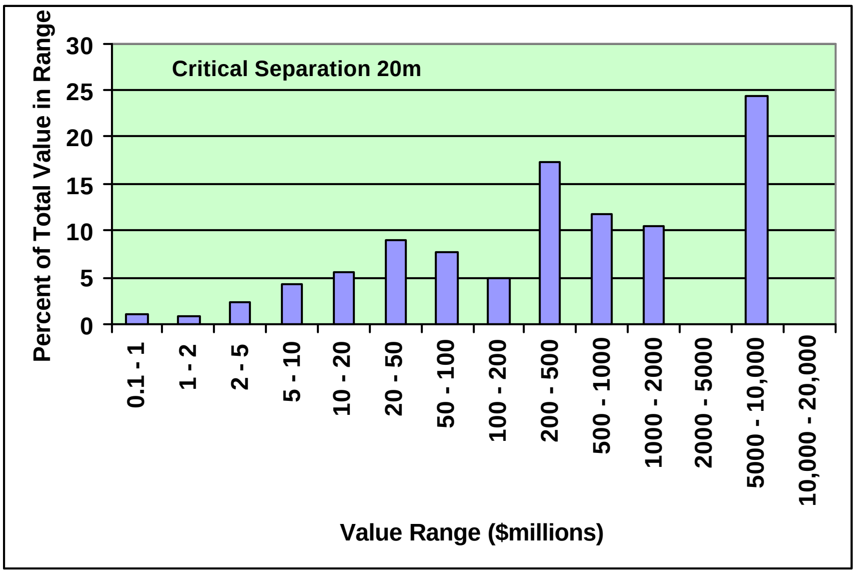

Figure 11: Distribution of the replacement value of Wellington City's buildings amongst the various sizes of burn-zone defined by a critical separation between buildings of 20m, assuming that all buildings are combustible.

7.0 APLICATIONS OF THE STATIC BURN-ZONE MODEL

7.1 Potential losses when Fire Spreads to and from all Buildings

To make use of the burn-zone model in gaining an overview of the significance of post-earthquake fire we have to specify a rule for allocation of ignitions. A very simple one is to assume that each building has equal probability of being ignited. Alternatively we could assign the ignitions in proportion to the floor area, but for the purposes of illustration we chose to allocate by building for simplicity. We randomly distribute a chosen number of ignitions amongst the buildings and, for all zones that are thus ignited, accumulate the total value of the buildings destroyed. Repeating this many times enables us to estimate the probability of exceedance of various levels of loss.

As an example, we consider the case where the critical separation is12m. The width of "buffer" space around each building is therefore 6m, and fire spread is possible whenever adjacent buffer zones come into contact. Figure 9 is for such a situation and shows burnout zones ranging from a single to many buildings.

We then randomly distributed 1, 3, 10, 30 or 100 ignitions over the buildings, accumulating the losses for each trial. This was repeated 10,000 times for each number of ignitions, and the results are summarised in Figure 12, which shows the probability of exceedance of various levels of loss.

The main features of Figure 12 are as follows:

- Regardless of the number of ignitions, the fire losses are always considerably smaller than the shaking loss ($6 billion, vertical dashed line) expected for a large earthquake on the Wellington fault [11,24].

- The 50th percentile loss (shown by the horizontal dashed line) is roughly proportional to the number of ignitions. It increases from about $10 million for 1 ignition to about $1.5 billion for 100 ignitions.

- The uncertainty in the loss decreases as the number of ignitions increases. For 1 ignition the loss ranges from $500 to $898,000,000, a factor of nearly 2 million. For 100 ignitions the range is $1 billion to nearly $3 billion, a factor of only 3.

The entire procedure was carried out for critical separations of 10, 12, 14, 16, 18, 20, 22, 24, 30 and 48m (Figures 13-15). The results show quite clearly that the fire losses remain significantly smaller than the large event shaking loss, regardless of the number of ignitions, provided the critical separation is no more than about 15m. Referring back to Table 3, this implies that for wind conditions from "calm" to "moderate breeze" post-earthquake fire is a relatively minor problem in comparison to shaking and other earthquake-related losses. However, once the conditions are such that the fire is able to cross gaps of 20m and more then the fire losses become very serious indeed.

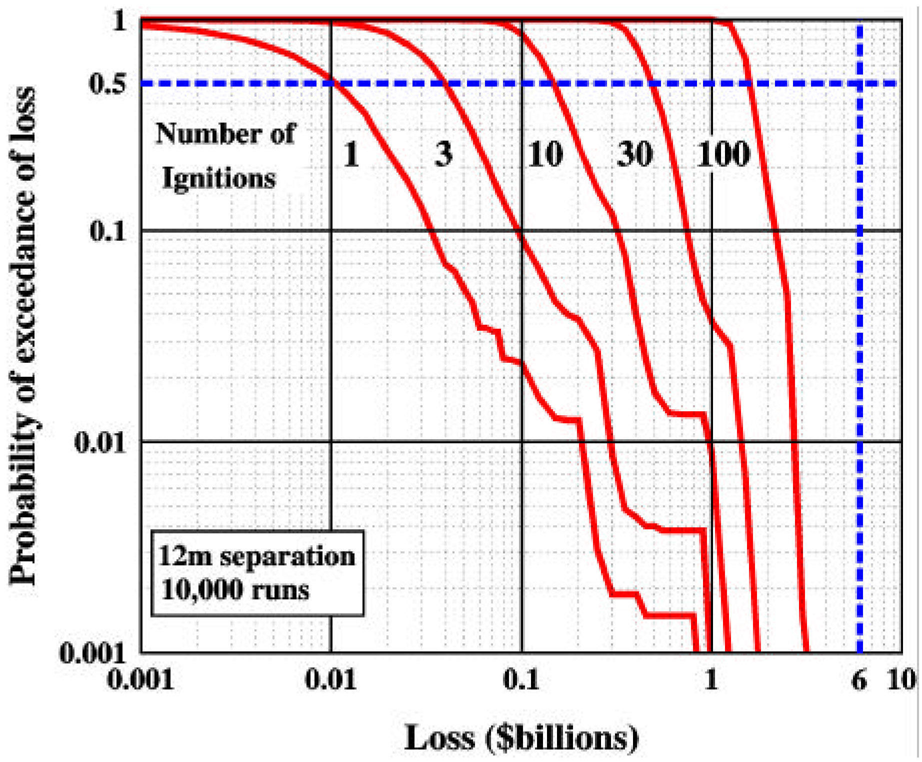

Figure 12: Probability of exceedance of various levels of loss for ignitions randomly distributed amongst the 75,800 buildings of Wellington City after the buildings have been grouped into burnout zones delineated by a critical separation of 12m. The losses are always considerably smaller than the shaking loss ($6 billion, vertical dashed line) expected for a large earthquake on the Wellington fault. The 50th percentile loss level is indicated by the horizontal dashed line.

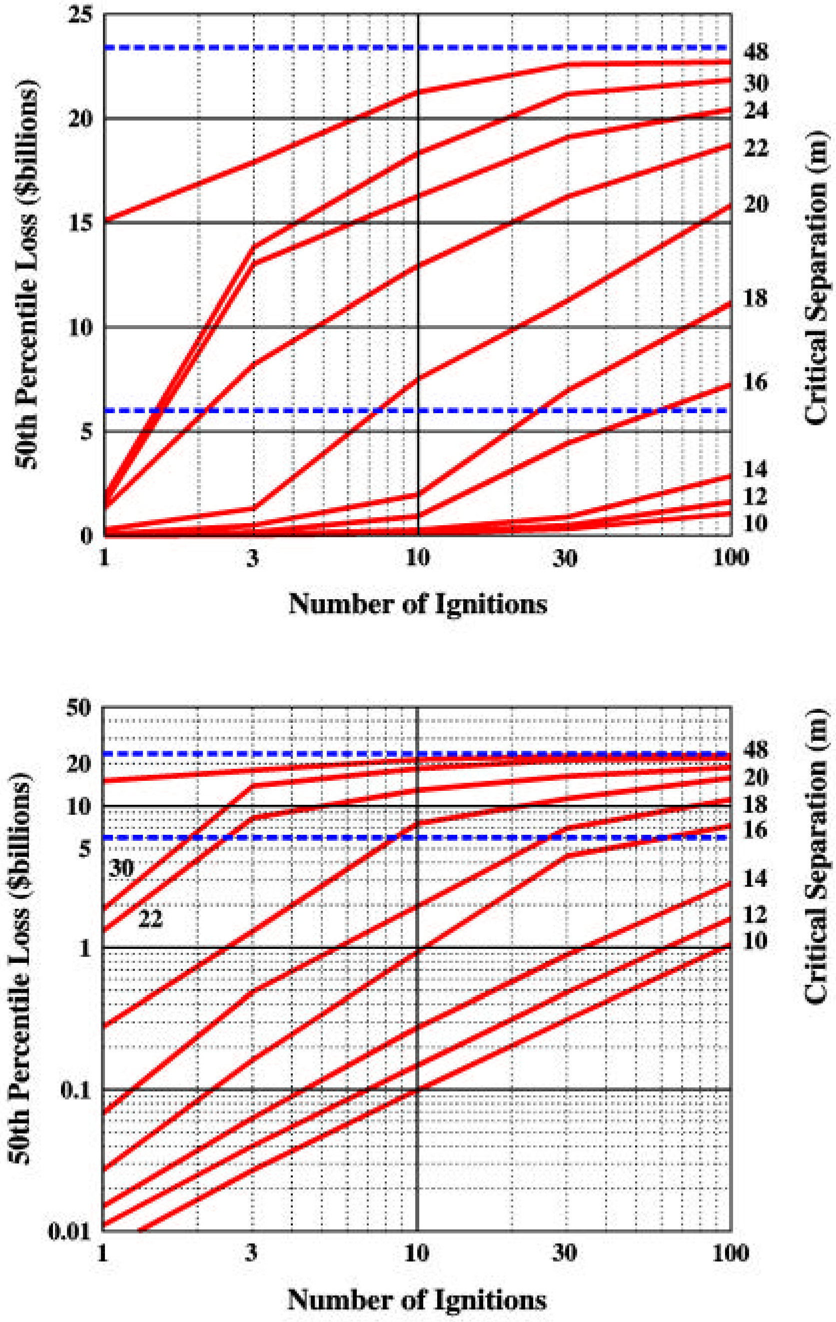

Figure 13: Effect of critical separation and the number of ignitions on the 50th percentile loss for fires affecting Wellington City. In the upper plot the vertical scale is linear and the horizontal scale is logarithmic, and in the lower plot both scales are logarithmic. The lower plot shows that the 50th percentile loss is proportional to the number of ignitions for critical separations of 10 to 14m. The estimated loss due to shaking damage in a magnitude 7.3 earthquake on the Wellington fault ($6 billion) and the total replacement value for buildings in Wellington City ($23.4 billion) are marked with dashed lines.

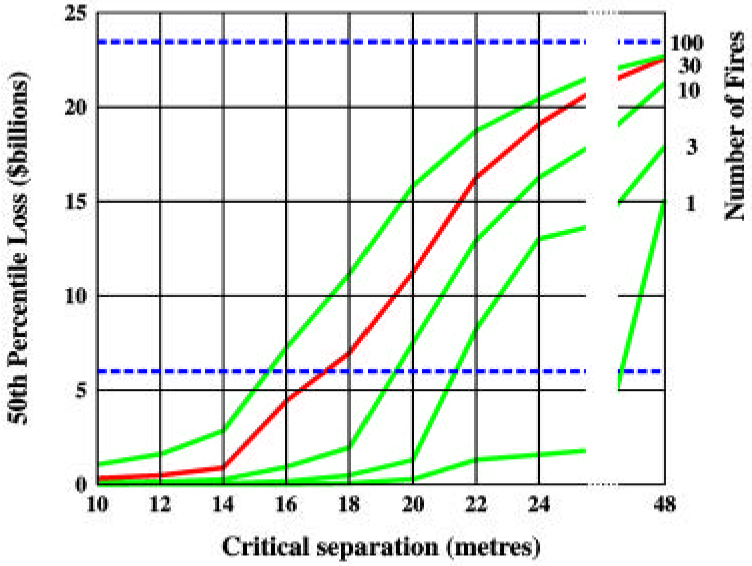

Figure 14: Effect of critical separation and the number of ignitions on the 50th percentile loss for fires affecting Wellington City.

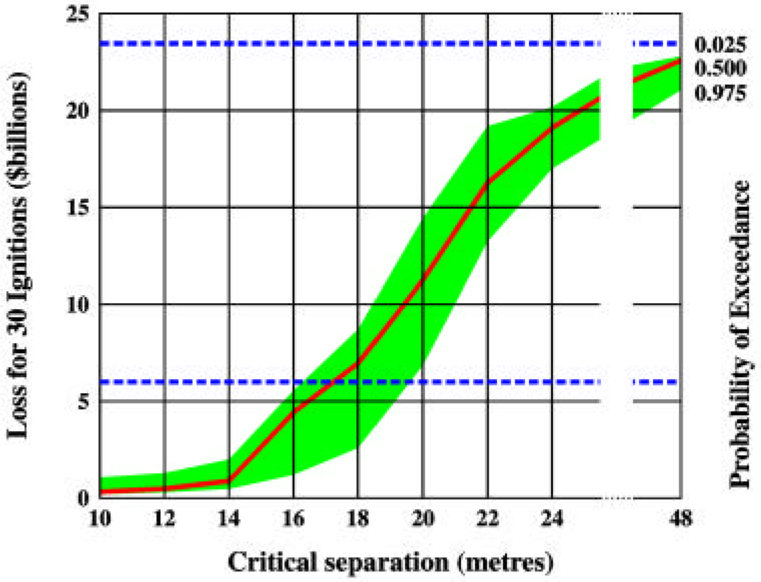

Figure 15: Effect of critical separation on estimated losses from 30 ignitions in Wellington City. The 50th percentile loss is shown by the heavy line, and the 95% confidence interval by the shaded band. The estimated loss due to shaking damage in a magnitude 7.3 earthquake on the Wellington fault is $6 billion (lower dashed line). Assuming 30 ignitions in such an earthquake the fire loss is much smaller than the shaking loss for critical separations up to 15m, but greatly exceeds the shaking loss for critical separations of 20m and above. The total replacement value for buildings in Wellington City is about $23.4 billion (upper dashed line).

Referring to the lower part of Figure 13 it can be seen that, for critical separations of up to 14m, the 50th percentile loss is closely proportional to the number of ignitions, and for 14m to 18m is roughly proportional. This implies that, for quite a wide range of conditions, simply minimising the number of ignitions and/or promptly containing any fires that do start are good way of minimising fire losses. For critical separations of 20m and above, particularly when there are multiple ignitions, there is an apparent saturation in the losses and reducing the numbers of ignitions is then less effective as a mitigation measure.

Figure 15 gives an indication of the variability in the estimates. For the illustrated case of 30 ignitions the 95% confidence interval is reasonably compact.

7.2 Fire Spreads neither to nor from Concrete-Clad Buildings

As already mentioned above, the situation in which fire can spread to and from all buildings is unduly severe. In order to represent a more realistic situation, we assume that fire is not able to spread either to or from concrete-clad buildings. This is implemented by removing all such buildings from the database prior to the buffering process and then reinstating them at the end as “single-building” burn-zones.

In a real fire situation we would expect a reasonably large proportion of concrete-clad buildings to be resistant to fire-spread. Some would be sufficiently damaged by earthquake shaking to lose their inherent protection and others already have sufficient unprotected openings to be susceptible. Similarly, some iron-clad and some brick-clad buildings would be resistant to fire-spread and some would not. Treating all concrete-clad buildings as being resistant to fire-spread, and all other buildings as not, is a crude but easily implemented way of simulating the overall resistance to fire-spread.

In Wellington there are 7427 concrete-clad buildings with a total value of $7,503 million. Isolating them from the fire-spread simulation has a significant effect on the estimated fire losses (Figures 16 and 17). For any given critical separation, the losses are roughly halved and, perhaps more significantly, the critical separation at which the fire losses start to become serious is increased from 15 to 20m. Thus winds stronger than “fresh breeze” are required before the post-earthquake fire losses will exceed the shaking losses.

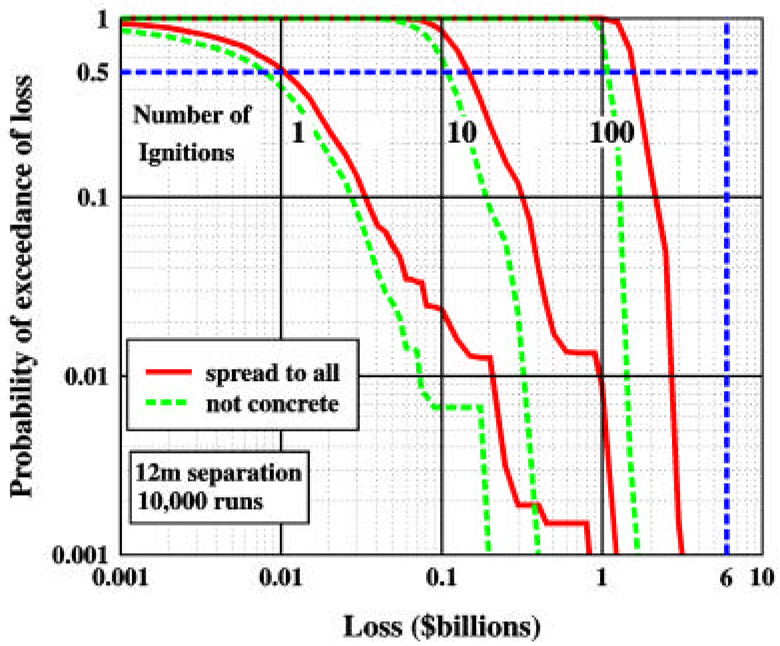

Figure 16: Effect of preventing fire-spread to and from concrete-clad buildings on the fire losses for a critical separation of 12m.

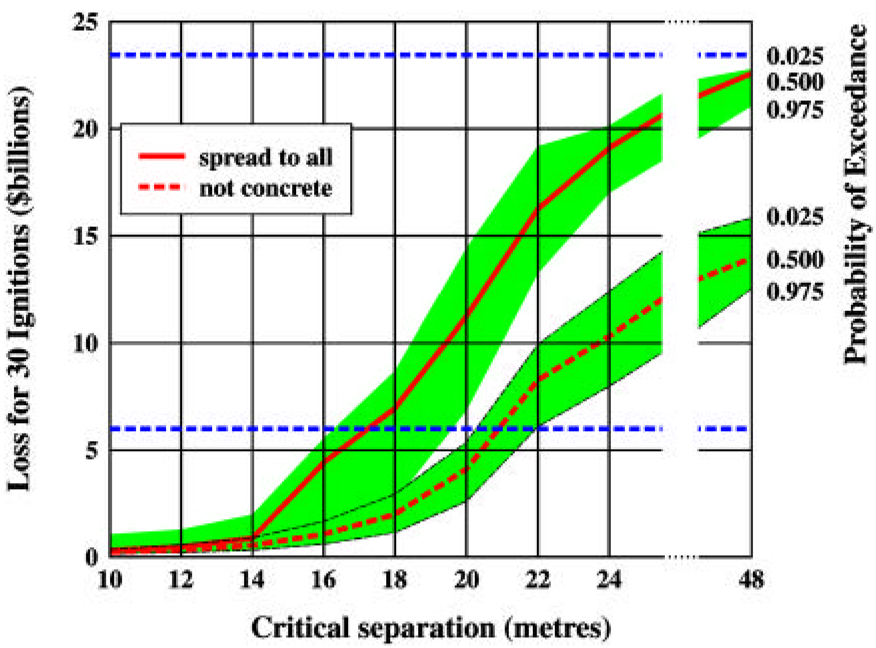

Figure 17: Effect of preventing fire-spread to and from concrete-clad buildings on the losses arising from 30 ignitions.

7.3 Subdivision of Large Burn-Zones

As a somewhat arbitrary simulation of the effect of creating additional firebreaks throughout Wellington, the burn-zones were subdivided. Two examples were considered. First, just the largest value burn-zones were each subdivided into three equal portions. For critical separations of 10-14m the top 30 zones were subdivided, for 16-20m the top 20, for 24m the top 10, for 30m the top 4, and for 48m the top 2. Second, all burn-zones were subdivided into two equal portions.

The reductions in losses from the extra “firebreaks”, Table 11 and Figure 18, were often not particularly large. At first sight this is surprising, because an intuitive approach to minimising loss from a spreading fire is to halt the spread by creating a firebreak. However the effectiveness of that approach depends on the fact that the fire is “known”. In the modelled situation the locations of the fires are not known in advance, and so in principal it would be necessary to subdivide every single burn-zone in order to guarantee significant reductions in losses.

In both cases the relatively small reductions in loss that occur when the critical separations are 20m and above is probably a result of the large number of ignitions. Even after the subdivisions much of the value remains concentrated in a small number of large zones and, when there are 30 ignitions, the probability that all are ignited remains high.

The reductions in loss were also small, for critical separations of 10 to 14m, when only the largest burn-zones were subdivided. A likely reason for this is that, for such small critical separations, the bulk of the value and the bulk of the loss resides in burn-zones smaller than those that were subdivided (Figure 10).

Critical Separation (m)	50th Percentile Loss ($millions) for 30 fires			Reduction over base case (%)	
	Base case	Large burn-zones subdivided into 3 parts	All burn-zones subdivided into 2 parts	Large burn-zones subdivided into 3 parts	All burn-zones subdivided into 2 parts
10	$310	$290	$160	7	48
12	$490	$420	$250	14	49
14	$890	$630	$450	29	49
16	$4,400	$2,000	$2,300	55	48
18	$7,000	$3,300	$3,900	53	44
20	$11,000	$6,800	$8,600	38	22
22	$16,000	$13,000	$14,000	19	19
24	$19,000	$16,000	$17,500	16	8
30	$21,000	$19,000	$19,500	10	7
48	$22,600	$22,500	$21,800	0.4	4

Table 11: Effect of creating additional urban firebreaks on losses from 30 ignitions.

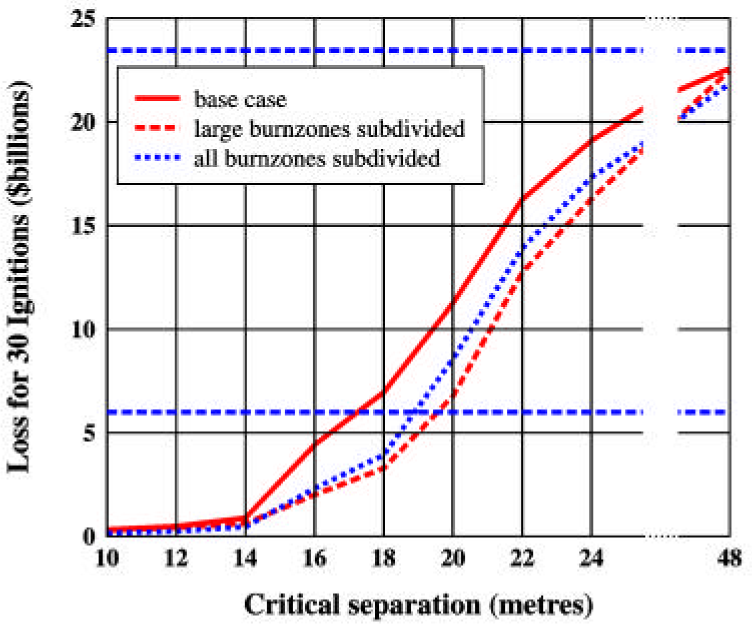

Figure 18: Effect of creating additional firebreaks on 50th percentile losses arising from 30 ignitions. The dashed line is the loss when large burn-zones are each divided into 3 equal portions, and the dotted line is the loss when all burn-zones are divided into 2 portions.

7.4 Potential Losses from a Single Ignition

In principal, either of the two models can be used to estimate the cost of not fighting fires by randomly locating single ignition points many times and averaging the losses. Results of such a simulation using the static burn-zone model are given in Table 12. For calm or light-wind conditions (i.e. when the critical separation is about 12m) the 50th percentile loss is about \$8 to \$11 million depending on whether or not fire can spread to concrete clad buildings. For very high wind conditions (large critical separations) the loss could exceed \$1 billion.

Critical Separation (m)	50th Percentile Loss (\$millions)	
	Fire Spreads to and from All Buildings	No Spread to and from Concrete-Clad Buildings
10	\$7	\$5
12	\$11	\$8
14	\$15	\$11
16	\$27	\$16
18	\$60	\$31
20	\$280	\$70
22	\$1,300	\$400
24	\$1,600	\$700
30	\$1,900	\$1,300
48	\$15,000	\$1,700

Table 12: Estimated 50th percentile losses from one ignition and various critical separations.

8.0 INITIAL DISCUSSION OF MITIGATION OPTIONS

One of the important uses of the fire-spread models is to provide a framework for evaluating the effectiveness of various ways of mitigating losses from post-earthquake fires. There are two aspects of the mitigation to be considered, i.e. measures to be taken before the earthquake, and measures to be taken after.

Neither model is yet fully developed. Two important features remaining to be incorporated are the effects of ground slope and vegetation. Bearing this in mind, some tentative conclusions that may be derived from the few applications of the models as outlined above are as follows:

- Losses due to fire following a major earthquake centred on Wellington City are likely to be smaller than losses due to shaking, provided the wind at the time is no stronger than a "moderate breeze". However fire losses could greatly exceed shaking losses for "near gale" and stronger winds.

  The first assertion, that fire losses are likely to be relatively small under low-wind conditions, is probably quite sound. It is derived from a "worst case" application of the static model in which all building claddings are assumed to be combustible and the necessary condition that the fire can spread uniformly in all directions is achievable.

  The second assertion, that fire losses could greatly exceed shaking losses for high-wind conditions, needs more investigation. According to the static model, fire losses exceed shaking losses when the fire is able to jump gaps of about 17 to 21m (Figure 17). For this to occur it would need to be wind-driven, in which case the assumption of uniform spread in all directions is not valid. However maps of the large burn-zones show that many have a very distinct north-south elongation, which is almost certainly a result of the strongly linear ridge-valley topography of Wellington. Thus complete burnout of many of the large burn-zones remains possible provided that the ignitions are suitably placed. All that is changed is that the probability is reduced.

- Added firebreaks appear not to be an effective way of minimising fire losses when there are multiple (30 or so) ignitions. Very large numbers of firebreaks could make a worthwhile difference to losses in low-wind conditions when fires are not able to jump gaps of 20m or more, but the cost of creating them would be very high. Simply providing buildings with fire-resistant claddings may be a much more cost-effective way of achieving the same result.

- For "calm" to "fresh-breeze" conditions, the fire loss is roughly proportional to the number of ignitions. Thus minimising the number of ignitions is a very good mitigation measure, as is the immediate containment of any fires that do start.

- The cost of not fighting fires is significant even under normal (i.e. non post-earthquake) conditions. For single ignitions the 50th percentile loss varies from about \$10 million in calm or light-wind conditions to more than \$1 billion for severe wind conditions.

8.1 Before the Earthquake

8.1.1 New Zealand building codes

History shows that a significant proportion of post-earthquake fires have been extinguished by building occupants [1,23]. The installation of fire hose reels in buildings as previously required by *The Acceptable Solutions for Fire Safety* [4] is probably of little value post-earthquake due to the likely unavailability of water supplies. The provision of hand-held fire extinguishers however is likely to result in a decrease in the number of ignitions that lead to major fires. A requirement for portable fire extinguishers in buildings is therefore recommended.

The latest version of *The Acceptable Solutions for Fire Safety* [4] has less severe requirements for boundary separations than did its predecessor. The use of the latest provisions can be expected to result in an increased occurrence of spread of fire between buildings. The justification for the relaxation of the provisions was that spread of fire between buildings is a rare occurrence. It should be noted that fire spread between buildings is often prevented because the NZFS is able to protect the exposed buildings, and not necessarily because of the passive protection measures required by the *Acceptable Solutions*. If the New Zealand Fire Service (NZFS) either is unavailable after an earthquake, or has no water, then buildings that meet the statutory requirements might not necessarily be protected against fire spread.

It is also important that fire rated glazing systems in areas with high seismic zone coefficients be able to survive earthquakes. Failure of such systems resulted in fire spread to adjoining buildings in Kobe [23]. Such systems must be designed, constructed or installed in such a manner that they will not be damaged with the levels of inter-storey drift expected in the ultimate strength limit state earthquake as defined by NZS4203 [30]. Any closures and penetrations between buildings and seismic gaps within buildings must also be designed, constructed or installed in such a manner that they will not be damaged with the levels of inter-storey drift expected in the ultimate strength limit state earthquake.

8.1.2 Prevention of ignitions

Minimising the number of ignitions is clearly highly desirable. Achieving this will require actions by many people, which in turn may require a programme of education about the potential danger from post-earthquake fires and training in what preventative actions should be taken.

8.1.3 Permanent fire breaks

The creation of additional permanent firebreaks is not supported by the results from the modelling so far. However further modelling needs to be done, assuming smaller numbers of ignitions than the 30 considered above and allowing for the effect of vegetation.

8.2 After the Earthquake

8.2.1 Immediate containment

Just as minimising the number of ignitions is highly desirable, so is the immediate control of any fires that start. Once again this requires action by the many people-on-the-spot. Education as to the importance of putting out the fires may be needed, as is training on what actions should be taken. Suitable fire-fighting equipment will have to be provided.

8.2.2 Priority setting

After any major earthquake close to a major urban centre in New Zealand the NZFS will face overwhelming demands for assistance. Potential activities will range from urban search and rescue to multiple-incident fire fighting. Prioritising will be essential.

At an overview level, the fire-spread models suggest that under light-wind conditions fires probably won't add greatly to shaking losses. In such conditions, the resources of the NZFS could be concentrated on search and rescue. The converse would be true under high-wind conditions.

At a more detailed level, once the locations of fires have been reported, the models can in principle be used to give situation-specific estimates of losses. In particular, when the wind speeds are high, the majority of fire losses can be caused by a small number of fires. Given a set of ignitions, the dynamic fire spread model can be used to determine which pose the greatest risks and resources could then be directed towards them.

8.2.3 Fire-fighting techniques

The greatest losses occur when wind-speeds are high enough that branding is a major mechanism for fire spread. The widths of firebreak needed to counter branding, i.e. 45m or more, are too large, and so firebreaks alone are inadequate for fire fighting. A combination of active and passive measures may mean that even relatively narrow firebreaks may, however, be helpful.

Fire fighting at a small firebreak would involve the use of the firebreak to prevent spread by radiant ignition, with active suppression being used to prevent the development of fires from sparks and brands. In the absence of water this could be done using hand-held fire-fighting equipment and methods such as shovelling dirt over embers or beating out flames, all of which are standard rural fire fighting techniques. Locations where embers have landed could be pin-pointed using infra-red cameras carried by hand or from helicopters.

Rural fire-fighting teams are trained in this sort of fire fighting. They are able to travel at short notice and to survive in the field. There are also large numbers of them available in New Zealand. They and their equipment could be transported to Wellington more easily than could conventional fire fighting personnel and equipment.

8.2.3 Creating Fire Breaks

Once the locations of fires are known, then firebreaks could in principal be effective for containment. Real-time use of the dynamic fire-spread model could facilitate optimum placement of the new breaks. Given a large enough degree of risk, even the demolition of buildings using heavy machinery and explosives could be countenanced. Loss estimates provided by the dynamic model could assist with the making of such decisions.

9.0 RECOMMENDED FURTHER DEVELOPMENT AND MODELLING

Important features that need to be added to both models are as follows:

- vegetation (which is an important fuel type that is presently ignored),
- occupants of buildings (for estimating displaced persons and casualties), and
- calibration against historical conflagrations and expert opinion.

For the fire-spread model alone the following are needed,

- modelling of the effects of ground slope and building height, and
- improved modelling of the typically closely-spaced highly-valued buildings in a central business district (the dynamic fire-spread model appears to under-predict losses in the CBD whereas the static buffer model appears to over-predict them).

An interesting and potentially valuable possibility for the static model is probabilistic modelling. On its own the static model does not relate the critical separations to various sets of climatic and other conditions, but such relationships could be established indirectly via the dynamic model. Once that is done, it would be relatively straightforward to set up a probabilistic model that could account for many of the variables involved, including in the size and location of an earthquake, shaking attenuation models, numbers of ignitions, season, and wind speed.

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