

Firebrands and spotting ignition in large-scale fires

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Abstract. Spotting ignition by lofted firebrands is a significant mechanism of fire spread, as observed in many large-scale fires. The role of firebrands in fire propagation and the important parameters involved in spot fire development are studied. Historical large-scale fires, including wind-driven urban and wildland conflagrations and post-earthquake fires are given as examples. In addition, research on firebrand behaviour is reviewed. The phenomenon of spotting fires comprises three sequential mechanisms: generation, transport and ignition of recipient fuel. In order to understand these mechanisms, many experiments have been performed, such as measuring drag on firebrands, analysing the flow fields of flame and plume structures, collecting firebrands from burning materials, houses and wildfires, and observing firebrand burning characteristics in wind tunnels under the terminal velocity condition and ignition characteristics of fuel beds. The knowledge obtained from the experiments was used to develop firebrand models. Since Tarifa developed a firebrand model based on the terminal velocity approximation, many firebrand transport models have been developed to predict maximum spot fire distance. Combustion models of a firebrand were developed empirically and the maximum spot fire distance was found at the burnout limit. Recommendations for future research and development are provided.

Additional keywords: fire spread, forest fire, post-earthquake fire, urban conflagration, wildland–urban interface fire.

Introduction

Spotting ignition by lofted firebrands, or pieces of burning wood, is a significant mechanism of fire spread (Tarifa *et al.* 1965a; Williams 1982). The threat of spotting ignition increases as the scale of the main fire enlarges because a larger fire produces a larger and stronger plume with faster vertical and radial fire-induced wind velocity (Pitts 1991; Trelles and Pagni 1997) capable of lofting larger firebrands a greater distance. Thus, spotting can become the dominant fire-spread mechanism in large conflagrations and wildland fires. Spot ignition, a discontinuous fire spread mechanism, frequently overwhelms fire suppression efforts, breaching large barriers and firebreaks. The atmospheric conditions that are favourable to contiguous fire spread, such as high wind velocity and low humidity, also enhance this discontinuous fire spread mechanism, increasing both spotting distance and ignition probability (Sheahan and Upton 1872; Bell 1920; National Board of Fire Underwriters 1923; Wilson 1962; Anderson 1968; Wells 1968; Pagni 1993; Greenwood 1999; Pernin 1999). The conditions of the recipient fuel are also critical, not just because firebrands ignite fuels, but also because the ignited recipient fuel becomes another source of firebrands. The criteria of ignition due to landed firebrands are strongly related to weather conditions. In the historical wind-driven conflagrations of London (1666), Chicago (1871), Peshtigo (1871), Berkeley (1923), Bel-Air (1961), Oakland

(1991), and Grand Forks during the Red River Flood (1997), spot ignitions were found to be a dominant mechanism in fire spread (Goodsell 1871; Sheahan and Upton 1872; British Fire Prevention Committee 1917; Bell 1920; National Board of Fire Underwriters 1923; Railroad Commission of the State of California Hydraulic Division 1923; Wilson 1962; Wells 1968; California Department of Forestry and Fire Protection 1991; National Fire Protection Association 1991; Brenner 1993; Pagni 1993; Sullivan 1993; Bredeson 1999; Greenwood 1999; Pernin 1999). Along with these wind-driven conflagrations, post-earthquake fires at San Francisco (1906), Tokyo (1923), Loma Prieta (1989), Kobe (1991) and Northridge (1994) were studied for spot fire conditions (National Board of Fire Underwriters 1906; Engle 1929; Bronson 1959; Brown and Hillside Press 1976; Scawthorn 1987; Hale and Hale 1988; Scawthorn and Khater 1992; Louie 1996; Quintiere 1997; Scawthorn *et al.* 1998; Kurzman 2001; City of Kobe 2005; Iversen 2006).

The phenomenon of spotting can be broken down into three main sequential mechanisms: generation, transport, and ignition of fuel at the landing position. These three mechanisms have many submechanisms. Thus, firebrand research requires covering a broad range of topics. For example, to understand firebrand generation, degradation of wood due to pyrolysis and combustion should be understood. Firebrand transport includes topics such as flame structures, airflow induced by the fire, interaction

between fires and local weather, aerodynamics around firebrands including drag forces, combustion of firebrands during flight with criteria for extinction, and heat transfer of firebrands during flight. In ignition by firebrands, ignition criteria for various recipient fuels, heat capacity of firebrands, and heat transfer between firebrands, air, and recipient fuel are involved. Smouldering combustion and its spread and development should also be considered. All of these subjects should be understood to some degree in order to gain a broad understanding of firebrand phenomena, even though not all the subjects above are incorporated in current firebrand research.

This paper reviews the literature that forms the current state of firebrand research. Many experiments have been performed to understand firebrand behaviour. Based on these experiments, many firebrand transport models have been developed. Most of the models were designed to estimate maximum spot fire distance. The phenomenon of spotting has again become an area of active research interest and there has been a recent proliferation of papers on the subject. Although we have attempted to provide an up-to-date review of current work, we have certainly missed the most recent developments in the field. Any error of omission is not intentional. This review covers literature through 2008. After a review of the literature, recommendations for future firebrand research are briefly suggested.

Firebrand and conflagrations

Historically, conflagrations have been one of civilisation's major disasters, from the Great Fire of Rome in 64 AD to the Cedar Fire of southern California in 2003 to the more recent fires in Australia, Greece, and Portugal to mention a few. Disastrous conflagrations have been recorded throughout history because of profound impacts on society. For example, the Roman historian Tacitus described the Great Fire of Rome in *Annals*. It is possibly the first recorded conflagration in Western civilisation; many conflagrations since have produced their own documents, some of which are cited in this paper. Evidence of spotting ignitions can be found in such documents even though many documents on historical conflagrations lack a scientific point of view. These documents also depict the conditions and the roles of firebrands in the spread of large-scale fires.

Conflagrations occur generally when strong winds drive a fire to overwhelm human suppression efforts. Besides atmospheric conditions, limited fire suppression resources can fail to control multiple simultaneous fires, resulting in a conflagration, for instance, during warfare or after an earthquake. Multiple fires commonly break out simultaneously after earthquakes owing to damage inflicted during the earthquake such as breakage of gas pipes, stoves or furnaces, and spilling chemicals. If strong winds blow after an earthquake hits, the damage of the post-earthquake fire can become larger than the damage of the earthquake itself. For example, the 1906 San Francisco earthquake (Bronson 1959; Kennedy 1963) and the 1923 Great Kanto earthquake (Quintiere 1997) were followed by fires more destructive than the earthquakes themselves. In these large post-earthquake fires, firebrand activity and spot fires were observed and played important roles in fire spread.

Lessons from historical large-scale fires

Discontinuity

Spotting ignition can break fire defence lines. In the 1666 London Fire (Bell 1920), people desperately formed a defence line around Saint Paul's Cathedral, but failed to save it because of firebrands that ignited the roof after the fire jumped across the defence line and surrounding churchyard. The 'leaping' fires, described as a fire behaviour characteristic of discontinuous roof-to-roof spread in the 1666 London Fire (Bell 1920), created by firebrands, make firebreaks vulnerable in many conflagrations. Historical evidence of fire leaping across firebreaks such as rivers – the Chicago River in the 1871 Chicago Fire (Sheahan and Upton 1872); roads – Powell Street in the 1906 San Francisco Fire (Bronson 1959), Mulholland Drive in the 1961 Bel-Air Fire (Greenwood 1999); freeways – San Diego Freeway in the 1961 Bel-Air Fire (Greenwood 1999), Highway 24 in the 1991 Oakland Hills Fire (Pagni 1993) is indicative of the problem. Firebrands jumped across sea to reach an island – Moon Island (Tsukushima) in the 1923 Tokyo Fire (Tokyo Imperial University 1923). In the Red River Flood in 1997, fire jumped approximately 11 buildings over the surrounding floodwater, in the city of Grand Forks, MN (Shelby 2004). The distance of spotting becomes as great as a few kilometres when the scale of a fire gets large, such as forest fires (Wells 1968) and anecdotal distances of 30 km have been reported in Australia (Chandler *et al.* 1983).

Spotting ignition sometimes makes fire spread unpredictably fast. Fourteen firefighters were trapped by the fast-spreading upslope fire initiated by spotting from the slow-spreading downslope fire and lost their lives in the 1993 South Canyon Fire on the Colorado Storm King Mountain Fire (Butler *et al.* 1998). When spotting becomes dominant, a fire suppression line loses efficacy. Figs 1–4 show the maps of the 1991 Oakland Hills Fire (Woycheese 2000). These maps, in which coloured areas indicate fire spread, show how much faster fire spreads through a large area owing to spotting. In the 1961 Bel-Air Fire report, this situation is described:

'There was no contiguous fire boundary. Instead, there were scores of large fires scattered over a wide area, each sending thousands of brands into the air to swarm out to ravage new sections.' (Greenwood 1999)

Weather conditions

Weather conditions, especially wind, are the most critical factor in spotting ignition, because strong wind increases firebrand hazard in all respects, enhancing firebrand generation, transport, and recipient fuel ignition by firebrands. First of all, strong wind can increase convective heat transfer to assist contiguous fire spread. Strong wind makes a main fire larger and increases buoyant force in the flame and plume, which can loft larger firebrands. Second, stronger wind can transport firebrands further, because the drag force on a firebrand, which is the driving force of firebrand transport, is proportional to the square of wind speed. Third, wind supplies oxygen; thus, strong wind helps ignition of recipient fuels and transition from smouldering to flaming combustion, unless the wind is strong enough to cool the firebrand off or detach the flame from the firebrand.

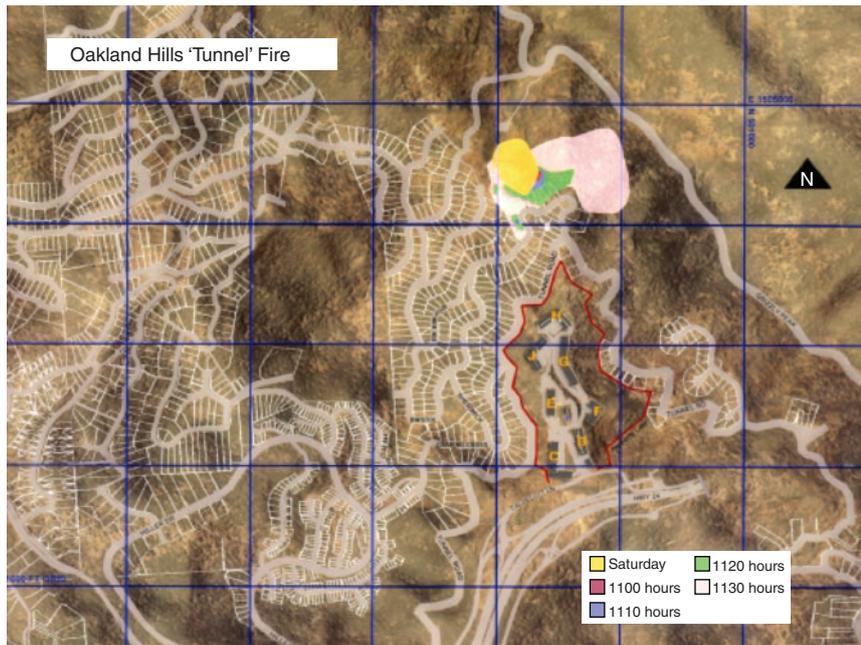


Fig. 1. Synopsis of propagation of the Oakland Hills Fire of 1991 as developed from eyewitness and emergency crew accounts and 911 phone calls by Dave Sapsis of UC Berkeley. The winds were blowing from the north-east as shown in Fig. 7. The blue lines are the California State grids, which have 300-m spacing. The fire propagation for the first half-hour of the Sunday conflagration is colour-coded as shown in the legend. From fig. 1.1 (p. 15) of Woycheese (2000), reproduced with permission.

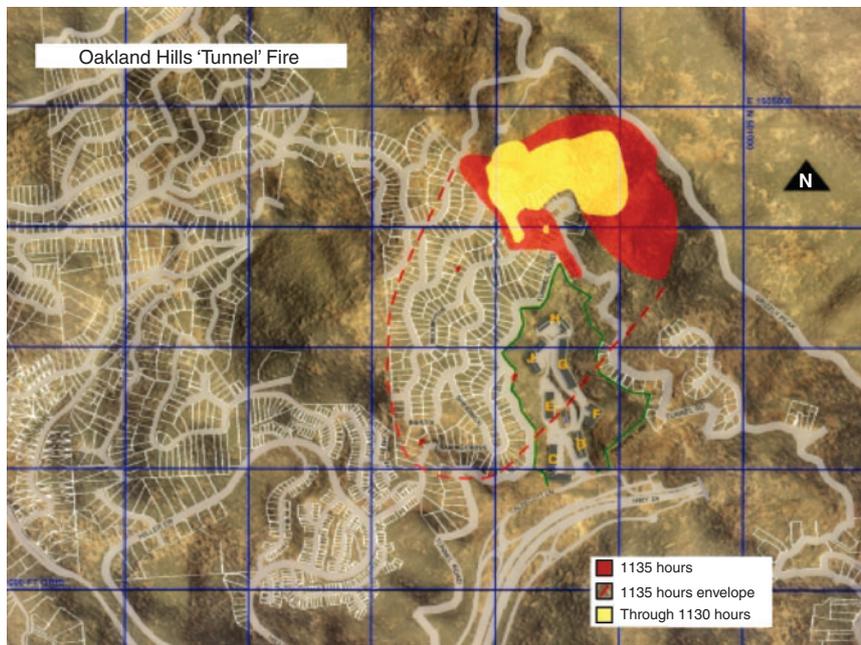


Fig. 2. Continuation of the spread of the Oakland Hills Fire of 1991 as developed by Dave Sapsis. The scope of the first 30 min of the fire is shown in yellow, and the propagation during the subsequent 5 min is outlined by the red dashed line, with the contiguous fire front shown by the solid red area. Note the three spot fires that have been initiated during this period to the south-west of the main fire. From fig. 1.2 (p. 16) of Woycheese (2000), reproduced with permission.

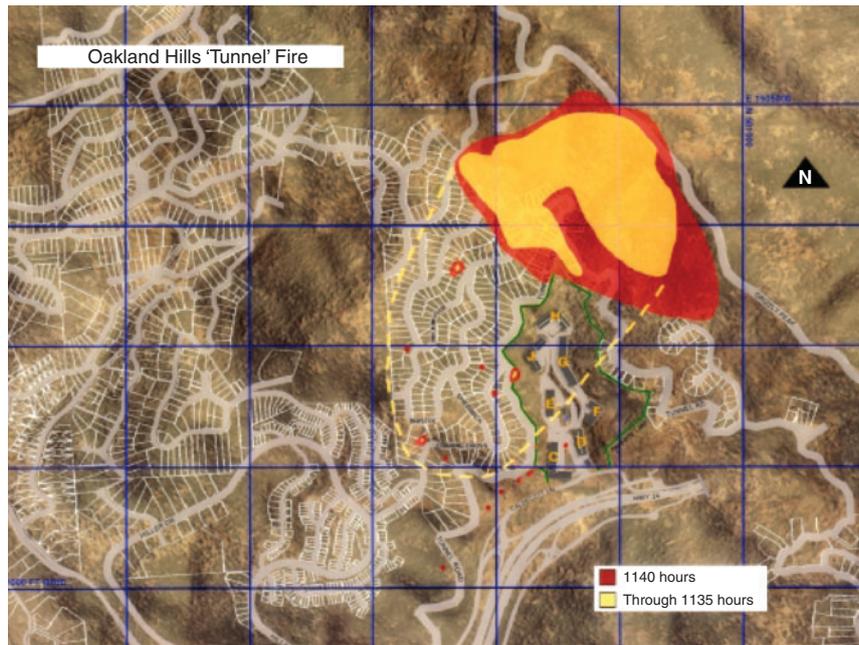


Fig. 3. Extent of the Oakland Hills Fire of 1991 through 1140 hours, as developed by Dave Sapsis, where the spread shown in the previous figure is represented by the area outlined in yellow. During the subsequent 5 min, the fire propagated as shown in red. The three spot fires have grown, and a multitude of new spot fires have been initiated during this 5-min period. From fig. 1.3 (p. 17) of Woycheese (2000), reproduced with permission.

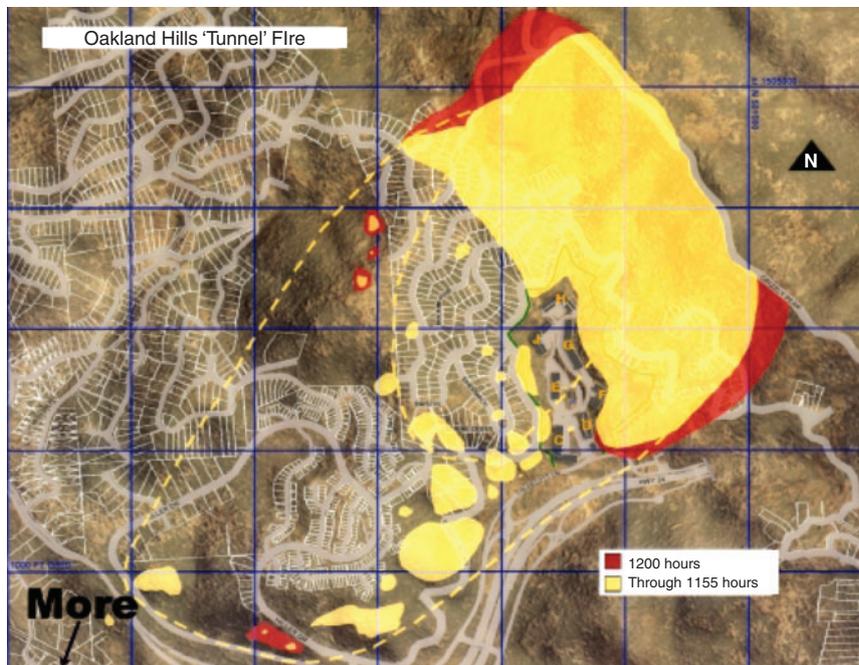


Fig. 4. Extent of the Oakland Hills Fire of 20 October 1991 through 1200 hours, as provided by Dave Sapsis. The scope of the fire through 1140 hours, as shown in Fig. 3, is indicated by inner yellow dashed line. By 1200 hours, spot fires have been initiated more than 1 km from the main, contiguous fire front. 'More' in the map indicates that there were more spot fires in south-west, which is downwind. From fig. 1.4 (p. 18) of Woycheese (2000), reproduced with permission.

Strong wind can combine with low relative humidity to increase the risk of spot fires. Low relative humidity also helps the ignition of recipient fuel because dry air cannot act as a heat sink during the firebrand transport and after landing. In addition, low humidity typically yields low moisture content of recipient fuels. Drought before large-scale fires and conflagration are very common, as shown in the 1666 London Fire (Bell 1920), in 1871 in Chicago (Sheahan and Upton 1872) and in Peshtigo (Wells 1968; Pernin 1999). In the 1991 Oakland Hills Fire, relative humidity was recorded as almost zero (Pagni 1993; Trelles and Pagni 1997). In regions with föhn wind, which is a dry wind associated with wind flow down the lee side of a plateau or mountain range and with adiabatic warming (Wilson 1962), the spot fire hazard increases. In the United States, föhn winds exist as the Diablo wind of the San Francisco Bay Area (1991 Oakland Hills Fire), the Santa Ana wind of southern California (1961 Bel-Air Fire), the East Wind in western Washington and Oregon and the Chinook wind of the Rocky Mountains. One extreme example of strong winds combined with conflagration is the 1923 Tokyo fire after the Kanto Earthquake: a typhoon was near the area where the earthquake struck. The Kanto earthquake and the ensuing fire resulted in ~100 000 deaths, including 38 000 due to a fire whirl – a flaming tornado (Quintiere 1997).

In the 1666 London Fire, the prevailing wind was described as ‘the bellowing wind’, and ‘the red flakes’, or firebrands, scattered and spread the fire in all directions (Bell 1920). Fig. 5 shows the weather pattern of the cyclonic storm that formed on 8 October 1871, the day of the Chicago and Peshtigo Fires (Pernin 1999). The arrow indicating wind direction in Fig. 5 corresponds with the fire spread direction. The wind was strong, 9.8 m s^{-1} (22 miles h^{-1}) in Chicago and 14.3 m s^{-1} (32 miles h^{-1}) in Peshtigo. In addition, temperatures were high, 26.1°C (79°F) in Chicago and 28.3°C (83°F) in Peshtigo. The scene was described

‘The wind blew a hurricane; the firebrands were hurled along the ground with incredible force against everything that stood in their way.’ (Wells 1968)

In 1923, the Tokyo Fire broke out and spread rapidly owing to strong winds from a typhoon near the Noto Peninsula (Scawthorn 1987). Fig. 6 is a hodograph, excerpted from a map of the Tokyo fire (Tokyo Imperial University 1923), which contains information about the fire including ignition sites, direction of fire spread and spot fire locations. The hodograph shows chronological wind velocity and direction, using tail-to-nose conjunction. The wind was strong on the first day (1 September 1923), ranging from 10.7 to 21.8 m s^{-1} , but weakened to $\sim 5 \text{ m s}^{-1}$ and changed its direction to the north at 0900 hours on the second day. The wind direction changed the fire spread direction to the north, which had mostly burned already, eventually allowing the fire to be extinguished at 0400 hours on the third day.

Fig. 7 is a hodograph of the 1991 Oakland Hills Fire, in the same fashion as Fig. 6. In addition to wind velocity, atmospheric temperature is shown as thickness and humidity is shown as colour of the arrow (Pagni 1993). The Oakland Hills Fire actually started on 19 October 1991 (19th ignition), but with a typical coastal pattern of light wind, it didn’t grow larger and

seemed to be under control. As the strong Diablo wind, which is a föhn wind in the San Francisco Bay area, blew (20th ignition) on the next day, the fire got larger and spot fires dominated fire spread within an hour (from 1100 to 1200 hours), as shown in Figs 1–4.

The importance of wind in spot fire phenomena can be demonstrated by the large-scale fires without significant wind. Recently, three fires following an earthquake, the 1989 Loma Prieta (San Francisco Fire Department 2005; Iversen 2006), the 1994 Northridge (Todd 1994; Scawthorn *et al.* 1998) and 1995 Kobe earthquakes (Louie 1996; City of Kobe 2005), are good examples. After these three earthquakes, there were multiple fires ignited owing to earthquakes, but there was no significant firebrand activity because of the absence of wind. In the 1995 Kobe earthquake, fire spread to a larger area and burned 7386 structures, but that was due to the high density of structures in Japanese urban areas, not as a result of fire propagation due to firebrand transport. If an earthquake strikes California under Santa Ana or Diablo wind conditions, there could be a conflagration with a bigger impact than previous post-earthquake fires. Note that both the 1989 Loma Prieta earthquake in northern California and the 1994 Northridge earthquake in southern California happened in the regions where föhn winds can blow, even though they actually happened under near zero-wind conditions.

Recipient fuels to be ignited

In urban conflagrations, discontinuous fire spread has been also referred as roof-to-roof spread because the roof is the recipient fuel. The roof-to-roof spread in urban areas is sometimes alleged to be caused by radiative heat transfer. This can be true for the highly dense urban areas like Kobe in Japan, but firebrands have been observed as the main cause of the roof-to-roof fire spread in many fires with high wind conditions. Thus the recipient fuel condition, such as the roof material in cases of urban and wildland–urban interface fires, is another important factor (National Board of Fire Underwriters 1923; Wilson 1962).

The fires initiated by firebrands in the 1666 London Fire burned down most structures made of wood (Bell 1920; Tinniswood 2004). Roof-to-roof fire spread was indicated in the 1871 Chicago fire too (Sheahan and Upton 1872). In the wildland–urban interface fires in California – Berkeley in 1923, Bel-Air in 1961, Oakland in 1991 – wooden shingles, which were popular in California as roof material, assisted fire spread. Wooden shingles increase fire hazard owing to both ease of ignition and subsequent firebrand production (National Board of Fire Underwriters 1923; Wilson 1962; Office of the City Manager 1991). Fig. 8 is an actual firebrand obtained from the 1991 Oakland Hills Fire, which was presumably produced from cedar shingle. It was found $\sim 1 \text{ km}$ away from the fire perimeter. Wooden shingle roofs were identified as the main factor that made fire worse in the official reports of the 1923 Berkeley Fire (National Board of Fire Underwriters 1923) and the 1961 Bel-Air Fire; the National Fire Protection Association (NFPA) report of the 1961 Bel-Air Fire was entitled ‘Devil wind and wood shingles’ (Wilson 1962). In the 1961 Bel-Air Fire, the aerodynamic firebrands made of wooden roof shingles could reach higher altitudes and be carried further by the upper strata of the Santa Ana winds. These became the long-range firebrands.

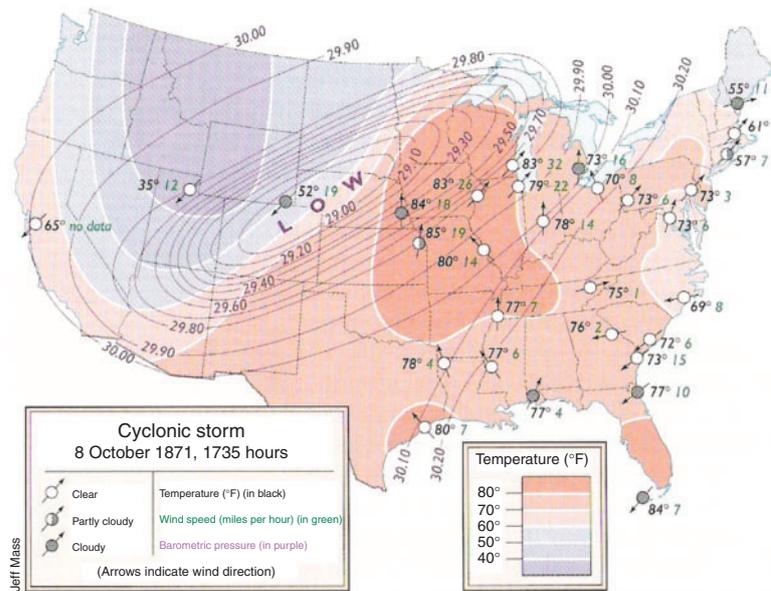


Fig. 5. Weather conditions in the US on 8 October 1871, the day of the Great Chicago Fire and Peshtigo Fire, are shown. The cyclonic storm pattern in late summer shows strong winds and high temperatures in the burned area. Moreover, 1871 had a severe summer drought in the Midwest. From fig. 1 (p. 14) of Pernin (1999). Map created by Jeff Maas. Reproduced with permission of the Wisconsin Historical Society.

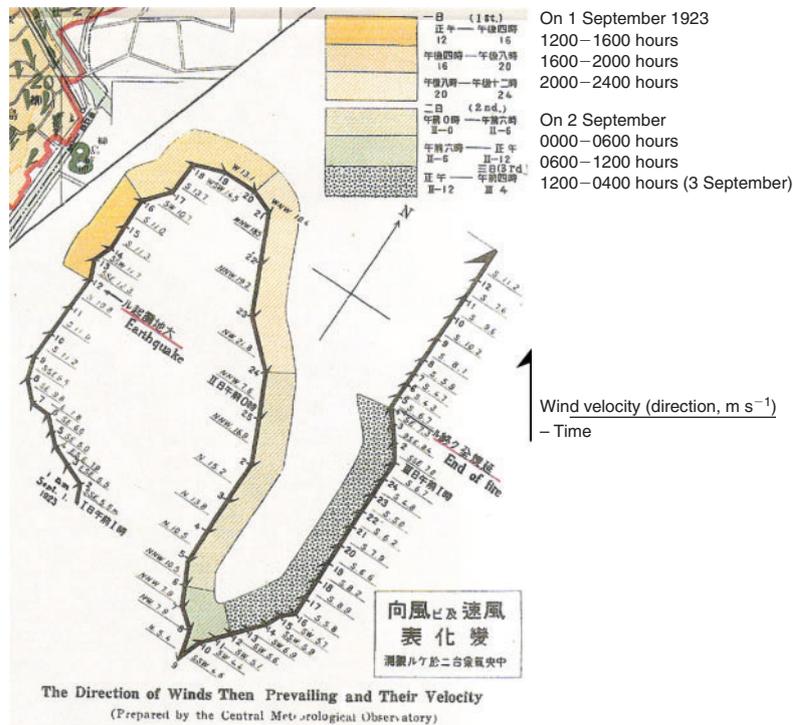


Fig. 6. The hodograph part of the Tokyo fire map that shows wind velocity vectors alongside a chronology of the fire. On the upper right corner, a colour legend for chronology is shown with day and time. On first day, the wind was strong – from 10.7 to 21.8 m s⁻¹. Later in the second day, the wind speed slowed to ~5 m s⁻¹, and eventually the fire was controlled at the ‘End of fire’ at 0400 hours of the third day (Tokyo Imperial University 1923).

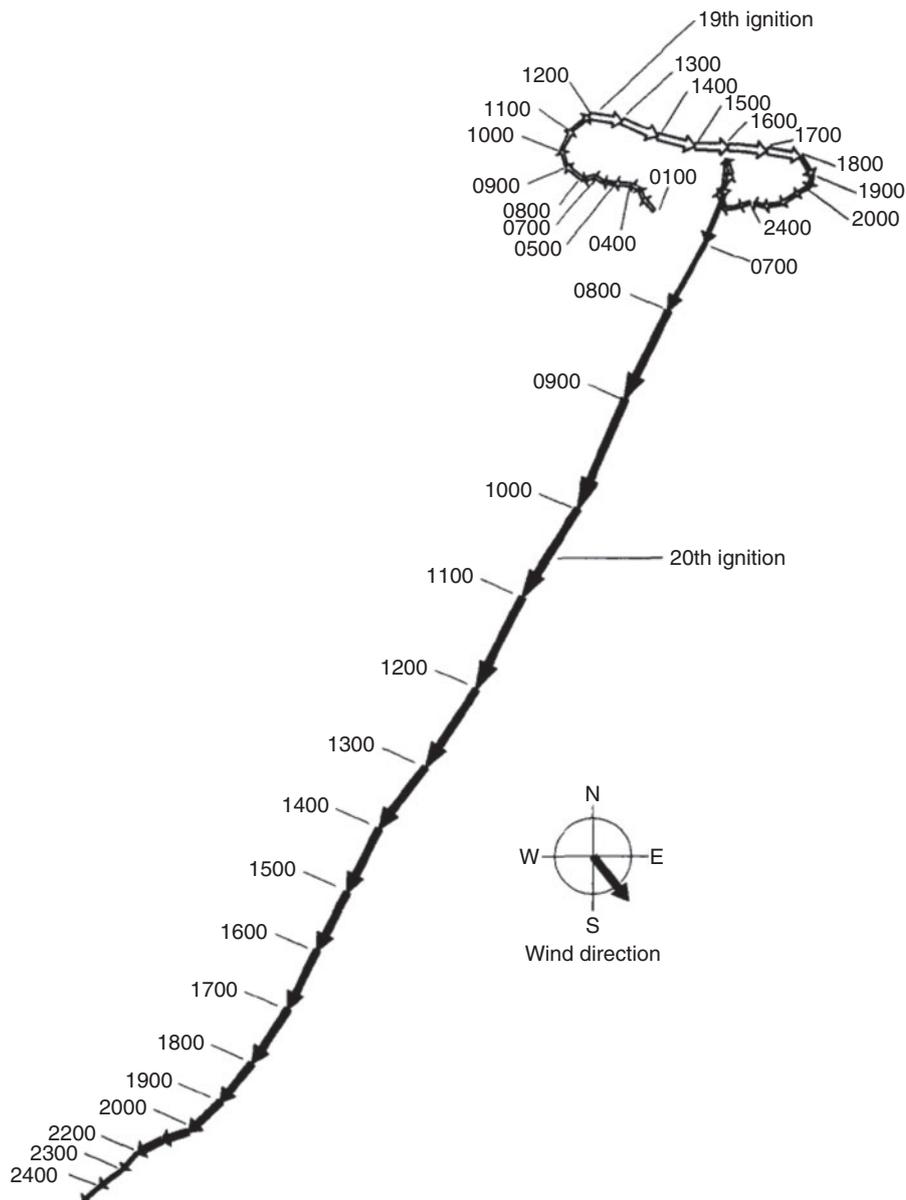


Fig. 7. Wind velocity vectors recorded at the Chabot Observatory for 19 and 20 October 1991. The wind direction is indicated as shown in the compass rose. The wind speed is given by the length of the velocity arrow, with the arrow on the compass rose corresponding to 5 m s^{-1} . The thickness of the arrow indicates the temperature: thin $< 25^{\circ}\text{C}$, thick $> 25^{\circ}\text{C}$. The colour of the arrow indicates the relative humidity: white $> 10\%$, black $< 10\%$. The 19 October data show a typical coastal pattern with light on-shore winds midday and light off-shore winds morning, evening, and night. Hot, dry, fast Diablo winds began pouring over the hills, nearly normal to the ridgeline, at 0600 hours on 20 October and continued unabated until 2000 hours. From fig. 2 (p. 336) of Pagni (1993).

'Unlike the flying brush brands which are often consumed before rising to great heights; the flat wood roofing materials soared to higher altitudes carried by strong vertical drafts.... The denser brands rose into this upper wind strata and were carried to the southwest in great profusion. New fires were ignited in the brush and among structures at great distances, at times spanning two and three canyons.' (Wilson 1962)

In this report, brush and chaparral fuels that were ignited by firebrands are mentioned. The firebrands that landed on brush and chaparral seemed to have more ability to ignite recipient fuel because of fuel bed porosity, which allows more oxygen supply to firebrand combustion.

Ignition of the recipient fuel requires energy transfer from firebrand to fuel, enough to raise the temperature of the recipient

fuel to ignition temperature. There are several factors in determining the required energy for ignition. In addition to the kind of recipient fuel itself, the moisture content of the fuel and relative humidity of the local atmosphere are important factors. With dry fuel in dry air conditions, the spotting ignition probability could increase drastically. This could be related to the fact that many large conflagrations and large-scale fires with spot fires occurred after drought or during the fall season when fuels and atmosphere are dry.

Spotting distance

For a given prevailing wind speed, the maximum spotting distance depends on the lifetime of burning firebrands (Tarifa *et al.* 1965a; Albin 1979). Thus the spotting distance gets larger when the fire grows larger and becomes more intense. Definitely, the firebrand's lifetime depends on its initial size, which is determined by the vertical speed of wind induced by the fire (Tarifa *et al.* 1965a; Lee and Hellman 1969; Muraszew 1974; Muraszew *et al.* 1975; Muraszew and Fedele 1977; Albin 1979; Woycheese 1996; Koo *et al.* 2007). For convective columns, the vertical wind speed increases with the heat release rates of the main fire. Another mechanism that lofts firebrands is a fire whirl (Muraszew and Fedele 1976, 1977). Strong convective columns and fire whirls are more common in large-scale fires such as forest fires. Therefore spot fire distance becomes more important in forest fires and wildland–urban interface fires. In these kinds of fires, spotting distance can be on the order of kilometres.

In the 1871 Peshtigo Fire (Wells 1968), several firebrands that travelled more than 10 km were found. They are thought to have been lofted by large fire whirls. Several reports written by the USDA Forest Service on other forest fires indicate the significance of fire whirls and spot fires. Fire whirls and numerous spot fires occurred in northern Idaho during the Sundance Fire, on 23 August 1967 (Anderson 1968). Muraszew suggested that most long-range firebrands are lofted by fire whirls, whereas short-range firebrands are mostly lofted by the convective plume (Muraszew and Fedele 1976). Firebrands escaping from a prescribed burn initiated several spot fires during the 4 May 2000 Cerro Grande fire in New Mexico (Hill 2000; United States National Park Service 2000). Some firebrands were even observed jumping across a canyon wider than 400 m. In the 1991 Oakland Hills Fire, a firebrand, shown in Fig. 8, that was found ~1 km west from the perimeter of the fire may have travelled several kilometres.

Byram's analysis on the travel distance of the firebrands found in the Peshtigo Fire summarises the significance of fire whirls in forest fires:

'George M. Byram has found that catastrophic fires may create convective columns that rise to a height of about 5 miles [~8 km]. The energy generated by such whirling chimneys of super-heated air can twist off large trees, as can the more ordinary kind of tornadoes. Such fires frequently carry embers nearly a mile in the air, then drop them far ahead of the fire front – a discovery that explains how a charred board from Peshtigo was found in the Menominee River



Fig. 8. A firebrand from the Oakland Hills conflagration: ~50-mm diameter, ~5-mm thickness, and 2.3 g (density of ~250 kg m⁻³). Presumed to be produced from cedar shingle. Ruler units are millimetres.

6 miles [~9.7 km] away and how a piece of wood was carried through the air for 7 miles [~11.27 km] before falling near a Lake Michigan vessel in the Green Bay.' (Wells 1968)

Firebrand research review

Because of the importance of spot fires in large-scale fire spread, the firebrand phenomenon has been studied since the 1960s. The firebrand research work reviewed in this paper is summarised in Table 1. The firebrand phenomenon and spotting ignitions are still considered some of the most difficult problems to understand in fire spread. The research work that has contributed to the current knowledge and understanding of the firebrand phenomenon is reviewed. As a result, recommendations for future firebrand research are presented.

Since Tarifa studied the lifetime and trajectories of firebrands for the first time (Tarifa *et al.* 1965a, 1965b, 1967), firebrand research has been focussed on maximum spot fire distance. The maximum spot fire distance is estimated as the distance that a potential firebrand could travel within its lifetime, which is the duration from lofting to its burnout. Many assumptions are incorporated in the estimation of the maximum spotting distance. However, maximum spotting distance has been used as a measure of spotting hazards, as Albin wrote, 'The severity of a potential spotting problem can be described numerically by the maximum spot fire distance to be anticipated under the conditions in question' (Albin 1979). In order to have a longer maximum spotting distance, larger firebrands should be lofted to stronger prevailing wind. Besides spotting distance, both larger firebrands and a stronger prevailing wind increase ignition probability (Blackmarr 1972; Bunting and Wright 1974). Besides firebrand transport models, firebrand phenomena have been studied experimentally. Combustion tests in wind tunnels have been the most fundamental experiments for firebrands (Tarifa *et al.* 1965a, 1965b, 1967; Muraszew *et al.* 1975;

Table 1. Compendium of firebrand research

Author	Year	Experiment	Firebrand model	Plume and wind model
Tarifa <i>et al.</i>	1965–67	Burning firebrands in wind tunnel	Sphere, cylinder with combustion	Given launching height in constant horizontal wind, inclined convective plume (Nielsen and Tao 1965)
Waterman (and Tanaka)	1969	Size and number distribution at generation (Waterman 1969)	–	–
Vodvarka	1969	Ignition of various fuel materials by firebrands (Waterman and Tanaka 1969)	–	–
Lee and Hellman	1969–70	Size and number distribution	–	–
Muraszew and Fedele	1974–77	Particles in vertical plume generator (1969)	Spheres with combustion (1970)	Turbulent swirling natural convective plume (1969)
		Burning firebrands in wind tunnel and fire whirl in vertical channel (1975)	Statistical model (1976)	Fire whirl (1977)
Clements	1977	Firebrand combustion in terminal velocity	–	–
Fernandez-Pello <i>et al.</i>	1982, 1998, 2006	–	Sphere with combustion (Fernandez-Pello 1982)	Given launching height (1998), McCaffrey plume (2006) in constant boundary layer wind
Albini	1979–83	–	Disc, cylinder and sphere (2006)	–
Woycheese and Pagni	1996–2000	Burning firebrands in wind tunnel	Cylinder with combustion (Muraszew and Fedele 1976)	Launching height from flame structure analysis in constant horizontal wind
Knight, Ellis <i>et al.</i>	2001	Various firebrand combustion in vertical wind tunnel	Non-dimensional model with combustion (Kinoshita <i>et al.</i> 1981)	Baum and McCaffrey plume model (Baum and McCaffrey 1989)
Colin <i>et al.</i>	2002	Statistical survey on fires and monitoring	–	–
Himoto and Tanaka	2005	–	Statistical model (SALTUS program)	–
Manzello <i>et al.</i>	2004–08	Fuel bed ignition by firebrands, generation from a burning tree; firebrand attack on structures using firebrands generator	Disc without combustion	Given launching height in turbulent boundary layer
Porterie <i>et al.</i>	2007	–	–	–
			Small world network model (Porterie <i>et al.</i> 2007); disc with combustion (Sardoy <i>et al.</i> 2007)	Steady-state crown fire (Porterie <i>et al.</i> 2005)
Koo, Pagni and Linn	2007	–	Disc and cylinder with combustion	HIGRAD/FIRETEC wildfire model (Linn and Cunningham 2005; Linn <i>et al.</i> 2005)

Woycheese *et al.* 1998, 1999; Knight 2001; Knight *et al.* 2001; Woycheese 2001; Knight and Sullivan 2004). Drag forces were measured during the combustion tests, to develop dynamic models of firebrands. In addition to these experiments on firebrand transport and combustion, firebrand generation and ignition of recipient fuels were tested to understand firebrand phenomena. In particular, the experiments done by the Illinois Institute of Technology Research Institute (IITRI) divided firebrand phenomena into three mechanisms: generation, transport, and ignition, and tried to cover all three topics in the 1960s (Vodvarka 1969; Waterman 1969; Waterman and Tanaka 1969).

Spotting distance models (firebrand transport models)

The study on maximum spotting distance of a firebrand should cover several physical process, namely dynamics models of a firebrand, firebrand combustion in wind, flow structure of flame and plume for firebrand lofting analysis, and wind field around and above the main fire. In order to simplify these coupled physical processes, assumptions and approximations have to be and have been taken cautiously. They are as important as the theories used for the development of models. The terminal velocity assumption, derived from wind tunnel experiment observations, has been used. Another assumption is dividing the firebrand's trajectory into two stages of lofting and propagation.

Tarifa's work on firebrand research (Tarifa *et al.* 1965a, 1965b, 1967) provided many basic ideas of firebrand research for the first time. It covered topics from experiments measuring the drag force on burning firebrands to models calculating spot fire distances based on burnout limits. From his experiments, Tarifa established the important approximation that firebrands travel at their terminal velocities, which became the basis of subsequent firebrand models. In establishing this approximation, he first developed two-dimensional fundamental equations of firebrand dynamics, shown as Eqn 1, based on a force balance during flight:

$$\begin{aligned} m \frac{dV_x}{dy} &= m \frac{dU_x}{dt} - m \frac{dW_x}{dt} = \frac{1}{2} \rho_s C_D A_p W^2 \frac{W_x}{W} \\ m \frac{dV_z}{dy} &= m \frac{dU_z}{dt} - m \frac{dW_z}{dt} = \frac{1}{2} \rho_s C_D A_p W^2 \frac{W_z}{W} - mg \end{aligned} \quad (1)$$

where m is the mass of the firebrand, V is its absolute velocity, U is the wind velocity, W is the relative velocity of the wind with respect to the firebrand, x indicates the horizontal direction, and z indicates the vertical direction; t is time, ρ_s is the density of the firebrand, C_D is the drag coefficient, A_p is the cross-sectional (projected) area, and g is the acceleration due to gravity. He measured weights and drag forces acting on burning firebrands in a wind tunnel as functions of time. With these experimental results, he derived laws of variation of the drag force and weight acting on the burning firebrands as functions of both time and relative wind speed. Then, using these laws, he found that the relative velocity drops to the terminal velocity in 2–3 s, whereas the burning lifetime of his firebrands was of the order of 2–3 min. He wrote, 'Except for a brief startup period, changes are sufficiently slow that the firebrand velocity adjusts to the force balance' (Tarifa *et al.* 1965a). As terminal velocity implies

zero acceleration, he set Eqn 1 equal to zero and established a good approximation of assuming that firebrands always fly at their terminal velocities.

In order to study the behaviour of objects moving at terminal velocity, Tarifa also performed free-fall tests for various shapes of non-burning firebrands (Tarifa *et al.* 1967). Tarifa's conclusions drawn from the free-fall tests for cylinders were: (1) cylinders always fall tumbling; (2) falling times of cylinders are of the same order as those calculated for cylinders falling in the position of maximum drag, with errors of less than 10%; and (3) when cylinders are dropped in groups, there is horizontal dispersion, but their fall times will differ by less than 10%. Similar conclusions were obtained with square plates.

Having established a simple model for how firebrands behave in wind, Tarifa attempted to calculate the trajectories of firebrands lifted by a plume and transported by horizontal wind. The structure of the convective plume induced by the fire determines the lofted height of the firebrand. Tarifa initially used simplified plume models. The simplest plume model was a convective column of constant wind speed, and the second model was the same convective column but inclined. Later, he used a convective plume model developed by Nielsen and Tao (1965), whose structure is shown in Fig. 9a. In each plume model, he assumed that firebrands are ejected by turbulence at random vertical positions and then picked up by a specified constant horizontal wind. With Nielsen and Tao's convective column model, the calculated trajectories of firebrands lofted by convective zones of various widths (L) and determined maximum spot fire distances are shown in Fig. 9b. In these cases, firebrands are cylinders of 8-mm diameter and 24-mm length, and the maximum spot fire distance was found to be ~2050 m with a 53 m-wide convective column. This distance represents the maximum spotting threat of this size firebrand for all sizes of fires. If the convective column is wider, i.e. the scale of the fire is larger, then the same size firebrand would burn out before landing.

Finally, from his wind-tunnel firebrand combustion experiments, Tarifa observed that the density and radius histories of a small sphere or cylinder of wood at constant wind speed undergoing convective combustion speeds could be approximated by the expressions:

$$\begin{aligned} \frac{\rho_s}{\rho_{s,o}} &= (1 + \eta t^2)^{-1} \\ \frac{r_s}{r_{s,o}} &= 1 - \left(\frac{\beta + \delta W}{r_{s,o}^2} \right) t \end{aligned} \quad (2)$$

where ρ is density, r is radius, t is time, and W is the relative wind speed. The subscripts s and o mean solid (firebrand) and initial value respectively, and the parameters η , β , and δ depend on the species of wood and moisture content of the firebrand. It was further observed from these relations that the density of the firebrand does not depend on the wind speed, and the law of radius change is similar to that of a combusting liquid droplet.

Lee and Hellman developed a model to determine trajectories of firebrands in turbulent swirling natural convective plumes (Lee and Hellman 1969; Lee and Hellman 1970). They developed a spherical firebrand model with constant density and

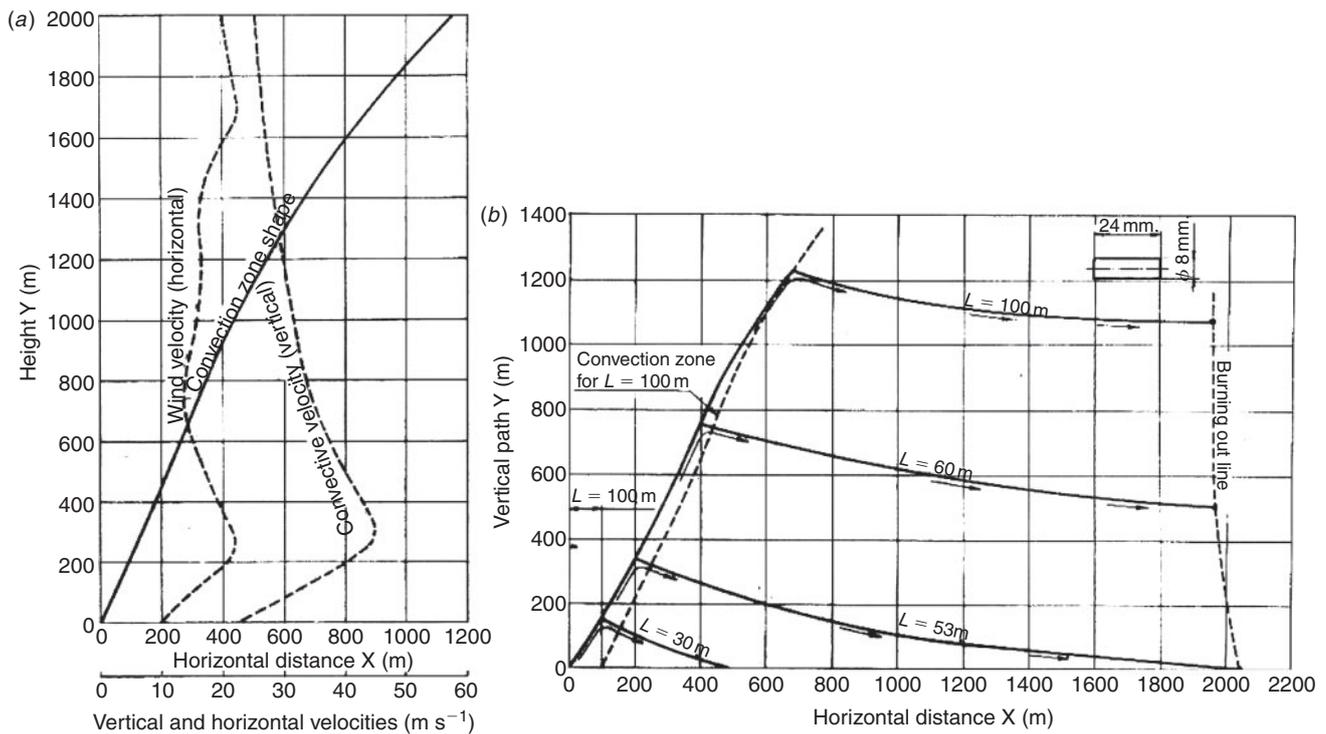


Fig. 9. (a) Wind profile of the convective zone of Nielsen and Tao's plume model. (b) Tarifa's firebrand trajectories and spot distances with the convective column model in (a). L is the width of the convective zone. From figs 31 and 32 (pp. 56–57) of Tarifa *et al.* (1967).

constant burning rate in a 2-D axisymmetric turbulent swirling convective plume. They tested their model by injecting particles into the vertical swirling plume generator. This experiment confirmed the important role of the force balance in firebrand motion and supported Tarifa's assumption that firebrands move at terminal velocity. Their results suggested that the magnitude of the particle velocity field depends on altitude and that the important parameters determining a particle's trajectory are the burning rate, initial size of the particle, density of the particle, and its initial placement in the plume. Experimentally, it was also observed that flat particles are more stable in the plume than spherical particles. Trajectories were obtained using a constant drag coefficient for two fluid flow fields of interest in forest fire research. One was the swirling turbulent natural convection plume, which approximates the velocity field above a fire whirl such as those observed occasionally in large-scale forest fires. The other was a tilted constant-velocity convection plume. In later work by Lee and Hellman (1970), they expanded the model to use the empirical velocity-dependent burning law Tarifa had reported (Tarifa *et al.* 1965a) instead of the constant burning rate.

Muraszew of the Aerospace Corporation in California studied firebrand phenomena in the 1970s and published a series of reports (Muraszew 1974; Muraszew *et al.* 1975; Muraszew and Fedele 1976, 1977). He reviewed the firebrand research that had been done before 1973 (Muraszew 1974) and performed firebrand burning tests in a horizontal wind tunnel and experiments on the structure of fire whirls in a vertical channel using wood cribs (Muraszew *et al.* 1975). Then, based on the review

and his experiments, a statistical model for spot fires was developed (Muraszew and Fedele 1976). Later, a short communication paper on the modelling of fire whirls and firebrands was written (Muraszew and Fedele 1977).

In his review report (Muraszew 1974), four categories of previous firebrand research were studied: firebrand trajectory models, including those of Tarifa (Tarifa *et al.* 1965a, 1965b, 1967) and Lee and Hellman (Lee and Hellman 1969; Lee and Hellman 1970), convective column modelling, modelling of piloted ignition of fuel by firebrands and growth of spot fires thereafter, and statistical modelling of firebrand generation and spot fire ignition. He suggested statistical approaches to model firebrand generation and ignition probability, and physical models to characterise the transport mechanism. As a consequence of the review, he recommended that future research focus on: (1) establishing the generation rate and size of firebrands as a function of fuel type and convective column characteristics from experiments; (2) studying the burning of firebrands in flight to establish the change in firebrand mass and size with time and dependence on initial size, fuel type, and relative velocity; (3) exploration of recipient fuel ignition criteria as a function of firebrand characteristics; and (4) characterisation of fire whirls in simple terms.

Muraszew reproduced Tarifa's wind-tunnel experiments on burning firebrands (Tarifa *et al.* 1965a) and Lee and Hellman's vertical-channel fire-whirl structure tests (Lee and Hellman 1969) using tangential boundary-layer inlets (TBLI) as forced air-swirl inducers (FASI) (Muraszew *et al.* 1975). His results showed that the burning law for firebrands is a relationship

similar to first-order wood pyrolysis, i.e. the regression rate of the diameter of a burning cylinder is linearly proportional to the wind velocity. This combustion model for burning cylinder firebrands was later adapted by Albini (Albini 1979) and is stated as follows:

$$\frac{d}{dt}(\rho_s d) = -K\rho_a W \quad (3)$$

where ρ is the density, d is the diameter, W is the relative wind speed, which is terminal velocity under the terminal velocity assumption, and t is the time. The subscript a means air, and s means solid (firebrand). K is the constant dimensionless regression rate, which was determined to be 0.0064 from his 33 wood combustion tests using combinations of 127-mm (5 inch) long \times 12.7- or 25.4-mm (0.5 or 1 inch) diameter cylinders in 4.5- or 6.7-m s⁻¹ (10 or 15 miles h⁻¹) wind. In addition to this combustion model, he observed glowing combustion on the windward side of the firebrands rather than flaming combustion and thus concluded that most firebrands in real fires will be in a state of glowing combustion when they reach the ground.

In Muraszew's third report (Muraszew and Fedele 1976), he developed a statistical approach to spot fire prediction to account for firebrands' random behaviour, as he had previously recommended (Muraszew 1974). Spot fires were divided into two classes: short-range spot fires due to firebrands lofted by a convective plume and long-range spot fires due to firebrands lofted by a fire whirl. Actually, this classification was suggested before Muraszew (Berlad and Lee 1968). For both cases, their report provides analytical and empirical formulae giving fuel characteristics, trajectories related to lofting mechanisms and firebrand generation under the assumptions based on the review and experiments. A firebrand generation function, giving the probability F_d that a particular size of firebrand will be lofted out of the fire was developed for both cases. The function depends on the intensity of the lifting mechanism and on the fuel characteristics, such as the size and density of firebrands and the intensity and degree of completion of burning of the fuel. It is stated as

$$F_d = 1 - \exp(-K(U_{z,o}/V_{ter})^2 - 1) \quad (4)$$

where K depends on the fuel model, varying from 0.0005 to 0.005, $U_{z,o}$ is the vertical wind velocity at the core base of the convection column or fire whirl, and V_{ter} is the firebrand terminal velocity within the column or fire whirl. Reasonable values of F_d were recommended to be 0.001 to 0.02 for convection columns and 0.01 to 0.4 for fire whirls. Later, Muraszew and Fedele wrote a short communication paper on how to model fire whirls and firebrands (Muraszew and Fedele 1977) where he presented calculations on the trajectories of long-range firebrands lofted by fire whirls. He divided the flow field into three regions: the fire whirl core characterised by solid body rotation, the ambient swirl around the core characterised by constant angular momentum, and above the core and swirl zone where the main force carrying the firebrands aloft is the ambient wind. Equations were then briefly introduced for

trajectories in the three regions and for burning laws determined from experiments for firebrands of cylindrical and flat plate shapes.

Albini developed a predictive model of spot fire distance (Albini 1979) for firebrands emitted from torching trees. The model was later extended to apply to firebrands emitted from a line thermal source (Albini 1981a, 1982), such as those produced in wind-driven surface fires (Albini 1983a, 1983b), as well as those produced from isolated sources such as burning wood piles (Albini 1981b); it was originally developed for field use with calculators and simplified nomogram solutions (Albini 1979), but it was later incorporated into BEHAVE (Andrews 1986) and is now used, as shown in Fig. 10, within BEHAVEPLUS (Andrews 1986; Andrews and Chase 1989) and FARSITE (Finney 1998).

The model is built on six submodels: the flame structure model, the model of a buoyant plume above a steady flame, the firebrand burning rate model, the lofting of firebrands by the flame and buoyant plume model, a model for surface wind over rough terrain, and the firebrand trajectories model. These submodels are used in the steps of the worksheet as summarised below.

1. Description of trees that produce firebrands: the species, diameter and height of trees, and the numbers of burning trees.
2. Flame height and duration: from tree properties, the flame height and the time of steady burning of tree crowns are evaluated through tabulated experimental data.
3. Adjustments to flame information: adjustment factors of the flame height and steady burning time due to the number of trees are obtained from nomograms. The flame height increases and the steady burning time decreases as the number of trees increases.
4. Maximum firebrand launching height: half of the tree height is added to the lofted height of the firebrand because the flame base is assumed as the middle of the tree. The burning rate model of a firebrand based on experiments by Muraszew *et al.* (Muraszew *et al.* 1975; Muraszew and Fedele 1976) is involved in this calculation.
5. Wind-speed adjustment: the wind is modelled horizontally and a logarithmic function of height, so the wind speed measured at any reference height is converted to the wind speed at the mean tree-top (canopy) height. Drag effects by the trees (in addition to the ground) are not considered.
6. Maximum spot fire distance over flat terrain: this is obtained from the nomogram as shown in Fig. 11, using three factors as inputs: the maximum initial firebrand height from the fourth step, the mean tree-top height, and the wind speed at the mean tree-top height.

Albini's model is the operational spot fire model, as it is incorporated within BEHAVEPLUS and FARSITE. In BEHAVEPLUS, Albini's model solves for the maximum spot fire distance and returns the result. However, FARSITE uses it to model the initiation of spot fires that will then spread contiguously in the given terrain, so a user needs to input an ignition probability. The idea that ignition frequency can be expressed in the form of a probability function of factors such as temperature,

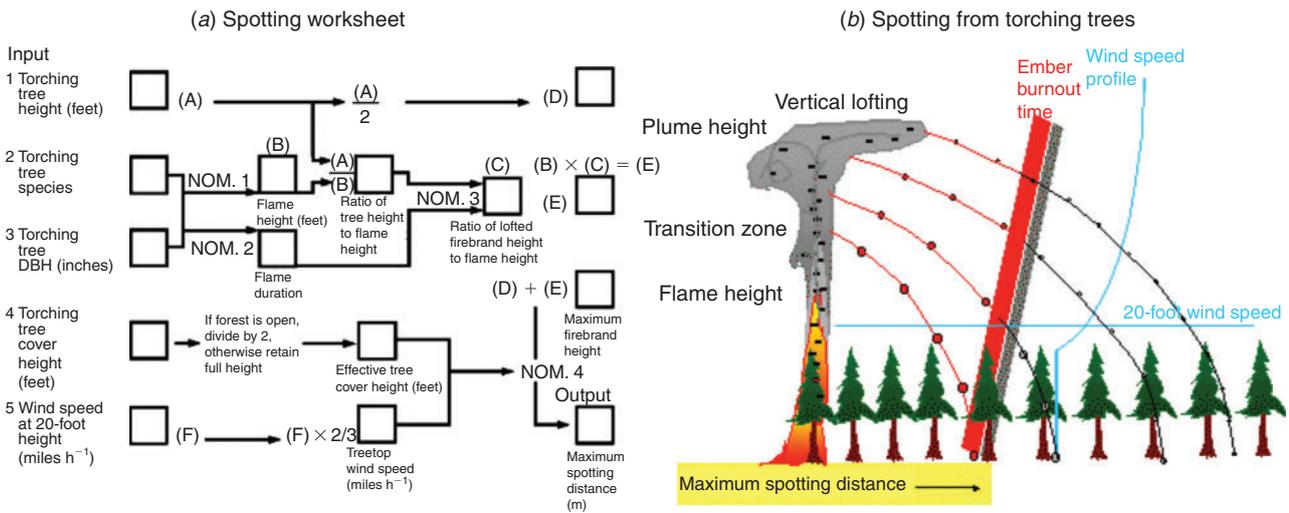


Fig. 10. (a) Spotting worksheet from Fireline Handbook Appendix B: Fire Behaviour (p. B-9) of National Wildlife Coordinating Group (2006); (b) concept diagram of spotting from torching trees in Albini's spotting distance model, screenshot of BEHAVEPLUS program help menu.

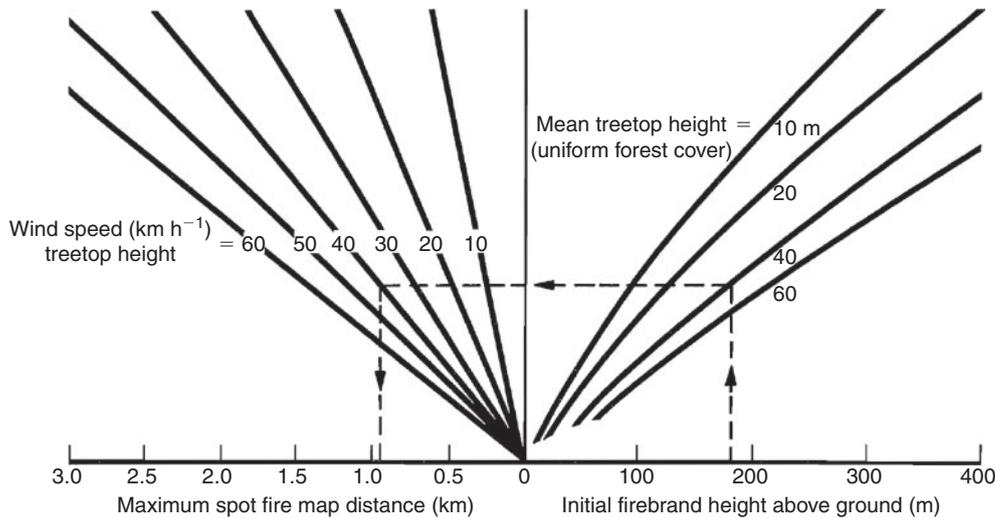


Fig. 11. Nomograph for predicting maximum spot fire distance over flat terrain. From fig. 8b (p. 14) of Albini (1979).

humidity and fuel moisture content, is justified by many researchers (Blackmar 1972; Bunting and Wright 1974; Bradshaw *et al.* 1984). However, there is no functional model for ignition frequency yet, so the user simply inputs a percentage representing the best estimation of the ignition probability.

Fernandez-Pello developed a theoretical combustion model for firebrands, whereas empirical combustion models had been applied in the firebrand models reviewed above (Fernandez-Pello 1982). He analysed forced convective burning of spherical PMMA (polymethyl methacrylate) particles using boundary-layer and flame-sheet approximations to describe the reacting flow. The governing boundary layer equations were solved, and profiles of the velocity, temperature and species distributions normal to the particle surface were presented, along with local mass burning rates, for a series of values of the azimuthal angle. A valuable explicit expression for the

particle regression rate was then developed in terms of the Reynolds number (Re) and mass transfer numbers (B). The predicted dependence of the regression rate on these parameters agreed qualitatively, as Kinoshita and Pagni had found previously (Kinoshita *et al.* 1981) with experimental observations for droplets vaporising and burning in forced convection.

Firebrands can be produced from other sources besides fires. A power line can produce small firebrands, causing spot fires. Tse and Fernandez-Pello provided an analysis of this problem and developed a predictive, numerical model to calculate trajectories, combustion rates, and lifetimes of metal particles and burning embers of different sizes (Tse and Fernandez-Pello 1998). High winds can cause power cables to come close enough together to arc or collide with trees and produce metal sparks or burning embers. Then they are carried by the wind and land in adjacent areas of dry vegetation to

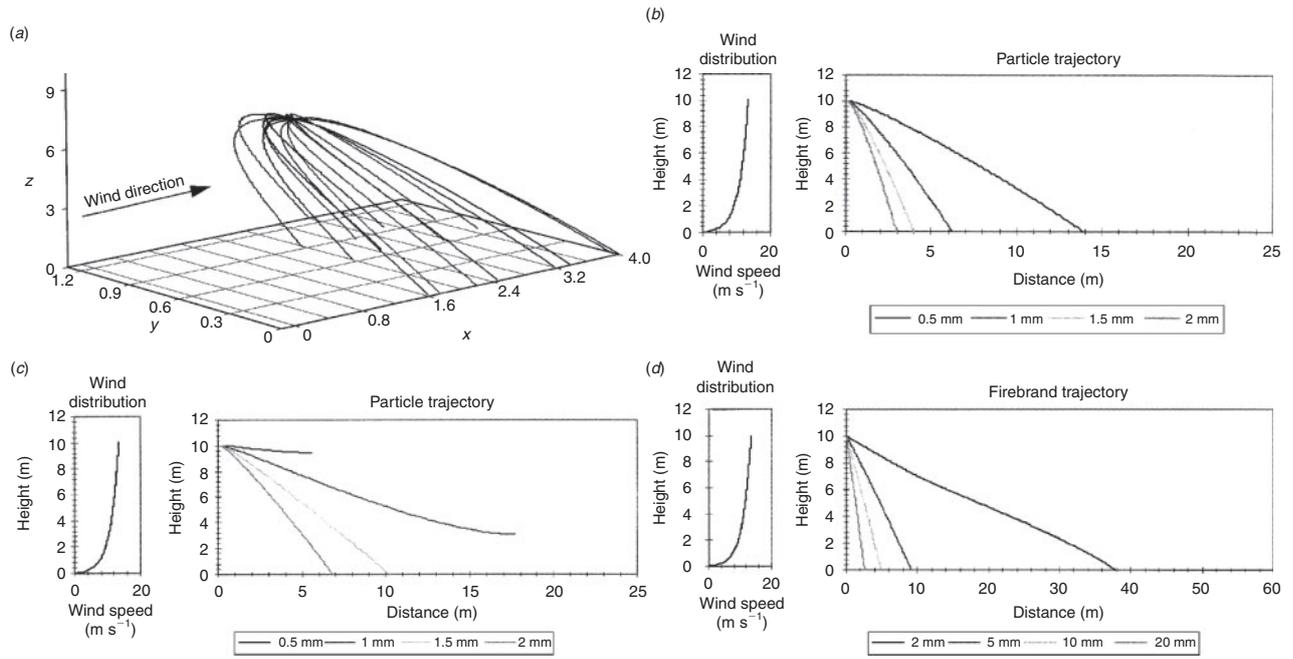


Fig. 12. Tse and Fernandez-Pello’s firebrand trajectories. (a) Copper particle trajectories at various ejection angles, 1.5-mm diameter particles, 14.3-m s⁻¹ (30 miles h⁻¹) wind speed. (b–d) Particle trajectories for various initial particle diameters, 14.3-m s⁻¹ wind speed: (b) copper; (c) aluminium; and (d) wood. From figs 3–6 (pp. 348–351) of Tse and Fernandez-Pello (1998), reproduced with permission.

initiate brush or grass fires. To investigate problem, both metal and wood firebrands were launched at the power-cable height of 10 m and carried by a 14.3-m s⁻¹ horizontal wind (30 miles h⁻¹) with a 10 m-thick ambient boundary layer, as shown in their results in Fig. 12. Three distinct cases were studied: (1) hot particles produced by arcing copper power lines; (2) burning sparks produced by arcing aluminium power lines; and (3) burning embers produced by the collision of high-voltage power lines with surrounding trees. The results show that the distances reached by wood firebrands were the greatest, followed by aluminium, and then copper owing to combustion effects on the trajectories. The copper particles, because they were not burning, maintained constant mass, so were not blown as far, and cooled down quickly, though they could still carry significant heat to their areas of impact. The aluminium particles could burn or blow out while in flight, but could also travel further than copper particles as their mass decreased. Burning embers could travel the furthest without extinction but also carried less heat than the metal particles. This study was later expanded to spheres, discs and cylinders of burning wood firebrand (Anthenien *et al.* 2006) with the McCaffrey plume model (Baum and McCaffrey 1989).

Woycheese and Pagni modelled the lofting of firebrands in a convective plume, calculated maximum propagation distances for lofted firebrands, and conducted wind-tunnel tests on burning firebrands (Woycheese 1996, 2000; Woycheese *et al.* 1998, 1999). For their first paper (Woycheese *et al.* 1998), they modelled rising spherical and disc firebrands using the Baum–McCaffrey plume model (Baum and McCaffrey 1989) and showed that there is an upper limit to the size of a loftable firebrand. The Baum–McCaffrey model divides the vertical flow field into three sections corresponding to the burning, intermittent

flame and plume zones. The dimensionless centreline velocity, U_p^* , for the three regions of dimensionless height z^* is:

$$U_p^* = 2.13(z^*)^{1/2}; z^* \leq 1.32 \tag{5a}$$

$$U_p^* = 2.45; 1.32 < z^* \leq 3.3 \tag{5b}$$

$$U_p^* = 3.64(z^*)^{-1/3}; z^* \geq 3.3 \tag{5c}$$

where $U_p^* = U_p/U_c$, $z^* = z/z_c$ and

$$U_c = \left(\frac{\dot{Q}_o g^2}{\rho_a c_p T_\infty} \right)^{1/5} \tag{6}$$

$$z_c = \left(\frac{\dot{Q}_o}{\rho_a c_p T_\infty \sqrt{g}} \right)^{2/5}$$

Here \dot{Q}_o is the rate of heat release for the fire and ρ_a , c_p , T_∞ and g are the ambient density, specific heat, temperature and acceleration due to gravity respectively. By comparing the maximum upward drag force with the gravitational force for firebrands of a given size, they obtained a maximum loftable size where these two values are equal. They found that the maximum loftable initial diameter is given by $d_{o,max}^* \approx 2/\rho_o^*$, where d^* and ρ_o^* are the firebrand diameter and air density, non-dimensionalised with characteristic height z_c and firebrand density ρ_s . In dimensional terms,

$$d_{o,max} \approx 2 \left(\frac{\rho_a}{\rho_s} \right) z_c = 2 \left(\frac{\rho_a}{\rho_s} \right) \left(\frac{\dot{Q}_o}{(\rho_a c_p T_\infty \sqrt{g})} \right)^{2/5} \tag{7}$$

The maximum height to which non-burning spheres can rise was calculated by finding the height at which the decaying plume velocity equals the firebrand's terminal velocity. For $C_D \approx 0.45$ as a drag coefficient, the maximum height was found to be $z_{\max}^* = 9.5(\rho_o^* d_o^*)^{-1.5}$, which in dimensional terms is:

$$z_{\max} = 9.5 \left(\frac{\rho_a}{\rho_s d_o} \right)^{1.5} \left(\frac{\dot{Q}_o}{\rho_a c_p T_\infty \sqrt{g}} \right) \quad (8)$$

Using the droplet-burning model (Turns 2000) for the combust-ing spherical firebrand regression rate, they calculated burnout heights. Furthermore, they found a collapse at the large end of the initial firebrand size distribution. All firebrands greater than a collapse diameter have the same burnout height, which is $z_b^* = 56$ for $d_o^* > 4000$ and $\rho_o^* = 1/7600$.

In their second paper (Woycheese *et al.* 1999), maximum propagation distances were defined as the maximum distance achievable while a firebrand is still burning. The maximum propagation distance was found as a function of \dot{Q}_o , U_w and wood type, or β , indexed by

$$\beta = 4.46 \left(\frac{\rho_a}{\rho_s} \right) \left(\frac{1}{\rho_a c_p T_\infty \sqrt{g}} \right)^{2/5} \quad (9)$$

For instance, cedar firebrands ($\beta = 1$), lofted by fires with $\dot{Q}_o = 1$ MW, 50 MW and 1 GW in 10 m s^{-1} wind, travelled a maximum of 49, 290 and 1100 m respectively, before landing at burnout. Firebrands between a collapse diameter of $d_{col} = 0.49 \dot{Q}_o^{0.269} \rho^{0.782}$ and a maximum loftable diameter of $d_{o,max} = 0.454 \beta \dot{Q}_o^{0.04}$ propagated the same maximum distance. The increased burning time inherent in larger firebrands was cancelled out by an increased time of flight because larger firebrands move more slowly. Hence, only firebrands with $0 \leq d \leq d_{col}$ need to be studied for a given \dot{Q}_o , U_w and β .

Woycheese's PhD dissertation (Woycheese 2000) develops analytical combustion and propagation models and presents data from over 500 wind-tunnel tests on burning firebrands. For the analytical portion, lofting and propagation of spherical and disc-shaped firebrands were determined numerically with two combustion models: spherical firebrands based on droplet burning, and disc-shaped firebrands based on opposed flow diffusion flame analysis (Kinoshita *et al.* 1981) for the surface combustion of disc firebrands. Maximum dimensionless propagation distances were then provided as functions of ambient, fire and firebrand properties. Disc-shaped firebrands were found to have greater propagation distances; spherical firebrands can travel ~ 1.1 km from a 90-MW fire, whereas disc firebrands with a thickness-to-diameter ratio of 1 : 10 can be transported 7.9 km. Woycheese concluded that discs approximate firebrands generated from roof and siding shakes and shingles, so there is a ready source for these far-travelling firebrands in wildland-urban interface (WUI) fires. Woycheese's PhD dissertation work also contains firebrand combustion tests in the wind tunnel and this is discussed in the next section.

From 1998 to 2001, a European project titled the SALTUS program, involving scientists from five Mediterranean countries (France, Greece, Italy, Portugal and Spain) was carried out for

the development of a statistical spot fire model (Colin *et al.* 2002). To understand the complexity of the firebrand phenomenon, a statistical survey of 245 extinguished fires, experiments and simulations, and monitoring of 48 wildfires to collect data were performed. The SALTUS work showed that spot fires are a very frequent phenomenon in southern Europe and that spot fire distances can be very large. In their results, 56% of the studied fires showed one or more spot fires at a distance of more than 10 m, in 32% of the fires, one or more spotting ignitions occurred at a distance of more than 100 m, and 8% of fires were observed to have spotting distances of more than 500 m. The observed average spotting distance was 228 m. The longest spotting distance was observed as 2.4 km.

Porterie *et al.* used a statistical approach based on the small-world network theory (Porterie *et al.* 2007). They proposed a forest fire spread model that includes short-range radiative and convective effects from flames as well as the long-range spotting effects of firebrands, which are considered by introducing a characteristic spotting distance. For a homogeneous fuel system, they found that development of spot fires can slow down the overall fire propagation process. Spread rate and burned area were significantly reduced as the degree of disorder increased for heterogeneous systems. The influence of the firebrands then became weaker. Recently, Sardoy *et al.*, from the same group in Marseille, France, modelled transport of a firebrand from a crown fire (Sardoy *et al.* 2007).

A 3-D physics-based model (Porterie *et al.* 2005) was used to pre-compute the steady-state gas flow and thermal field induced by a crown fire. The thermal degradation and combustion of woody fuel particles were studied to determine the burning characteristics of firebrands. Firebrands were determined whether they were flaming or in glowing states based on the product of $\rho_f^{wo} \times \tau$ (ρ_f^{wo} , initial firebrand density; τ , firebrand thickness) for disc firebrands. Results show that for the firebrands that remain longer in the thermal plume, the distance covered on landing is independent of the initial diameter and correlates well with $I^{0.1} U_{wind}^{0.9} (\rho_f^{wo} \times \tau)$, where I is the fire intensity and U_{wind} is the wind speed. The normalised firebrand mass fraction on landing was obtained as the correlation with flight time normalised with $(\rho_f^{wo} \times \tau)$ for flaming firebrands, and for glowing firebrands with $\rho_f^{wo} \times D_o^{5/3}$, where D_o is initial firebrand diameter.

Whereas the firebrand models reviewed above considered a single firebrand, next two studies concerned multiple firebrand trajectories with the consideration of turbulence in fires. Himoto and Tanaka (2005) numerically modelled the scattering of non-burning disc firebrands in a turbulent boundary layer produced by a large eddy simulation (LES) model. In their simulations, the firebrand diameters varied from 0.4 to 1.2 mm and the thickness varied from 0.04 to 0.12 mm. The computational domain was 2.48 m long \times 1.0 m high \times 1.0 m wide. The density of the firebrands was varied as 50, 100, and 150 kg m^{-3} . One of the simulation results is shown in Fig. 13. The purpose of their simulation was for comparison with their non-dimensional model; thus a rather small scale of computational domain was chosen. Then, a scaling dimensionless parameter B^* for the firebrand transport was derived as Eqn 10:

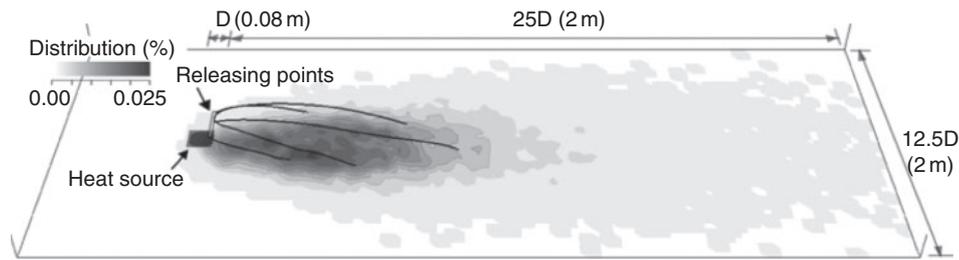


Fig. 13. Himoto and Tanaka's firebrand scattering in a turbulent boundary layer simulation. The density of the firebrands is 150 kg m^{-3} . D is the square-shaped heat-source side dimension, which is 0.08 m , and the source heat release rate is 4 kW . Firebrands were discharged at a height of 0.08 m . The firebrand diameters (disc) varied from 0.4 to 1.2 mm and the thickness varied from 0.04 to 0.12 mm . From fig. 3c (p. 439) of Himoto and Tanaka (2005), reproduced with permission.

$$B^* \equiv \frac{U_\infty}{(gD)^{1/2}} \left(\frac{\rho_P}{\rho_\infty} \right)^{-3/4} \left(\frac{d_p}{D} \right)^{-3/4} \left(\frac{\dot{Q}}{\rho_\infty c_P T_\infty g^{1/2} D^{5/2}} \right)^{1/2} \quad (10)$$

where U_∞ is wind velocity, g is acceleration due to gravity, D is heat source length, ρ_P is the firebrand density, ρ_∞ is the ambient air density, d_p is the firebrand width, \dot{Q} is the heat release rate, c_P is the specific heat of air, and T_∞ is ambient temperature. Numerically obtained mean travel distances in a windward direction, as well as standard deviation, were correlated with B^* with reasonable accuracy.

Koo and Pagni (Koo 2006; Koo *et al.* 2007) studied firebrand transport in detailed wind fields around wildfires using FIRETEC, which is a physics-based multiphase transport model for wildfires. FIRETEC couples models for macroscale effects of processes such as combustion, radiation, convective heat transfer and aerodynamic drag (Linn 1997; Linn *et al.* 2002, 2005; Linn and Cunningham 2005). Disc and cylinder shapes of combusting firebrands were modelled for Koo and Pagni's study. A firebrand dynamics model based on momentum balance was developed, and mass loss of a firebrand due to combustion, which affects its trajectory, was considered. Firebrand histories were considered in grassland fires with 1 , 3 and 6 m s^{-1} wind and in forest fires with 6 m s^{-1} wind in a $320 \times 320\text{-m}$ flat terrain domain. Fig. 14 shows the firebrands visualised for a grassland fire with 6 m s^{-1} wind.

Firebrand size distributions and travel distances were obtained for these wildfire scenarios. Fig. 15 shows typical scatterplots of travel distance and initial size for discs and cylinders. Each dot in the figure represents a firebrand. Firebrand launching sizes were assumed to be the maximum loftable sizes based on the strength of the local vertical wind velocity, induced by the buoyancy force of fire. Firebrands are launched from burning fuel with an arbitrary generation rate, which was one firebrand per second in one computational cell of size $2 \times 2 \text{ m}$. Burnout effects were significant in these simulations. Discs were found to be aerodynamically more efficient than cylinders. Strong winds made firebrands travel further. However, they elongated flight times and accelerated burning rates. Thus, the transported firebrand mass dropped as the wind speed increased. The maximum loftable size distributions were found to depend primarily on fuel conditions, whereas the travel distances were found to depend strongly on ambient wind speeds. As expected,

spot fire hazards in grassland fires were observed to be lower than in forest fires. In the forest fire simulation, two kinds of ponderosa pine tree forests were used: one with a fully covered canopy and the other with a patchy canopy, which has clumps of trees with open canopy. The patchy canopy was found to produce firebrands that were transported further. However, the full forest was found to produce a larger number of firebrands of substantial size.

Experiments on firebrands

Researchers at IITRI performed experiments and field studies on firebrands, and three major reports were produced. Waterman (1969) conducted laboratory experiments on firebrand generation from roofs. Waterman and Tanaka (1969) studied ignition of various materials of recipient fuels by manufactured firebrands, which were based on their firebrand-generation experiments from the roofs. Vodvarka (1969) studied structure fires that generated firebrand landing sizes and locations, compiled consultant reports on fires involving firebrands, and polled firefighters and fire marshals for their experience with firebrands in the field. IITRI's experimental research covered three major mechanisms in spot fires: firebrand generation, firebrand transport, and ignition by firebrands.

Waterman's laboratory experiments on firebrand generation (Waterman 1969) were performed to assess the capability of various roof constructions to produce firebrands when subjected to a building fire. Various types of actual roofs were placed in a two-storey fire chamber. By means of a screen trap and quenching pool, all firebrands generated were collected, and the effects of building heights and wind-induced internal pressure were simulated by imposing additional pressure on the fire chamber interior. The results indicated that changes in internal pressure produced marked changes in firebrand production. Of the types of roof construction evaluated, wood-shingled roofs were the greatest firebrand producers. For all the trials, the firebrands produced were of low density and appeared to be in a state of glowing combustion at the time of generation or shortly thereafter. Even though this experiment concerned firebrands generated in structural fires, the results indicated that the upward force of a wildfire plume, which is similar to the internal pressure in a structural fire, is an important factor in firebrand generation and size distribution of generated firebrands.

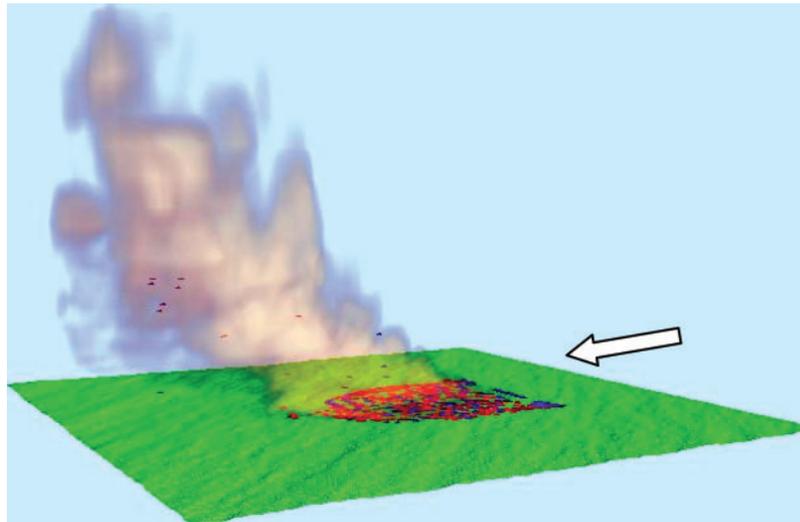


Fig. 14. Firebrand visualisation with wind blowing far-right to near-left. Individual firebrands are visualised by blue and red dots representing ~ 600 - and ~ 1200 -K temperatures respectively. Firebrands are shown both in the air and after landing. The white arrows indicate wind direction. This snapshot is for the grassland fire simulation with 6-m s^{-1} ambient wind at 100 s. From fig. 1b of Koo *et al.* (2007).

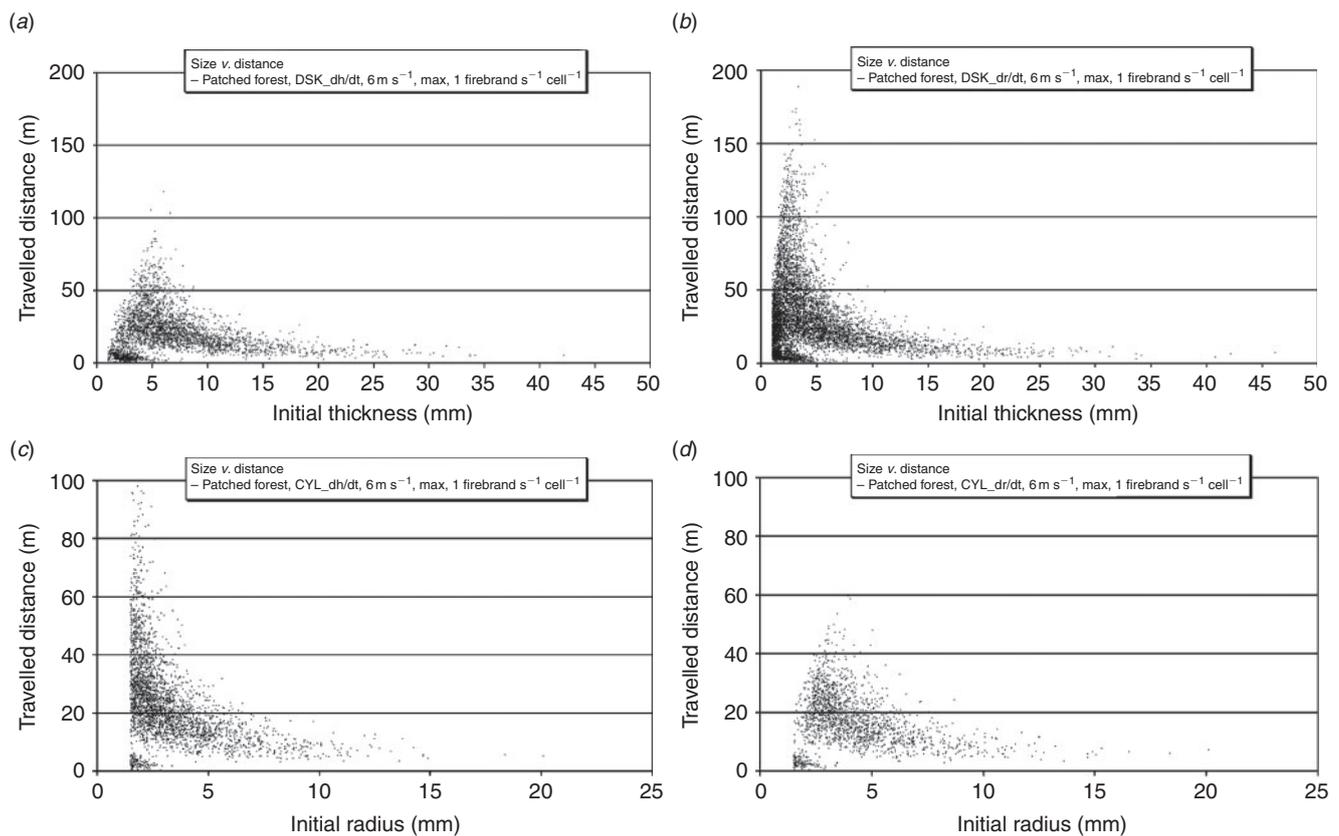


Fig. 15. Travel distance *v.* initial radius scatterplots of the firebrands in the forest fires with partially opened canopy. Four firebrand models are applied: (a) discs with axial regression model (DSK_dh/dt); (b) discs with radial regression model (DSK_dr/dt); (c) cylinders with axial regression model (CYL_dh/dt); (d) cylinders with radial regression model (CYL_dr/dt). For fuel conditions, partially opened canopy was used and wind conditions are 6 m s^{-1} . Each dot indicates one firebrand that landed on unburned surface fuel. Firebrand density was assumed to be 300 kg m^{-3} . For these simulations, firebrands lighter than 0.02 g were not considered, which is equivalent to a 1-mm thickness for disc firebrands and 1.5-mm radius for cylinder firebrands. From fig. 4b, d, f, g of Koo *et al.* (2007).

Waterman observed that most of the firebrands from his experiments were glowing, which agrees with other research (Muraszew and Fedele 1976; Woycheese 2000). The ignition probability of recipient fuels by firebrands cannot be easily determined from whether a firebrand is flaming or glowing. Flaming firebrands can emit a greater amount of heat flux than glowing firebrands. However, lifetimes of flaming firebrands are shorter than those of glowing firebrands. In addition, transition from flaming to glowing combustion can happen for firebrands and vice versa. Ignition of recipient fuel should be treated as an energy transfer process from firebrands to the fuels, which is strongly coupled with the combustion characteristics of firebrands.

Waterman and Tanaka studied the ignition of recipient fuel (Waterman and Tanaka 1969). The sizes of firebrands were determined based on their previous work. Their standard maximum firebrand size was named the 'C' firebrand, which is normally a square of 38.1×38.1 mm with 19-mm thickness. 'C' firebrands usually weighed 3 g. Based on Tarifa's experiments and their own observations, only glowing firebrands were placed on various materials because firebrands burned with flames for a short period followed by an extended period of glowing combustion. Recipient materials were urban fuels: various roof materials, structural exterior wood surfaces, cardboard, paper and fabrics. Generally, ignition probability was greater with $2.2\text{--}2.7\text{-m s}^{-1}$ (5–6-mile h^{-1}) wind than with $0.9\text{--}1.3\text{-m s}^{-1}$ (2–3-mile h^{-1}) wind and greater with steady wind than with oscillating wind. The effects of additional radiant heat flux were significant, even though heat fluxed applied was below 8.4 kJ m^{-2} , where the firebrands would merely cause pilot ignition.

They concluded that firebrands made out of lumber sheathing were more dangerous than firebrands made out of cedar shingle. The lumber-sheathing firebrands ignited recipient fuels more frequently than the cedar-shingle firebrands did because of lumber's inherent ability for self-reinforced glowing combustion as the density of lumber sheathing was five times larger than that of cedar shingle. Because of the lightness of cedar, cedar shingle was found to be more susceptible to firebrand ignition than any other exterior building materials. Other materials, such as canvas, cardboard, and paper, showed much greater susceptibility. Even though carpets were found to not be serious contributors of firebrand ignitions, other indoor materials were found to constitute the major portion of susceptible urban recipient fuels; beds and fabric-upholstered furnishings were the most readily ignited fuels. This result showed that the intrusion of firebrands into the structure radically increases ignition probability. According to CSIRO's recent research on spot fires in the 2003 Canberra Fires (Leonard and Blanchi 2005), over 60% of the burned structures were attacked only by firebrands, and over 90% of the burned structures were destroyed in the absence of direct flame contact. Mitchell designed an outside sprinkler system, named the Wind-Enabled Ember Dousing System (WEEDS), to protect homes from firebrand intrusion (Mitchell 2006; Mitchell and Patashnik 2007).

The report of Vodvarka (1969) consists of three parts: five experimental fires, four summaries of consultant reports, and a field-studies questionnaire of 475 fire officers. In the experiments, information was gathered on the numbers and sizes of

firebrands produced by five structural fires. Polyethylene sheets, 3×3 m and 0.1 mm thick, were spread on the ground downwind from the fire so that hot firebrands could melt through the sheets, leaving a record of their size and number. Fig. 16 shows an example of firebrand collection results in house-burning tests. Most of the firebrands observed had a size of 1/32 of the 'C' firebrand of Waterman's definition (Waterman and Tanaka 1969). The firebrand number density decreased with distance as well as with firebrand size. However, the number densities appeared to be large enough to be significant factors for distances up to 60 m. The results indicated that roofing material is an important factor for firebrand number density and building height affects the size distribution. These agreed with Waterman's conclusions from the laboratory experiments. Although the data were not extensive, Vodvarka suggested that they might be used in conjunction with information on ignitions by firebrands to make estimates of probabilities of fire spread by flying firebrands.

The summaries of the consultant reports provided data and figures describing firebrands in structure fires. Four fires including two accidental fires were considered. Number density of firebrands at landing locations and size distributions were recorded for all cases along with the travelled distances of firebrands, which were up to 274 m. Differences between the previously described tests and two accidental fires were due to the presence of well-developed winds during the fires. The previously described field tests were performed under light wind conditions of $0.4\text{--}1.3\text{-m s}^{-1}$ (1–3 miles h^{-1}), whereas the accidental fires happened under $4.5\text{--}11\text{-m s}^{-1}$ (10–25 miles h^{-1}) wind conditions. The questionnaire part compiled fire officers' experiences with firebrands. To the 19-question survey, ~250 respondents gave answers about firebrand production and general conditions prevailing at the time. The survey shows that the firebrands did not produce ignitions of other structures or vegetation in 25 to 50% of the fires that produced firebrands. It also shows that firebrands were produced mostly from roof covering materials, such as wood shingles and shakes, were highly capable of initiating spot fires, and had a wide range of travelled distance, from ~3 m to over ~90 m. Not surprisingly, roofs seemed to be most susceptible to ignition by firebrands. The report detailed many eyewitness accounts from fire officers, describing the interesting behaviour exhibited by firebrands. The report recommended formulating statistical models for fire spread by firebrands.

Clements (1977) of the USDA Forest Service performed drop tests of burning firebrands, based on the terminal velocity approximation developed by Tarifa. He determined the terminal velocities of various types of firebrands by dropping them from a given height, timing their free-fall, and integrating the equation of motion for falling objects in air. Leaves from 14 hardwood species, needles of three pine species, cones of six pine species, saw-palmetto fronds, reindeer moss, Spanish moss, and paper-birch bark were tested. The flaming and glowing times were recorded for cones of four pine species in flight in a vertical wind tunnel. It was found that firebrands that had a high percentage of samples flaming in flight and on landing also tended to have higher terminal velocity. The glowing times of pinecones were found to be an order of magnitude greater than the flaming times. Clements concluded that firebrands with substantial sizes, which can lead to ignitions, can be a serious hazard. Lastly,

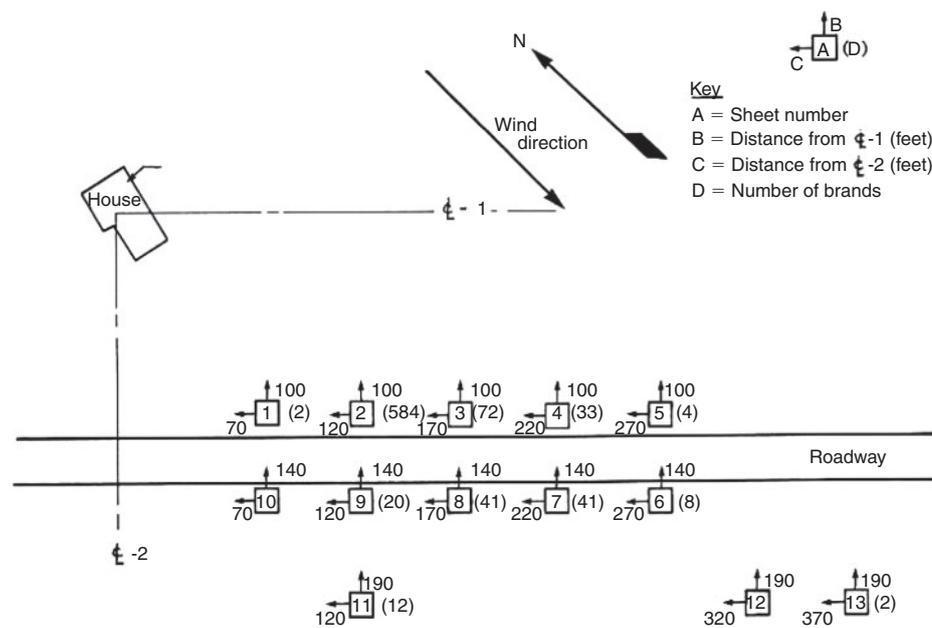


Fig. 16. Plastic sheet layout for Burn 68–4 in Illinois Institute of Technology (IIT) Research Institute's house burn test. From fig. 16 (p. 27) of Vodvarka (1969).

he recommended experiments on dry fuel-bed ignitions by firebrands.

The maximum loftable firebrand size can be determined by the strength of updraft induced by fire. As the initial size of firebrands determines the lifetime of burning firebrands and the size at landing determines the possible energy transfer to the recipient fuel, the maximum size of a firebrand for given conditions is a significant factor in firebrand behaviour. Thus several researchers, including Tarifa, performed terminal velocity measurements in a vertical wind tunnel. The most recent experiments using a vertical wind tunnel were performed by CSIRO in Australia (Knight 2001; Knight *et al.* 2001). The vertical wind tunnel designed by CSIRO, which was used successfully for the study of untethered firebrand terminal velocity, has two unique features: the vertical working section has a divergent taper that allows a firebrand to find its terminal velocity within a velocity gradient, and the velocity of the boundary layer of the working section has been forced to a higher speed than the central zone to stop the firebrand impacting on the working section walls. This facility enabled the first study of the aerodynamics and combustion properties of eucalyptus bark as firebrands.

Woycheese's PhD dissertation (Woycheese 2000) contains firebrand combustion tests in the horizontal wind tunnel at the University of California at Berkeley, conducted on disc-shaped firebrands of different species and sizes in various forced-flow conditions. Some of these experiments were used to develop mass, volume and density history curves, whereas others provided flame and surface combustion location and duration data. Seven species of wood were tested: balsa, western red cedar, Douglas fir, red oak, Honduras mahogany, redwood and walnut, and the effects of diameter and length-to-diameter ratio were examined for samples with 25- and 50-mm diameters and ratios

of 1 : 3 and 1 : 9 in constant relative velocities ranging from 1 to 7 m s^{-1} . Fig. 17 shows a comparison of firebrand combustion behaviour under the same conditions for cedar and fir wood types in these experiments. These tests showed that wood density and relative wind velocity are important factors in determining firebrand combustion characteristics.

Furthermore, Woycheese divided wood types into two distinct species groups based on density: balsa, western red cedar and Honduras formed a group of low-density species that typically burn to completion, whereas Douglas fir, red oak, redwood and walnut formed a group of high-density species that self-extinguish with considerable residual mass and volume. This distinction indicated that discs generated from shingles pose a large propagation risk due to slow, complete burning of the firebrand. Fig. 18 is a map of burning regimes for end-grain (grain direction parallel to the disc axis) disc firebrands of two different sizes with the same thickness-to-diameter ratio, suggesting that size may also be an important parameter determining firebrand combustion characteristics.

Manzello *et al.* (2005a, 2005b, 2006a, 2006b) at the National Institute of Standards and Technology (NIST) ran experiments on the ignition of various fuel bed types by burning firebrands. They deposited flaming and glowing firebrands of ponderosa pine on pine needle, shredded paper beds, and in cedar crevices (Manzello *et al.* 2006a) and on pine straw and hardwood mulch beds and cut grass beds (Manzello *et al.* 2006b) and observed whether ignition followed, as shown in Table 2. Multiple firebrands were deposited on each fuel bed, and the diameter of the firebrands were either 25 or 50 mm, keeping the thickness-to-diameter ratio at 1 : 3, as in Woycheese's tunnel tests (Woycheese 2000).

Under light winds of 0.5 to 1 m s^{-1} , both flaming and glowing firebrands had the ability to initiate spot fires, though

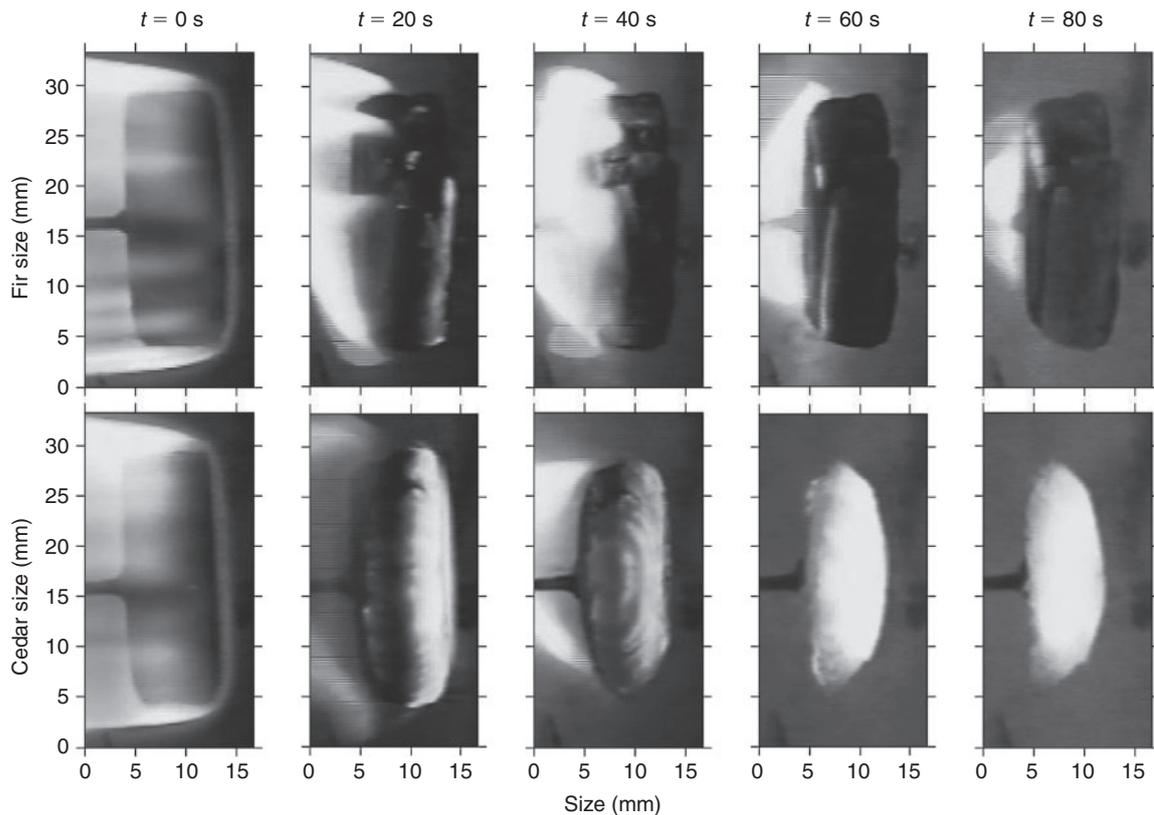


Fig. 17. Woycheese's firebrand combustion experiments: comparison of combustion images for end-grain Douglas-fir and western red cedar samples with a 1.8-m s^{-1} relative wind from right to left. Both pieces are initially 25 mm in diameter and 8 mm thick. The fir extinguishes at 90 s with 50% residual mass, whereas the cedar burns to completion after 210 s. The white colourings in this figure on the surface of the samples are regions of surface combustion. From fig. 5.9 (p. 94) of Woycheese (2000).

the applicability of the flaming firebrand results may be limited because it has been observed that most of the firebrands in wildfires (Bunting and Wright 1974) and other experiments (Tarifa *et al.* 1967; Waterman 1969; Waterman and Tanaka 1969) were glowing. The glowing firebrands initiated smouldering ignition in shredded-paper fuel beds and in two cases of pine-needle fuel beds. This might be the most realistic scenario of spot fire initiation. Ignition characteristics can change in stronger wind conditions, in which spotting ignition becomes prevalent. In higher wind, flaming firebrands may have less potential to ignite fuel beds owing to the cooling effect of the wind, and glowing firebrands may have more potential owing to the increased heat-release rate caused by the additional oxygen supply. Heat transfer and thermal characteristics of the landed firebrand, recipient fuel and ambient wind would determine whether the firebrands ignite recipient fuel on landing or not. Specifically, the amount of heat supplied by firebrands, which depends on the number, state and size of firebrands, the moisture content of recipient fuel and the ambient wind speed are three important factors. With these factors, a map of ignition on firebrand landing can be obtained from experiments. Fig. 19 is a qualitative map of ignition on firebrand landing, which has three axes with these factors. Near the origin, recipient fuel would not be ignited on

firebrand landing. Thus, ignition criteria may be expressed as a surface in this type of graph.

Following the ignition tests, Manzello *et al.* performed experiments to determine the size and mass distribution of firebrands generated from a single Douglas-fir tree (Manzello *et al.* 2007a). The experiments were performed in the Large Fire Laboratory at NIST. Various heights (2.6–5.2 m) and various moisture contents (10–50% moisture content) of trees were used. For all the experiments, the firebrands were cylindrical shapes. The average size of firebrands and distributions of size were recorded. The bigger tree was observed to produce bigger firebrands, just as Vodvarka observed that a bigger structure fire could produce bigger firebrands (Vodvarka 1969). Manzello's work was the first set of experiments capturing firebrand generation characteristics from an actual tree, such as size distribution and generate rate, and could be compared with Waterman's tests on roof materials in the fire chamber (Waterman 1969) and Vodvarka's field experiments on structure fires (Vodvarka 1969).

Recently, Manzello *et al.* developed a unique experimental apparatus, known as the Firebrand Generator (Manzello *et al.* 2008a), used to generate a controlled and repeatable size and mass distribution of glowing firebrands (Manzello *et al.* 2007b, 2008b). The size and mass distribution of firebrands produced

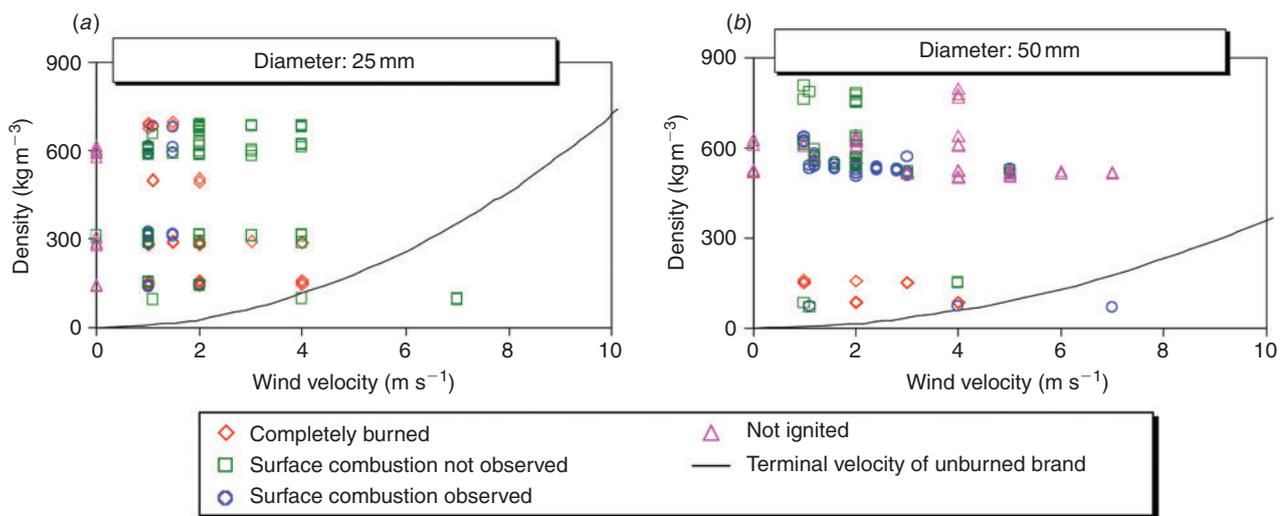


Fig. 18. End-grain disc firebrand burning regime map and experimental data of Woycheese’s disc firebrand combustion experiments: (a) 25-mm diameter and (b) 50-mm diameter firebrands with the same thickness-to-diameter ratio of 1 : 3. ‘Surface combustion not observed’ and ‘surface combustion observed’ refer to existence of flame on the windward side. The fir firebrand in Fig. 17 is an example of a firebrand without surface combustion, whereas the cedar firebrand is an example of one with surface combustion.

Table 2. Experiments of Manzello *et al.* on the ignition of fuel beds by flaming and glowing firebrands

Three types of recipient fuel are used with two dry-mass-based moisture contents. Ambient wind varies between 0.5 and 1 m s⁻¹. From table 1 (p. 430) of Manzello *et al.* (2006b), reproduced with permission. Abbreviations are: FI, flaming ignition; NI, no ignition; NT not tested; SI, smouldering ignition

Firebrands deposited	State of firebrand	Air flow (m s ⁻¹)	Firebrand size (mm)	Pine straw		Hardwood		Grass	
				Dry	11%	Dry	11%	Dry	11%
1	Glowing	0.5	25	NI	NI	NI	NI	NI	NI
1	Glowing	0.5	50	NI	NI	NI	NI	NI	NI
1	Glowing	1	25	NI	NI	NI	NI	NI	NI
1	Glowing	1	50	NI	NI	NI	NI	NI	NI
1	Flaming	0.5	25	FI	FI	FI	NI	FI	NI
1	Flaming	0.5	50	FI	FI	FI	NI	FI	NI
1	Flaming	1	25	FI	FI	FI	NI	FI	NI
1	Flaming	1	50	FI	FI	FI	NI	FI	FI
4	Glowing	0.5	25	NI	NI	NI	NI	NI	NI
4	Glowing	0.5	50	NI	NI	SI	NI	NI	NI
4	Glowing	1	25	NI	NI	NI	NI	NI	NI
4	Glowing	1	50	SI to FI	SI to FI	SI to FI	NI	SI to FI	NI
4	Flaming	0.5	25	NT	NT	NT	NI	NT	FI
4	Flaming	0.5	50	NT	NT	NT	NI	NT	FI
4	Flaming	1	25	NT	NT	NT	NI	NT	FI
4	Flaming	1	50	NT	NT	NT	NI	NT	NT

from the generator was selected to be representative of firebrands produced from burning vegetation, based on their previous firebrand generation experiments (Manzello *et al.* 2007a). The vulnerability of roofing materials to firebrand attack was ascertained using fluxes of firebrand produced using this device. Fig. 20 shows a schematic of the Firebrand Generator and mounting assembly for the vulnerability test. The experiments were performed at the Fire Research Wind Tunnel Facility (FRWTF) at the Building Research Institute (BRI) in Tsukuba, Japan. The sections constructed for the testing included full

roofing assemblies (base layer, tar paper and shingles) as well as only the base-layer material, such as oriented strand board (OSB). The results of the investigations on vulnerability of building material to firebrand attack using the Firebrand Generator are expected to provide significant data for developing new building codes and standards to reduce structure losses in urban and wildland–urban intermix fires.

More recently, Gould *et al.* published a book about Project Vesta of CSIRO, which includes data on firebrand size and transport distance from prescribed fires (Gould *et al.* 2009).

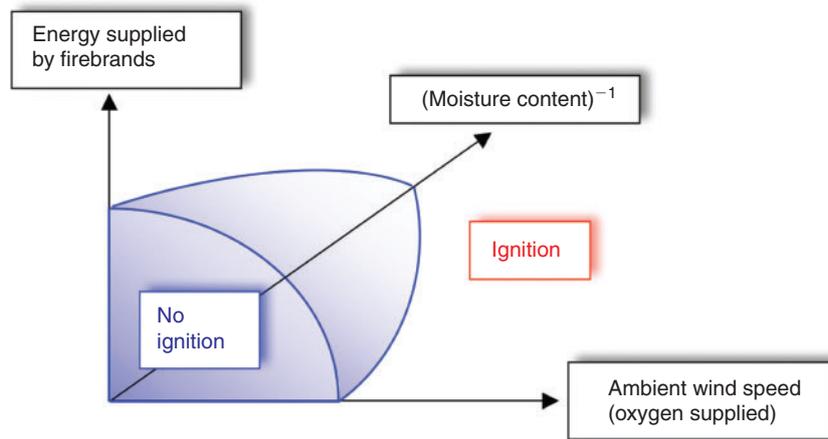


Fig. 19. A qualitative map of ignition on firebrand landing. Firebrand energy content, inverse moisture content and ambient wind speed are set as axes. Near the origin, recipient fuel would not be ignited on firebrand landing. Thus, ignition criteria may be expressed as a surface as shown in the map. Within the surface, fuel will be not ignited and outside the surface, fuel will be ignited.

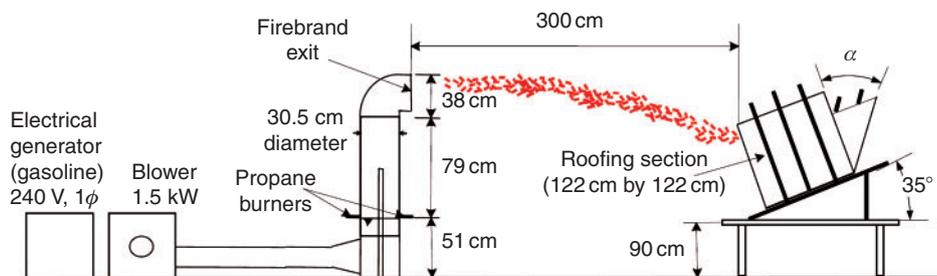


Fig. 20. A schematic of the firebrand generator and a full-scale roofing section mounting for vulnerability test. From fig. 4a (p. 149) of Manzello *et al.* (2008b), reproduced with permission.

Given the recent nature of their recent publication, it is not included in this review; however, the interested reader is encouraged to investigate this study as well.

Recommendations

Knowledge on firebrands and spot fires has been developed through ~50 years of research. However, these studies are not yet complete enough to form a reliable physics-based operational model that predicts spotting distances and assesses the risk of potential spot fires. To reach this goal, future work should focus on properly characterising the three basic mechanisms behind the spot fire phenomenon: firebrand generation, firebrand transportation and ignition on landing. Compared with knowledge about firebrand transport mechanisms, research on firebrand generation and ignition by firebrands is still insufficient to develop a predictive model. Thus it is recommended that more research on firebrand generation and ignition by firebrands be conducted.

Firebrand generation research should focus on the rate of firebrand production in the main fire and the lofting of firebrands out of the fire. Firebrand production is a result of the pyrolysis and

degradation of wood elements in the main fire. The ignition and combustion study on various materials, including vegetation in wildlands and structural materials should be focussed on degradation of the fuel, because firebrands are actually fractured solid fuel that is burning and able to burn other fuel. Both experimental and theoretical studies on the fracture of solid fuel due to combustion should be performed. In addition to that, larger-scale experiments or field studies on fires that can be a source of firebrands should be performed to develop generating functions for firebrands. As shown in research by Waterman (1969), Muraszew and Fedele (1976), Albin (1979) and Koo *et al.* (2007), the main fire buoyant force determines which sizes of firebrands will be lofted. Thus, analyses of the characteristics of the contiguous main fire and its flame structure should be improved. Besides the size of firebrands, the number density of produced firebrands and firebrand generation frequency should be studied through these larger-scale burning tests and field tests. As most firebrand transport models were built for a single firebrand trajectory, current firebrand study lacks the understanding about firebrand generation number density and frequency. Field and laboratory tests that are similar to the field

study of Vodvarka (1969) and the work of Waterman (1969) should be reproduced, as Manzello recently did (Manzello *et al.* 2007a), to gain more data on firebrand generation. These data should be parameterised and integrated into the existing firebrand models. If the ignition of the recipient fuel could be characterised as probability functions, then firebrand generation density and frequency will be the key parameters in determining spot fire hazard, along with spotting distances.

In order to obtain more knowledge of firebrand behaviour, firebrand transport research should examine more detailed dynamics and combustion models, which can then be accompanied by more detailed flow fields. Dynamics models should be based on the force balance during flight. As the shape and density changes of firebrands significantly affect their trajectory, combustion models are essential. Along with firebrand models, fire behaviour models describing wind velocity fields around fires, which determine the drag force in the dynamics model that ultimately determines the trajectory, need to be accurately modelled in and around the fire. Much research has focussed on plume and wind models, as shown in Table 1. The level of complexity of dynamics–combustion–windfield models should correspond to each other. For example, the terminal velocity assumption developed by Tarifa is better for use with a simplified, steady-state wind field. According to Tarifa, the response time of firebrands to terminal velocity is 2–3 s. This is much smaller than the lifetime of a firebrand, small enough to be ignored in a constant wind field. However, with more detailed wind field data and real fires, the wind field will keep changing on a smaller time scale, owing to turbulence in fires, and thus the terminal velocity assumption will no longer be valid. Utilising growing computational power, more sophisticated fluid dynamics models for fires are now available (Linn *et al.* 2002). Thus, more detailed models than currently employed should be developed based on coupled physics in firebrand dynamics and combustion with windfields. For the purpose of predicting spotting hazard, however, the model should be developed with appropriately simplified assumptions. A study with a detailed model will provide understanding of the firebrand phenomenon, and the theoretical basis of these assumptions. The information about possible firebrand travel distance is an important output of such a spotting hazard assessment tool.

Modelling of fuel ignition on landing should assess whether enough heat is transferred to the fuel to cause ignition and initiate a spot fire. The firebrand phenomenon should be treated as one of the energy-transfer mechanisms in fire spread: if enough energy to ignite the unburned fuel is transferred by firebrands, then spotting ignition occurs. Thus, ignition of recipient fuel should be studied with a focus on two aspects: the required energy for ignition of recipient fuel, related to atmospheric and fuel conditions, and the amount of energy carried by a firebrand. Analyses of the combustion of a firebrand during flight in terms of extinction criteria should be performed in order to determine how much energy the firebrand is bringing to the fuel. Heat transfer should be modelled between the firebrand, recipient fuel and atmosphere with regard to the ignition criteria of the recipient fuel, including humidity effects. Experiments on the ignition of various

recipient fuels by firebrands are recommended to understand this spotting ignition process. The spot fire hazard directly depends on the recipient fuel condition and previous experimental studies showed that the materials inside structures are more likely to be ignited than outside building materials in the case of urban fires and WUI fires. Through the reviews of spotting-dominant conflagrations, it is recommended to design structures to prevent firebrand intrusion to decrease spotting hazard substantially. Thus, if spot ignition models are incorporated into firebrand transport models and firebrand generation models, then the spot fire hazard can be assessed more reliably, and the integrated firebrand model can actually be of assistance in allocating resources in wildfires and a tool for developing new building codes and standards to reduce structure losses in urban and WUI fires.

Another mechanism in the spotting ignition process to be studied is transition from smouldering combustion to flaming combustion. Burning firebrands are likely to be in glowing combustion, as observed in experiments, field studies and real fires (Vodvarka 1969; Waterman 1969; Waterman and Tanaka 1969; Muraszew *et al.* 1975; Clements 1977; Woycheese 2000). Therefore, many spot ignitions may start with smouldering ignition at contact with glowing combusting firebrands, then progress to flaming fires, as Manzello *et al.* (2006a, 2006b) showed in their experiments. In a spotting hazard assessment model, ignition by firebrands would be expressed as some probability functions or criteria of initiation of a flaming combustion of the recipient fuel.

Conclusions

In order to study firebrand phenomena, large-scale historical fires were reviewed and previous experiments and models of firebrands were discussed. Spotting is an important mechanism in the spread of large-scale fires, such as urban conflagrations, forest fires, WUI fires and post-earthquake fires. The impact of firebrands is directly influenced by weather conditions, especially wind and humidity. Wind drives firebrand transport and humidity is a key parameter in determining whether ignition by firebrands occurs. Therefore, firebrands need to be studied in order to reduce the threat posed by discontinuous fire spread due to spotting. As shown by Tarifa, a firebrand during flight is in momentum balance, so dynamics models that analyse the drag force on a firebrand have been developed using the terminal velocity assumption. Additionally, combustion models have been developed to capture the effects on firebrand trajectories. Plume models have been employed as temporary surrogates for the true flow-field generated by the interaction of the fire with the ambient wind. Even though many experimental studies have been performed, more studies of firebrand generation and fuel ignition on landing are still needed. Spotting ignition is a complex problem; however, efforts to understand this phenomenon should be kept up to get better knowledge of fire behaviour in catastrophic conflagrations, wildfires and WUI fires.

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