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Wildland fire spot ignition by sparks and firebrands

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ABSTRACT

Wildland and Wildland Urban Interface (WUI) fires are an important problem in many areas of the world and may have major consequences in terms of safety, air quality, and damage to buildings, infrastructure, and the ecosystem. It is expected that with climate changes the wildland fire and WUI fire problem will only intensify. The spot fire ignition of a wildland fire by hot (solid, molten or burning) metal fragments/sparks and firebrands (flaming or glowing embers) is an important fire ignition pathway by which wildfires, WUI fires, and fires in industrial settings are started and may propagate. There are numerous cases reported of wildfires started by hot metal particles from clashing power-lines, or generated by machines, grinding and welding. Once the wildfire or structural fire has been ignited and grows, it can spread rapidly through ember spotting, where pieces of burning material (e.g. branches, bark, building materials, etc.) are lofted by the plume of the fire and then transported forward by the wind landing where they can start spot fires downwind. The spot fire problem can be separated in several individual processes: the generation of the particles (metal or firebrand) and their thermochemical state; their flight by plume lofting and wind drag and the particle thermo-chemical change during the flight; the onset of ignition (smoldering or flaming) of the fuel after the particle lands on the fuel; and finally, the sustained ignition and burning of the combustible material. Here an attempt has been made to summarize the state of the art of the wildfire spotting problem by describing the distinct individual processes involved in the problem and by discussing their know-how status. Emphasis is given to those areas that the author is more familiar with, due to his work on the subject. By characterizing these distinct individual processes, it is possible to attain the required information to develop predictive, physics-base wildfire spotting models. Such spotting models, together with topographical maps and wind models, could be added to existing flame spread models to improve the predictive capabilities of landscape-scale wildland fire spread models. These enhanced wildland fire spread models would provide land managers and government agencies with better tools to prescribe preventive measures and fuels treatments before a fire, and allocate suppression resources and issue evacuation orders during a fire.

1. Introduction

Wildland and Wildland Urban Interface (WUI) fires may have major consequences in terms of safety, air quality, and damage to the ecosystem [1]. According to the National Interagency Fire Center the average of wildfires in the US from 2006 to 2015 was 71,594 with close to 7 million acres burnt annually [2]. The financial losses of some of these fires are staggering in terms of civilian and firefighter losses. The loss of structures has also increased significantly in part due to the urban development of the wildland. With current drought conditions in much of the western areas of the United States the danger of wildfires has continued to increase. Furthermore, it is expected that due to weather pattern changes because of climate change the problem will become even more severe in the future worldwide.

The spot fire ignition of a wildfire by hot (solid, molten oxidizing or burning) metal fragments/sparks and firebrands (flaming or glowing embers) is an important fire ignition pathway by which wildfires, wildland urban interface (WUI) fires, and fires in industrial settings are started and may propagate. Hot metal fragments and sparks can be generated by power line interactions, hot work (friction, grinding, welding), overheated brakes, vehicles' exhaust systems, ballistic impacts, explosions, pyrotechnics, and other sources of incandescent particles [3–8]. The particles generated by these events can fly away from the originated source by initial momentum or can be carried away by wind. Depending on the energetic characteristics of these particles and the target fuel bed on which they land, the particles are potentially an ignition source of vegetation. Once the wildfire has been ignited and starts growing, subsequent fire spotting by firebrands becomes a

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potential major mechanism for the spread of wildfires or WUI fires. [9]. Firebrand spotting can lead to more rapid fire spread than flame front propagation because firebrands generated by burning vegetation or structures can be lofted by fire plumes, and transported downwind to ignite secondary fires or structures remote from the flame front. Civilians and firefighters alike can become trapped between spot fires without escape [10].

There have been many fires which have been allegedly caused by hot metal particles and sparks. According to published data [11–13], powerlines, equipment, and railroads cause approximately 28,000 natural fuel fires annually in the United States. There are some references which have compiled lists of such fires [4,5,12,13], but many remain unreferenced. After ignition the wildfire can propagate as a combination of a surface fire and a firebrand spotting assisted fire. Some of these fires are catastrophic with extensive damage. An example of these catastrophic fires is the 1991 Oakland Hills fire in Northern California, were embers from vegetation and structures caused the rapid spread of the fire resulting in 25 deaths and more than 3000 homes burned [14,15]. Another catastrophic example is the 2007 Southern California firestorm known as the Witch Creek and Guejito Fires that eventually burned almost 200,000 acres and destroyed over 1100 homes. The California Department of Forestry and Fire Protection [16] report for these fires alleges they were ignited by hot particles generated by power lines clashing. The fast spreading characteristics of these fires were due to spotting by embers as described by Maranghides and Mell [17]. The 2011 Travis and Bastrop Counties wildfires in Texas are another example of catastrophic WUI fires. Some of these fires were allegedly started when power lines interacted with each other and nearby trees during high winds [18]. The 2015 Butte Fire in Northern California has been reported as started by powerline interactions with trees. Over 70,000 acres were burned and the blaze destroyed 921 structures [19]. There are many other examples in New Zealand, Australia and Southern Europe of wildfires that were initiated by hot metal particles or firebrands and propagated very quickly by firebrand spotting. It has been reported that in New Zealand 275 fires were ignited by sparks or flying brands from 2005 to 2010 [20]. In Australia, some of the devastating wild fires in Sydney in 1994 [21] and of the Black Saturday event of February 2009 were also generated by sparks and propagated extremely fast by firebrand spotting [22].

Particles and sparks produced by hot work have been involved in multiple incidents [3–5]. An example is the 2012 Taylor Bridge fire in Washington State which was reportedly caused by sparks from rebar cutting saw or welding [23]. The fire eventually consumed in excess of 23,000 acres and destroyed approximately 60 homes and in excess of 200 outbuildings [23]. Other aspects of combustible material ignition by hot metal particles and sparks are also of technical and social interest. For example, sparks from welding, or dripping molten solder from pipe soldering, are known to have started fires in wooden buildings under construction [3]. Sparks have started fires by igniting expanded polyethylene insulation in buildings [24,25]. Notable is the ignition of the Beijing Television Cultural Center fire in 2009 where sparks from fireworks ignited insulating and waterproofing materials on the walls and roof [26]. Another recent (2016) major incident is the explosion of fireworks and subsequent fire of the firework market in Mexico City [27].

The spot fire ignition of a combustible material by a firebrand is another important aspect of this problem. Firebrands are generally generated during an ongoing fire, but can also be generated by conductors interacting with trees or by wood cutting or friction. Pieces of bark, needles, leaves, small branches are good candidates for firebrands. Short distance spotting (meters from the main fire front) may occur continuously while isolated spots may occur at longer distances (up to a few kilometers) [9,10,28]. The firebrands may land with enough energy to ignite underbrush, grass or structures. The latter is particularly important in terms of danger to lives and property. In fact it has been observed that most structures destroyed during WUI fires are not ignited by direct flame impingement, but rather by embers penetrating vents/eaves or direct ignition of roof construction and other soft targets [29–31]. Following the devastating 1994 Sydney, Australia wild fires, a statistical study determined that 75% of houses were ignited by firebrands, while 25% were ignited by firebrands and flame radiation [21]. The Oakland Hills Fire [14,15] and the 2002 Hayman Fire [32] are also examples of major life and property losses in WUI fires.

Fire spotting ignition and the subsequent spread of fire is a complex problem involving multiple physicochemical processes in the solid and gas phases. These processes depend on many factors, including the generation of the particles, the size and thermo-chemical state of the particle (inert or burning), Trajectories of the particles from their generation to their landing, characteristics of the shower of particles if any (dense or light), the fuel bed where they land (fuel type, porosity, moisture content, temperature), and environmental conditions (temperature, humidity, wind velocity). Understanding and prediction of the problem is of scientific significance but overall it has the potential to reduce fire losses and to save lives. For example, the identification of the minimum particle size capable of igniting combustibles typically found in common spot fires together with the identification of combustibles fuel beds with a high ignition propensity would help developing predictive tools that could be used to reduce fire risks. These could include identifying high-risk power line runs so that utilities could prioritize fuels treatments. Clearance distances along highways and railroads could be set in an intelligent way to avoid unnecessarily large clearances while still reducing the likelihood of spot fire initiation. This type of information could be used for regulatory guidance and test standards for fire-safe construction, and efficient allocation of fire suppression resources during fire events. Wildfire spread models could be provided with a way to accurately predict firebrand spot fire initiation as a function of terrain, weather and fuel bed characteristics. These enhanced fire spread models would provide land managers and government agencies with better tools to prescribe preventive measures and fuels treatments before a fire and allocate suppression resources and issue evacuation orders during a fire.

Although progress has been made in the understanding of some of these aspects of the problem, there is still a lot to do. Here an attempt has been made to summarize the state of the art of the problem. Emphasis is given to those areas that the author is more familiar with, due to his past and current work on the subject.

2. Spot wildfire processes

The spot wildfire problem can be separated in several individual processes: the generation of the particles (metal or firebrand and their thermochemical state; their flight by plume lofting and/or wind drag; the particle thermo-chemical change during the flight; the onset of ignition (smolder or flaming)) of the fuel bed after the particle landing, the sustained ignition of the combustible material, transition to a flaming fire and its potential spread.

2.1. Particle generation

2.1.1. Metal particles

There are different ways for hot metal particles to be generated. Power line interactions, hot work or mechanical interactions (impact, friction, cutting) are among the potential sources. The characteristics of the generated particles (size, number, thermo-chemistry) depend on the type of metal and mechanism of generation. In high winds, the conductors of power lines (generally aluminum or copper) oscillate (referred to as buffeting or galloping) and may come sufficiently close to each other to arc or clash [33–35]. During the conductors clashing, metal fragments may be produced and ejected from the arcing location due to the gas expansion caused by the arc or by mechanical forces from the conductors' impact. The current of the arc and the duration of the arc determines the amount of material removed from the conductor, the size and number of the generated particles, the ejection direction and velocity, and the thermodynamic state (molten or burning) of the particles [34,35]. Some of the metal from the conductor may evaporate in the process although it appears that the majority of the metal melts rather than evaporate [4]. There are only a few studies published of the characteristics of the generated particles after arcing of conductors. Particularly relevant are the works of Ramljak et al. [4] and Pleasance and Hart [33] with clashing aluminum conductors at amperages between 100 and 500 A. The work of Ref. [4] provides a statistical study of the size and frequency of particles generated by clashing power lines at different currents. The results show a probability distributions of particles with maximum frequency in the 0.75 mm range. The work of Ref. [33] provide similar results although the larger percentage of particles were in smaller sizes. Particles generated by welding have similar characteristics to those from conductors clashing although in general they may be bigger [36,37]. The size of the particles generated by machinery interaction depend on the type of metal and the energy and removal process (friction, cutting). Particles generated by friction are generally small (sparks) of the order of 100 s of μm although they are normally generated in the form of continuous showers [7,38]. Particles generated by cutting are generally larger and thin (metal shavings) and their characteristics depend on the cutting mechanism. If there is sufficient heat generation the shavings can curl as material are cut into hollow relatively spherical particles [39].

Another important aspect of the particle generation process is the thermo-chemical state of the particle at generation. Depending on the type of metal and the generation mechanism the particles may be solid, molten, oxidizing on the surface or burning in the gas phase (flaming). When formed during conductors, or electrodes, arcing the metal particles can be heated above their melting and boiling points if exposed long enough to the arc. The metal particle may burn as a vapor (flame) if the metal oxide vaporization temperature is greater than the temperature of the metal boiling point (Glassman criterion [40]). Aluminum is often ejected at a high enough temperature to burn in the gas phase (flaming), because the boiling point of the aluminum oxide (3800 K) is much higher that of aluminum (2750 K). The burning mechanism is characterized by a diffusion flame surrounding the evaporating droplet [40–42]. However, if the particle is ejected at a lower temperature than the boiling point of the aluminum, an oxide layer may be formed on the droplet surface that may prevent the gas phase burning of the aluminum [43,44]. The aluminum surface oxidation is much slower and less energetic than flaming, although the heat released in the reaction may increase somewhat the particle temperature [33,45]. Wind shear forces can remove the oxide layer allowing the onset of flame burning of the aluminum [43,44]. If the arcing process is too short the aluminum particle may simply be ejected in the molten state. In the case of copper it has a boiling point (2070 K) that is smaller than that of the oxide (2850 K) and according to Glassman criterion [40] it does not burn in the vapor phase. A literature search confirms this prediction at least in air [43]. Thus for copper arcing the particles are generated in the molten state. Also they are smaller than the aluminum particles because they often break into small particles during the generation process [6,46]. Although iron can burn in the gas phase given that the boiling point of the iron oxide (3403 K) is smaller than that of the iron (3670 K) the difference is relatively small, which favors the surface oxidation rout [40]. The surface oxidation reaction is slow and controlled by the rate of oxygen transport to the surface (diffusion or convection) and the rate of oxygen diffusion in the oxide layer. Although the oxide layer is thin the heat released by the reaction can increase the particle temperature during the oxidation process [45].

2.1.2. Firebrands

Firebrands are primarily generated from burning wildland fuels (grasses, shrubs, trees) or wooden structures (structural members, shakes, singles) that break into smaller burning pieces and are lofted by a buoyant fire-induced plume. Wildland or structures fires can generate firebrands when fuels that carry the fire thermally decompose, lose structural integrity, and smaller pieces of fuel separate from the larger parent fuel. Although less common, firebrands can also be generated by power line interactions with trees or structures [47]. The characteristics of the embers depend on the type of vegetation and the intensity of the originating fire. In addition to the physical characteristics (size, density, etc.) they may be flaming or glowing (smoldering). Due to its inherent complexity, the firebrand/heated particle generation process may be best analyzed with stochastic models that take empirical data as input. The work of Tarifa et al. [48] is an early study to determine the characteristics of firebrands from a wildfire. Another early study is that of Ref. [49] although more empirical. In the last few years Manzello and co-workers [29,30,50–59] have embarked on an experimental program to characterize the number and size distribution of brands generated by different fuels, and their work is making significant progress in the understanding of the problem. Particularly novel is the development of several types of firebrand generators ("Dragons") [51,52] and their application to characterize firebrand evolution and ignition of vegetation and buildings components in WUI fires.

The thermo-chemical characteristics of the generated firebrands is also another aspect of the problem. Although the embers can be generated flaming once char is generated the burning turns to glowing combustion (smoldering). The intensity of the ember burning and the heat released depends on several factors including the wood characteristics (type, porosity), char layer and environment [48,57,60]. As the char builds up it restrains the burning of the virgin wood by preventing the oxygen from reaching the interior of the particle [48].

2.2. Particle transport

After embers or sparks are generated they may be lofted in a fire plume and/or transported by ambient winds. This aspect of the spot fire development is the one that has been studied the most. Plume correlations or CDF simulations for axisymmetric and line fires [61–68] can be used in conjunction with drag coefficients to determine the lofting (vertical) force applied to an ember; the lateral (horizontal) force components are determined in a similar way based on the wind's velocity profile.

The trajectories and burning rates of embers lofted by ground fires have been studied by several researchers over the years. Pioneering work was conducted by Tarifa et al. [48,68] that experimentally determined drag and burning rates of spheres, cylinders and plates of various woods, which were then used to calculate the maximum range of possible fire spread based on terminal fall velocities. This early work have been followed by several theoretical and experimental studies of the transport of firebrands addressing different aspects of the problem [28,69–77]. The transport of metal particles has received less attention probably because it does not have the frequency, and clear impact, of the firebrands in the development of wildfires. The published works on the subject [33,43,44,78] differ primarily in the depth that the different aspects of the problem are treated.

Calculating the trajectories of embers or metal particles consist on the application of Newton's laws of motion to a flying particle. The formulation of the problem follows the well establish ballistic equations although with the added complexity that the particles are hot and maybe burning and consequently that the temperature, size, and mass of the particles may change in time. The reader is referred to Refs. [43,48] for a complete description of the problem formulation. Although the problem looks straight forward there are a number of issues that complicate its solution. The primary one is the modeling of the ember or metal particle burning process because if the particle is burning, then the particle diameter and mass are functions of the burning rate and consequently time. The time dependent variation of the particle mass and diameter affects the gravity and drag forces and through them the particle trajectory. Diameter variations will affect also the heat transfer from the particle to the surrounding air. In the case of firebrands the woody material burns through a heterogeneous surface combustion reaction (glowing smolder) of the wood in the outer volume of the ember and by a homogeneous gas phase combustion reaction (flaming) in the air surrounding the ember. Flaming is more likely to occur initially followed shortly by glowing. The heat from these reactions maintains the in depth pyrolysis of the wood which is time dependent due to the char build up. As the char layer surrounding the ember grows, the transport of oxygen to its interior is deterred which eventually prevents further burning of the ember. Thus burning of the wood changes the mass of the ember and the diameter depending on the heat released by the reaction and the char formation. The modeling of these processes is difficult and complicates the accurate prediction of the firebrand trajectories. An approach is to use experimental data to develop empirical correlations of the variation with time of the ember diameter and mass as done in [43]. The experiments of Tarifa et al. [48,68] remain to date the best data on firebrand mass loss rate and size regression rate as a function of the relative wind velocity. These data was used in [43] to develop an effective regression rate equation for spherical firebrands by fitting the data with a diameter to the fourth power law. Following a similar approach Anthenien et al. [75] developed burning rate expressions for cylinders (twigs) and very thin disks (leaves). Although these studies provide a first step in the modeling of firebrand burning, there is still a need for ember burning characterization that would provide information about the transient effects in the ember burning process and surface temperature as char builds-up, such as the effect of the type of wood on the burning rate [79], death versus live vegetation [80].

The modeling of the burning rate in the formulation of the trajectories of metal particles also complicates the solution of the problem. In the case of aluminum particles, they can be generated in the molten state, oxidizing on the surface or burning in the gas phase with flame surrounding the Al droplet. For flame burning the aluminum particles have to be heated during the particle generation process (arcing) above the melting point of the Al_2O_3 (2327 K) so that the oxide does not accumulate on the particle surface and prevents the Aluminum from burning [43,44]. Also, even in an oxide layer is formed, it can be stripped away by wind shear allowing the gas phase burning of the aluminum. In these cases the Aluminum particle will burn similarly to a liquid fuel droplet with a burning rate described well by a diameter squared law [40], and the burning constant obtained from experimental data on Aluminum burning [42,81]. If the particle is heated below this temperature and an oxide layer is formed the rate of Aluminum oxidation will be slow and the particle will cool down during the trajectory by radiation and convection. The solution of the equations is simpler in this case following well establish methods of the heat transfer literature [43]. The copper particles are analyzed following also this approach since they do not burn in the gas phase [43]. Iron or steel particles (sparks) generated in grinding processes are generally not hot enough to burn in the gas phase, but they may oxidize in the solid phase during the particle trajectory. The oxidation process is slow and limited by transport of oxygen to the surface and within the steel oxide layer. Depending on the energetic characteristics of the oxidation reaction and the heat losses to the surrounding air the oxidation reaction may increase somewhat the particle temperature from that at generation by transferring part of the heat released by the reaction to the interior of the particle [46].

The transfer of heat from the particle to the surrounding air is another aspect of the problem that must be considered. As the particle travel from its generation location it loses heat to the surrounding air by convection and radiation. For the cases where the particle does not burn or oxidizes, the particle will cool down during the flight. If the particle is molten, the rate of solidification can be obtained from a lumped energy equation with the heat loss is dependent on both the convective and radiative cooling rates. For solid inert particles, the rate of temperature change can be obtained using a lumped energy equation [43]. The heat transfer coefficient is calculated from the Nusselt number for the corresponding geometry. For this calculation, the film temperature of the air surrounding the particle is used to estimate the air thermal properties. Since the particle temperature changes with time, so does the Reynolds and Nusselt number which affects the drag force and heat transfer coefficient [43].

The ejection velocity of the particles during their generation is another parameter of the problem that may be important in some specific cases. It appears in the formulation of the problem as a boundary condition. For the firebrands transport it is appropriate to assume that the ember separates from its parent material with zero initial velocity. However, for metal particles generated during an arcing process (conductors clashing or welding) the particles are ejected from the arcing location with an initial velocity and in multiple directions due to the gas expansion caused by the arc. Measurements from videos of power line clashing [3] and in other unpublished works indicate that the ejection velocity is of the order of 1 m/s [33,43]. The document of Ref. [33] reports laboratory experiments where ejection velocities as high as 20 m/s are measured. However, it is questionable the accuracy of the measurements because the velocities are calculated from high speed videos within milliseconds of the arcing and the report acknowledges potential problems with camera saturation from the arc flash that lasts 100 ms. The ejection velocities in metal grinding are better defined since depend strongly on the rotation speed and diameter of the grinding device.

Models similar to those of Refs. [43] and [75] can be used to calculate the trajectories of the particles for different environmental conditions. For aluminum particles, for example, the calculation show that larger particles land closer to the ejection location and that smaller particle may burn out before landing on the ground [43]. The particles ejected in the wind direction travel farther than those ejected against the wind and as a result the particles land in an ellipsoid area downwind. Similarly large embers land closer to the generation location and small firebrands burn before landing. Combining topographical maps of a wildland fire location with wind models of the area and the particle trajectories it is possible to predict potential locations of wildfire spotting [82]. Such predictions could be used by the firefighting command center to allocate suppression resources and issue evacuation orders during a fire.

2.3. Fuel bed ignition

Once the particle lands on the fuel bed the particle transfers its energy to the surrounding fuel and air. If the particle has enough energy the fuel is heated and pyrolyzes, while the particle cools down in the process. The pyrolyzate mixes with the air and a flammable gaseous mixture may be generated near the particle. If the particle is still hot enough and big enough it can act as a pilot and ignite the gaseous mixture as a flame. If it is not hot enough to cause the flaming ignition of the fuel it still can provide enough energy to initiate the flaming of the gas by spontaneous ignition. Alternatively, the hot particle can initiate a self-sustained smolder of the fuel that eventually may transition into flaming. Thus, this complex ignition process depends on several factors, including the size, temperature, and state of the particle at landing. If the particle is a metal whether it is solid, molten, oxidizing, flaming, or if it is an ember whether it is inert, smoldering/glowing or flaming. The characteristics of the fuel bed on which the particle lands (fuel type, temperature, density, porosity, void fraction, moisture content), the landing characteristics of the particle (fully or partially embedded on the fuel bed, bouncing, splashing) and environmental conditions (temperature, humidity, wind velocity). Naturally a study of this complexity must be parameterized.

2.3.1. Experimental work

2.3.1.1. Firebrands. Only relatively few studies have examined the critical conditions that can lead to fire initiation after the landing of a metal particle or firebrand on a natural fuel bed. The later subject is quite broad since it includes wildland and WUI fires. Notable is the pioneering work of Manzello and Co-workers [50–59,83–88] of the ignition of natural fuel beds and structural components by showers of firebrands. These WUI related studies address a number of practical issues such as firebrand penetration in home roofs and vents and subsequent fire ignition, ignition of fences and decks by accumulation of firebrands etc. An important result is that with firebrand showers the accumulation of firebrands in deck crevices, fence corners, vertical walls and garden mulch, etc. enhances the ability of the firebrands to ignite structures. In addition to the unique information contained in these works, one important aspect is the improved understanding of WUI fire development and its application to building fire codes modification. Another interesting approach to obtain data on the generation of firebrands in wildland fires is the investigation of Filkov et al. [89] that describes a study of the production of firebrands during prescribed fires in a pine forest. The study provides interesting information on type of firebrands produced, mass and size distribution of firebrands, and velocity of the firebrands.

Examples of small scale experiments attempting to understand the basic mechanisms of the ignition of natural fuel beds by firebrands is the exploratory work of Refs. [90,91]. In those experiments wooden cylinders of different sizes are ignited to flaming or glowing and drop on a fuel bed of cellulose or saw dust. The ignition of fuel beds by the "laboratory" firebrands are observed with IR videos to determine the characteristics of the process. The work resulted primarily in qualitative information about the problem. Recently Urban et al. [92] have been conducting studies on the effect of the moisture content of the fuel (FMC) on the smolder ignition of sawdust by firebrands. Moisture content of the fuel is one of the most important parameter of the problem, if not the most important, because it determines the limiting condition for ignition of a fuel in terms of its natural state. In the experiments of [90] embers made from wooden cylinders of various sizes up to 12 mm in diameter and length are brought to glowing combustion with a flame and then dropped onto the sawdust below. The FMC boundary which for a given size firebrand there is a 50% chance of smolder igniting the sawdust is determined by performing a logistic regression on the experimental results. Results from this work show that larger embers are capable of igniting sawdust with a higher FMC, which is reasonable since they have a larger energy content to evaporate the water contained in the fuel. The largest ember studied, 11.1 mm, had a FMC ignition boundary of 40%. The FMC ignition boundary then decreased as the particle size decreased. It was found that a 1.6 mm ember was unable to ignite a smolder in a fuel with a moisture content below 1%.

2.3.1.2. Metal particles. The subject of spot ignition by metal particles is also broad, particularly because of the number of parameters involved. Early studies on the subject are the experiments of Refs. [33,46,93] The most detailed study is that of Rowntree and Stokes [93] that presents data on the ignition of Barley grass by hot aluminum particles and discusses the dependence of the ignition event on the temperature and size of the particles. The author and co-workers [94–102] have been studying the problem with the objective of providing a better understanding of the physic-chemical mechanisms controlling the spot fire ignition process. The basic experimental approach is to heat a particle of a specific metal typically encountered in spot fires (steel, aluminum, copper, brass) to a given temperature and then drop it onto a fuel bed of interest (cellulose powder and paper strips, natural and powdered dry grass, and natural and powdered dry pine needles, sawdust), and to observe if flaming ignition or smolder ignition occurred. Most of the studies were limited to observe the onset of flaming ignition because smolder ignition is more sensitive to experimental variations, and it is difficult to determine if smolder would eventually transition into flaming. Ignition or no ignition of the fuel by the particle was determined as a function of the parameters involved in the problem. Because of the many parameters influencing the ignition process the study was conducted varying systematically some of the parameters of the problem, such as the type of metal of the particle, its size and temperature, whether solid or molten, the type of fuel bed, the fuel moisture.

Different aspects in the study of the effect of the type of metal on the flaming ignition behavior of cellulose fuel beds are reported in Refs. [94–100]. In the study of Ref. [94] the fuel bed void fraction and method of heating the particles were different than in the other studies which is reflected in the differences of results. A summary of the flaming ignition boundaries with powder cellulose as fuel and for stainless steel, aluminum, copper and brass spheres is shown in Ref. [99,100]. Cellulose was selected as a "laboratory" fuel because is a major component of woody biomass and is well characterized and homogenous. The boundaries in these plots correspond to a 0% ignition likelihood. For all metals, the temperature required for ignition decreases with particle diameter. This relationship is strongest for small particles. The data suggest that there are two ignition regimes: a large diameter regime where ignition is primarily dependent on particle surface temperature, and a small diameter regime where both bulk energy and temperature play important roles. Large particles all have large energy because of their mass, thus energy is not a factor in the fuel ignition but temperature is. Small particles have small energy because of their small mass and consequently they may not have enough energy to ignite the fuel. Consequently size (mass) and temperature (energy) are both determining factors for ignition by small particles. Overall no major differences are observed in the ignition boundaries for the different metals. Notable is that aluminum has a thermal conductivity that is an order of magnitude larger than that of steel and this is not reflected significantly in the ignition potential of solid aluminum particle versus the steel particle. Melting however has a marked effect on the impact behavior of the aluminum particles. The ignition temperature boundary of molten aluminum is clearly lower than other metals and has a flatter region corresponding to the melting temperature of aluminum. In this region, the aluminum solidifying contributes significant energy to the fuel, equivalent to a ~400 °C temperature rise in a solid aluminum particle, which explains the lower temperature for ignition of aluminum particles.

The flaming ignition boundaries obtained with aluminum particles and different fuel beds were reported in Ref. [101]. The fuel beds tested were α-cellulose, a dry grass blend, and pine needles in both powder form and as paper strips (cellulose), natural dry grass and pine needles. The fuels were chosen to be representative of fine 1-h natural fuels such as duff and litter. Comparing the different ignition boundaries of these fuels provides insight into the effects of fuel morphology and the addition of lignocellulosic compounds on the ignition boundaries. Consistent with the results with cellulose as fuel the results show a hyperbolic relationship between particle size and temperature. For larger sized aluminum particles, the ignition boundaries are not very sensitive to particle size, while for small particle sizes the ignition boundary is very sensitive to the particle size. The results show that the ignition boundaries for pure alpha-cellulose fuels are very sensitive to changes in the fuel bed macrostructure while the grass blend fuels are not as strongly affected. It is also seen that pure cellulose ignites at lower temperatures than vegetation. This suggests that the lignin and the more diverse chemical structure of actual natural fuels deter their ignition when compared with pure cellulose. It also shows that fuel in powder form ignites at a lower temperature than in natural form which shows that the morphology of the fuel is also an important factor in the ease of ignition.

Although most of the work reported above was based on flaming ignition, it is recognized that smolder ignition it is also a likely form of wildfire initiation. As a follow-up of previous work Urban et al. [102] conducted a study to observe the ignition differences between flaming and smolder. Comparison of the flaming ignition and smolder ignition boundaries are given for a powdered grass blend as fuel and stainless steel and aluminum particles. The determination of sustained flame spread, extensive smolder spread or transition to flaming was not pursued. Each of these phenomena are sufficiently complex as to deserve their own study. In this work self-smolder was defined when a visible char layer surrounding the particle had a thickness greater that the particle diameter and movement of the smoldering front was observed. This criteria was supported by readings from an IR camera, which showed increasing temperatures after a period of cooling. As a final check, a handful of tests were performed where the smoldering front was allowed to propagate freely through the entire sample over the course of 1 h. The experimental ignition boundaries in terms of the particles diameter and temperatures show that for the same particle properties smolder ignition occurs at lower temperature than flaming ignition. This is understandable because the energetic and temperature requirements for smolder initiation are smaller than those for flaming ignition.

An evident conclusion of the results summarized above is that there is not a single ignition temperature (smoldering or flaming) of a combustible fuel bed, and that the ignition temperature depends of the characteristics of the ignition source and fuel bed. In the above referenced works the lowest flaming ignition temperature observed was around 600 °C for the largest aluminum particles (8 mm diameter) igniting cellulose powder, and 500 °C for smolder ignition of sawdust grass blend powder. For even larger particles the ignition temperature might be lower, but the data indicates an asymptotic trend toward the above values. It should be noted that the study of Pitts [103] for the ignition of cellulosic fuels heated with a hot plate is sometimes referenced to report the ignition temperature of cellulosic fuels (290 °C and above). However, it should be taken into account that the heating source in Ref. [103] is not representative of a hot metal particle or ember igniting a cellulosic fuel. In those tests the heating plate is much larger than common hot metal particle sizes and it is kept at constant temperature with an electrical heater that prevents the plate from cooling down as it heats the fuel bed as it occurs with a metal particle or ember. Thus, it is understandable that the cellulosic fuels would ignite at those low temperatures.

The possible existence of a minimum particle size for ignition is another important issue in the present problem. In the studies reported above, in Refs. [95–102] the method used to heat the particles had a maximum temperature of 1100 °C. In Ref. [93] a few tests were conducted with temperatures up to 1400 °C and 1300 °C in Ref. [94]. At these temperatures, the minimum particle size for ignition of cellulosic fuels was approximately 2 mm in diameter for both flaming and smoldering [93,95]. Rowntree and Stokes [93] extrapolated their results to higher temperatures and predicted smaller aluminum particles for ignition, although this has not been verified. They conducted however some tests of the probability of showers of aluminum particles of different sizes igniting barley grass [93]. The particles were generated by arcing aluminum electrodes which produced a shower of particles of different sizes. In the tests the particles temperature was not measured although it is implicit that it was larger than 1400 C since they were generated by arcing. They found that particles smaller than 1 mm could ignite some of the fuels tested although with a very low probability (~3% max). Particles with 2 mm diameter showed probabilities of ignition of the order of 20%. It is unclear however if accumulation of the particles was a factor in the observed results. As it was discussed above regarding showers of sparks from hot work, even if the particles have very high temperature if they are very small they may not have the energy necessary to ignite the fuel unless there is an accumulation of particles in a location.

As indicated above, the moisture content of the fuel is one of the most important parameters of the problem for dead fuels because the moisture is typically largely water which must be evaporated before a solid fuel can be pyrolyzed or smoldered. It should be noted that for live fuels, other effects such as water being trapped in cell walls and significant changes in the chemical composition of the fuel depending on the time in the growing season affects the moisture effect on the fuel ignition. Very few studies have been conducted on the effect of moisture on the ignition of natural fuels by hot metal particles. Zak et al. [95] did some preliminary experiments on the effect of moisture on the ignition of cellulose by steel and brass particles of different sizes. As expected larger particles and higher temperatures were needed to ignite the cellulose for higher moisture content. A more systematic study is that of Wang et al. [104] that studied the effect of the fuel moisture content and of wind on the flaming and smolder ignition of pine needles by hot steel particles. They also found that for a given particle size as the FMC was increased the critical temperature for ignition of the fuel also increased. The experimental data was correlated with simple expression for the critical temperature for ignition in terms of FMC and particle diameter [104]. An aspect of this issue that needs to be addressed is the existence of a limiting value of the FMC beyond which a natural fuel will not ignite by hot particles.

2.3.2. Theoretical modeling

The experiments have clearly established that ignition of fuel beds by hot particles cannot be described on the basis of a particle's thermal energy content alone, i.e. minimum ignition energy concepts that have been applied to the ignition of flammable gases do not apply to condensed-phase materials. Unlike ignition of a flammable gas mixture by a hot particle, in the ignition of a cellulosic fuel by a hot particle, the particle must have enough energy to first thermally decompose or pyrolyze the natural fuel. Afterward the particle must have enough extra energy and high temperature to either: initiate a self-propagating smolder reaction; or initiate the flaming ignition of the flammable mixture of pyrolyzate and air near the particle. The later could be through a spontaneous ignition process if the particle temperature is relatively low or a pilot type ignition if the particle temperature is high. Thus in order to model the ignition process, a theoretical model must properly simulate porous solid and gas heat and mass transfer, flow transport and chemical reactions in the condensed and/or gas phases.

A few analytical studies related to ignition of fuel beds by particles have been conducted. In particular, “hot spot” theories have been applied to natural fuels [105,106] but the work of Ref [94] suggests that their predictive capabilities are more qualitative than quantitative. A possible explanation is that the hot spot theory was developed for far more energetic materials such as solid propellant which do not include gas phase mixing, or the presence of competing endothermic and exothermic thermal decomposition reactions. Another simplified approach to model the spot ignition problem without solving the full governing equations is that of Zak [107] that used a one-dimensional model (spherical symmetry) to predict the flaming ignition of a powdered combustible material (cellulose) by a hot metal particle. By extracting the scaling parameters that control the different mechanisms involved in the flaming ignition of the fuel the analysis provides insight into the problem. This theoretical model was later extended with Urban et al. [102] to model the smolder ignition of a porous material by a hot metal particle. The 1-D spherical smolder ignition model showed that near the smoldering ignition boundary the hot metal particle that initiated the smolder would also cool down and act as heat sink. Smoldering ignition would only occur if the smoldering front could overcome the heat losses to the particle.

Although these later approaches are promising, it is likely that to model the problem accurately it will be necessary to develop detailed numerical models of the problem. An example of such approach is the model developed by Lautenberger and Fernandez-Pello in Refs. [108,109] of the spotting ignition of a porous fuel bed by a firebrand. The model description is split into three parts: 1) Condensed phase, which applies inside the porous fuel bed and includes both a solid and a gas phase, 2) Gas phase, which applies in the exterior ambient, and 3) Boundary/initial conditions which describe the particle. The condensed phase computational model formulation is based on the GPyro computer code [110] and includes the two-dimensional conservation equations for a porous combustible material undergoing thermal and oxidative reactions. The reaction mechanism used is based on a mechanism to simulate the oxidative pyrolysis of white pine [111]. The mechanism consisted of four steps and included a reaction to account for moisture evaporation. The condensed phase analysis is coupled to the Fire Dynamics Simulator (FDS) Version 5.1.3 [112] with some simplifications and approximations. The boundary and initial conditions on the gas phase (handled by FDS) and the powdered cellulose (handled by the pyrolysis model) are described in detail in Ref [109]. A temperature wake forms downstream of the volumetric heat source that represents the firebrand, with the gas-phase temperature rise above ambient due primarily to heat provided by this heat source. A quasi-steady state is reached, where the temperature increases slightly with time as the surface temperature of the cellulose increases, reducing heat losses from the heated gas to the solid. The model predicts that the cellulose is heated preferentially downstream of the ember, as one would expect. The temperatures are low enough that minimal smoldering occurs, with a thin char layer forming only near the cellulose surface where it abuts the heat source representing that firebrand. The model also calculates the concentrations of various gas-phase species inside the decomposing porous solid (cellulose in this case). This is critical for predicting the transition from smolder to flaming as well as accounting for differences in burning behavior in inert and oxidative environments.

The model and resultant computer simulations appear to be capable of discerning between conditions that will or will not lead to initiation of a spot fire after landing of a firebrand. However, additional work is required to characterize practical materials and to better understand the boundary condition between the firebrand or heated particle and the fuel bed. Because the heat transfer between the particle and the fuel and environment is a critical mechanism in the problem, a 3-D model is needed to predict quantitatively the spot ignition problem. Also challenging is determining the material properties and reaction kinetics of various fuels that must be supplied as input to the model. The reaction kinetics of the firebrand as the char layer increases and the wood temperature decreases also requires further study.

3. Concluding remarks

The problem of the spotting of wildfires by hot particles is complex and difficult to predict. In this paper by describing the distinct individual processes involved in the problem and discussing their current know-how status an approach is underlined to help developing models of wildfire spread where spotting is important in their initiation or propagation. The methodology of studying each individual step in sequence to build up the information required to develop a predictive model for wildfire ignition by heated metal particles and firebrands could be used to simulate different aspects of the wildfire problem. For example, it could be used together with statistical data of weather patterns and vegetation distribution in the development of wildfire hazard maps that could guide identifying high-risk power line runs so that utilities could prioritize fuels treatments [113]. Another example of the use of such methodology is to determine clearance distances along highways and railroads in an intelligent way to avoid unnecessarily large clearances while still reducing the likelihood of spot fire initiation. This type of information could be used for regulatory guidance and test standards for fire-safe construction, and efficient allocation of fire suppression resources during fire events. Furthermore, wildfire spread models could be provided with a way to better predict firebrand spot fire initiation as a function of terrain, weather and fuel bed characteristics. These enhanced wildland fire spread models would provide land managers and government agencies with better tools to prescribe preventive measures and fuels treatments before a fire and allocate suppression resources and issue evacuation orders during a fire.

However, as pointed out in the discussion of the individual process several aspect of the problem still need further study. For example, the overall differing characteristics of the fuel bed, including fuel type, morphology, porosity, moisture content, etc. makes the modeling problem very challenging because of the variety of fuel beds encountered in the wildland. In the case of ignition by metal particles information is needed of the characteristics of very small particles (sparks) and their ignition propensity. Also needed is information about accumulation of sparks in a localized spot from showers of sparks. If the shower is dense the metal fragments and sparks will land close enough to interact with each other or may accumulate to produce larger particles. If the shower is disperse the particles may be treated individually. Similar results may occur with showers of firebrands. Thus the characterization of the showers of sparks or firebrands in realistic situations is important. Another important aspect of the problem is the characterization of the burning processes (flaming, surface oxidation, oxide or char accumulation) of metal particles and embers. Also needed are models that can discern between smolder ignition, spontaneous ignition or piloted ignition to flaming.

One approach to overcome these problems is to use statistical methods to determine the ignition propensity of a metal particle or firebrand. For the fuel bed characteristics, probability data of the ease of ignition of a given fuel beds could be used. When addressing the particles as the source of ignition a statistical approach such as a Monte Carlo for the simulation of the size of particles, density of the spray of particles, burning characteristics, seems very useful. Another possible approach is to look at limiting cases such as considering the powder form of the fuel rather than the grass or needle form since the powder fuel is the easiest one to ignite. Also, limiting cases could be used for the particle characteristics at landing, such as considering a single particles or a very dense spray, average size particles, flaming or smoldering, etc. These approaches together with the available know-how about the wildland spot fire ignition mechanisms could provide current fire spread models with a way to accurately predict firebrand spot fire initiation as propagation as a function of weather and fuel bed characteristics.

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References

[1] G. Rein, Smouldering combustion phenomena, Sci. Technol. 1 (2009) 3–18.
[2] National Interagency Fire Center ⟨www.nifc.gov/fireInfo/nfn.htm⟩.
[3] V. Babrauskas, Ignition Handbook: Principles and Applications to Fire Safety Engineering, Fire Investigation, Risk Management, and Forensic Science, Fire Science Publishers, Issaquah, WA, 2003.
[4] I. Ramljak, M. Majstrovic, E. Sutloviec, Statistical Analysis of Particles of Conductor Clashing (2014, Dubrovnic May 13-16, 2014)Energycon (2014)

638–643.
[5] National Fire Protection Association, 2014. NFPA 51B:Standard for Fire Prevention During Welding, Cutting and Other Hot Work. [Online] ⟨http://www.nfpa.org/catalog/services/onlinepreview/online_preview_document.asp?Id=51B14#⟩.
[6] H. Wakelin, Ignition Thresholds for Grassland Fuels and Implications for Activity Controls on Public Conservation Land in Canterbury (Retrieved from), University of Canterbury, 2010 ⟨http://www.ir.canterbury.ac.nz/handle/10092/4245⟩.
[7] K. Mikkelsen, An Experimental Investigation of Ignition Propensity of Hot Work Processes in the Nuclear Industry. ⟨https://uwspace.uwaterloo.ca/handle/10012/8396⟩, 2014.
[8] M. Finney, T. Maynard, McAllister, I. S. Grob, A Study of Ignition by Rifle Bullets, Available at: ⟨http://www.fs.fed.us/rm/pubs/rmrs_rp104.pdf⟩ (accessed 26 November 2014), 2013.
[9] F.A. Albini, Spot Fire Distance from Burning Trees: A Predictive Model GTR-INT-56. s.l.: USDA Forest Service, 1979.
[10] E. Koo, P.J. Pagni, D.R. Weise, J.P. Woycheese, Firebrands and spotting ignition in large-scale fires, Int. J. Wildland Fire 19 (2010) 818–843.
[11] J.P. Prestemon, T.J. Hawbaker, M. Bowden, J. Carpenter, M.T. Brooks, K.L. Abt, R. Sutphen, S. Scranton, Wildfire Ignitions: A Review of the Science and Recommendations for Empirical Modeling (Technical Report), US Department of Agriculture: Forest Service, Asheville, NC, 2013.
[12] M. Ahrens, Brush, Grass and Forest Fires (Technical Report), National Fire Protection Association, Quincy, Massachusetts, U.S., 2013.
[13] US Fire Administration. ⟨Http://www.usfa.fema.-gov/statistics/estimates/wildfire.shtm⟩.
[14] J.G. Routley The East Bay Hills Fire Oakland-Berkeley, CA. US Fire Administration Technical Report Series. USFA-TR-060/October 1, 9991.
[15] P.J. Pagni, Causes of the 20 October 1991 Oakland-hills Conflagration, Fire Saf. J. 21 (1993) 331–339.
[16] M. Gilbert; California Department of Forestry and Fire Protection Investigation Report: Incident number 07- CA-MVU-10432, ⟨http://www.fire.ca.gov/fire_protection/downloads/redsheet/CA-MVU-010502_complete.pdf⟩.
[17] A. Maranghides, W. Mell, A Case Study of a Community Affected by the Witch and Guejito Fires, NIST Technical Note 1635. ⟨http://fire.nist.gov/bfrlpubs/fire09/art028.html⟩, 2009.
[18] S. Badger, Large-Loss Fires in the United States – 2011, National Fire Protection Association, Quincy, MA, 2012.
[19] CalFire Butte Fire Incident Report: http:/cdfdata.fire.ca.gov/incidents/incidents_details_info?incident_id=1221.
[20] Emergency Incident Statistics 2009–2010, New Zealand Fire Service, Wellington, N.Z., 2010.
[21] G. Ramsey, N. McArthur, Building in the Urban Interface: Lessons from the January 1994 Sydney Brushfires (Technical Report), National Institute of Standards and Technology, Hobart, Tasmania, 1995.
[22] The Victorian Bushfires Royal Commission Final Report, 31 July 2010.
[23] State of Washington Department of Natural Resources, Kittitas Taylor Bridge Fire Wildland Fire Investigation Report, Incident No: 12-E-CBX County, (2012).
[24] S. Wang, H. Chen, N. Liu, Ignition of expandable polystyrene foam by a hot particle: an experimental and numerical study, J. Hazard. Mater. 283 (2015) 536–543.
[25] S. Wang, X. Huang, H. Chen, N. Liu, G. Rein, Ignition of low- density expandable polystyrene foam by a hot particle, Combust. Flame 162 (11) (2015) 4112–4118.
[26] The Beijing Television Cultural Center Fire, 9 February 2009, ⟨https://en.wikipedia.org/wiki/Beijing_Television_Cultural_Center_fire⟩.
[27] S. Solis, M. James, At least 29 dead, dozens hurt in Mexican fireworks blast, USA Today (20–2016) 2–3.
[28] N. Sardoy, J.-L. Consalvi, B. Poterie, J.-C. Loraud, C.A. Fernandez-Pello, Modeling transport and combustion of firebrands from burning trees, Combust. Flame 150 (2007) 151–169.
[29] S.L. Manzello, Y. Hayashi, Y. Yoneki, Y. Yamamoto, Quantifying the vulnerabilities of ceramic tile roofing assemblies to ignition during a firebrand attack, Fire Saf. J. 45 (2010) 35–43.
[30] S.L. Manzello, S.H. Park, S. Suzuki, J.R. Shields, Y. Hayashi, Experimental investigation of structure vulnerabilities to firebrand showers, Fire Saf. J. 46 (2011) 568–578.
[31] J.P. Cohen, A Site-Specific Approach for Assessing the Fire Risk to Structures at the Wildland/Urban Interface (SE GTR-69), USDA Forest Service, 1991.
[32] RussellT. Graham, Hayman Fire Case Study Gen. Tech. Rep. RMRS-GTR-114. Ogden, UT: U.S. DA, 2003.
[33] G.E. Pleasance, J.A. Hart, An Examination of Particles from Conductors Clashingas Possible Source of Bushfire Ignition. State Electricity Commission of Victoria (SEC), Victoria, Australia, Research and Development Department, Report FM-1, 1977.
[34] T. Blackburn, Conductor Clashing Characteristics of Overhead Lines, in: Proceedings of Electrical Energy Conferences, p.202, 1985.
[35] B.D. Russell, C.I. Benner, J.A. Wischkaemper, Distribution feeder caused wildfires: mechanisms and prevention, Prot. Relay Eng. (2012) 43.
[36] T. Tanaka, On the flammability of combustible materials by welding splatter, Rep. Natl. Res. Inst. Police Sci. (1977) 151–158.
[37] K. Kinoshita, Y. Hagimoto, Temperature measurement of falling spatters of arc welding, *in: Proceedings of the 22nd Annual Meeting Japan Society for safety Engineering*, 1989, pp. 145–148.
[38] V.K. Wingerden, I. Hesby, R. Eckhoff, Ignition of Dust Layers by Mechanical Sparks, in: Proceedings of 7th Global Congress on Process Safety, Chicago,Ill, 2011.
[39] D.M. Ratterman Pai, M.C. Shaw, Grinding swarf, Wear 131 (2) (1989) 329–339.
[40] I. Glassman, Combustion, 3rd. ed., Academic Press, 1996, p. 437.
[41] T.A. Brzustowski, and I. Glassman, "Vapor phase Diffusion Flames in the Combustion of Magnesium and Aluminum. I. Analytical Development" in: Proceedings of Heterogeneous Combustion, Academic Press, N.Y., 1964, pp. 75–116.
[42] R.F. Wilson, F.A. Williams, Experimental Study of the Combustion of Single Aluminum Particles in O2/Ar. in: Proceedings of the Thirteenth (International) Symposium on Combustion, The Combustion Institute, 1971, pp. 833-845.
[43] S.D. Tse, A.C. Fernandez-Pello, On the flight paths of metal particles and embers generated by powerlines in high winds - a potential source of wildland fires, Fire Saf. J. (2006) 333–356.
[44] F.A. Mills, X. Hang, Trajectories of sparks from arcing aluminum power cables, Fire Technol. 20 (1984) 5–14.
[45] J.L. Urban, D.C. Murphy, C. Fernandez-Pello, Oxidative heating of iron sparks and hot particles, in: Proceedings of Spring Technical Meeting, Western States Section/Combustion Institute, Seattle, WA, March 20-21 (2016).
[46] A.D. Stokes, Fire ignition by copper particles of controlled size, J. Electr. Electron. Eng., Aust. 10 (1990) 188–194.
[47] J.A. Wischkaemper, C.I. Benner, B.D. Russell, Electrical Characterization of Vegetation Contacts with DistributionConductors – Investigation of Progress Faults Behavior, in: Proceedings of the PES T & D Conference & Expo., Chicago, Il, 2008.
[48] C.S. Tarifa, P.P. Del Notario, F.G. Moreno, A.R. Villa, Transport and Combustion of Firebrands, U.S. Department of Agriculture Forest Service, 1967 (Final Report of Grants GF-SP-114 and GF-SP-146. Madrid, May).
[49] H. Yoshioka, Y. Hayashi, H. Masuda, T. Noguchi, Real-scale fire wind tunnel experiment on generation of firebrands from a house on Fire, Fire Sci. Technol. 23 (2004) 142–150.
[50] S.L. Manzello, A. Maranghides, W. Mell, Firebrands generation from burning vegetation, Int. J. Wildland Fire 16 (2007) 458–462.
[51] S.L. Manzello, J.R. Shields, T.G. Cleary, A. Maranghides, W.E. Mell, J.C. Yang, Y. Hayashi, D. Nii, T. Kurita, On the development and characterization of a firebrand generator, Fire Saf. J. 43 (2008) 258–268.
[52] S.L. Manzello, S. Suzuki, The new and improved Dragon's LAIR (Lofting and Ignition Research Facility), Fire Mater. J. 36 (2012) 623–635.
[53] S.L. Manzello, T.G. Cleary, J.R. Shields, W. Mell, J.C. Yang, Experimental investigation of firebrands: generation and ignition of fuel beds, Fire Saf. J. 43 (2008) 226–233.
[54] S.L. Manzello, A. Maranghides, Shields, W.E. Mell, Y. Hayashi, D. Nii, Mass and size distribution of firebrands generated from burning Korean Pine (Pinus koraiensis) trees, Fire Mater. J. 33 (2009) 21–31.
[55] S. Suzuki, S.L. Manzello, M. Lage, G. Laing, Firebrand generation data obtained from full scale structure burn, Int. J. Wildland Fire 21 (2012) 961–968.
[56] S. Manzello, T. Yamada, A. Jeffers, Y. Ohmiya, K. Himoto, A.C. Fernandez-Pello, Summary of workshop for fire structure interaction and urban and Wildland-Urban Interface (WUI) fires-operation Tomodachi-Fire Research, Fire Saf. J. 59 (2013) 122–131.
[57] S. Suzuki, S.L. Manzello, Y. Hayashi, The size and mass distribution of firebrands collected from ignited building components exposed to wind, Proc. Combust. Statut. 34 (2013) 2479–2485.
[58] S. Suzuki, A. Brown, S.L. Manzello, J. Suzuki, Y. Hayashi, "Firebrand generated from full-scale structure burning under well controlled laboratory conditions", Fire Saf. J. 63 (2014) 43–51.
[59] S. Suzuki, S.L. Manzello, Firebrand production from building components fitted with siding treatments, Fire Saf. J. 80 (2016) 64–70.
[60] J.P. Woycheese, P.J. Pagni, Combustion Models for Wooden Brands, in: Proceedings of 3rd International Conference on Fire Research and Engineering, Boston, MA, 1999.
[61] H.R. Baum, B.J. McCaffrey, Fire Induced Flow Field-Theory and Experiments Fire Safety Science, in: Proceedings of the Second International Symposium, Wakamatsu, et al. edits, Washington DC, 1989, pp. 129-148.
[62] K.B. McGrattan, H.R. Baum, R.G. Rehn, Smoke plumes from large fires, UJNR panel on Fire Research,NIST, Gaithersburgh, MD, 1995.
[63] J.G. Quintiere, B.S. Grove, A unified analysis for fire plumes, Proc. Combust. Inst. 27 (1998) 2757–2766.
[64] J.P. Woycheese, P.J. Pagni, D. Liepmann, Brand propagation from large-scale fires, J. Fire Prot. Engr. 10 (1999) 32–44.
[65] H. Huang, R. Ooka, S. Kato, H. Otake, Y. Hayashi, CDF simulation of thermal plumes and firebrands scattering in urban fires, Fire Sci. Technol. 23 (2) (2004) 152–163.
[66] K. Himoto, T. Mauyama, T. Tanaka, A study on the brand spotting in urban fires-LES analysis on the scattering of square disks in a turbulent boundary layer, in: Proceedings of the 10th Interflammation, 2004, pp. 1039–1050.
[67] K. Satoh, K. Kuwahara, K.T. Yang, A numerical study of forest fire progression and fire suppression by aerial fire fighting, in: Proceedings of the International Mech Eng Cong & Expo.Anaheim, CA, 2004.
[68] C.S. Tarifa, P.P. del Notario, F.G. Moreno, On the flight paths and lifetimes of burning particles of wood, Proc. Combust. Inst. 10 (1965) 1021–1037.
[69] S.L. Lee, J.M. Hellman, Firebrand trajectory study using an empirical velocity-dependent burning law, Combust. Flame 15 (1970) 265–274.
[70] A. Muraszew, J.B. Fedele, W.C. Kuby, Trajectory of firebrands in and out of fire whirls, Combust. Flame 30 (1977) 321–324.
[71] F.A. Albini, Potential Spotting Distance from Wind-Driven Surface Fires, USDA Forest Service Research Paper ZNT-309, 1983.
[72] F.A. Albini, Tranport of firebrands by line thermals, Combust. Flame 32 (1983)

277–288.
[73] J.P. Woycheese, P.J. Pagni, D. Liepman, Brand lofting above large-scale fires, in: Proceedings of 2nd International Conference on Fire Research and Engineering, Boston, MA, 1998.
[74] K. Himoto, T. Tanaka, Transport of Disk-shaped firebrands in a turbulent boundary layer, in: Proceedings of the 8th International Symposium on Fire Safety Science, 2005, pp. 433–444.
[75] R.A. Anthenien, S.D. Tse, C. Fernandez-Pello, On the trajectories of embers initially elevated or lofted by small scale ground fire plumes in high winds, Fire Saf. J. 41 (2006) 349–363.
[76] N. Sardoy, J.-L. Consalvi, J.-L. Kais, B. Poterie, C. Fernandez-Pello, Numerical study of ground-level distribution of firebrands generated by line fires, Combust. Flame 154 (2008) 478–488.
[77] E. Koo, P. Pagni, R. Linn, Using FIRETEC to describe firebrand behavior in wildfires, Fire Mater. 2007 (2007) (San Francisco, CA).
[78] C.J. Rallis, B.M. Mangaya, Ignition of veld grass by hot aluminum particles ejected from clashing overhead transmission lines, Fire Technol. 38 (2002) 81–92.
[79] J.P. Woycheese, Wooden disk combustion for spot fire spread, in: Proceedings of the 9th Interflam, 2001, pp 101–112.
[80] S. McAllister, M. Finney, Convection ignition of live fuels forest fuels, Fire Saf. Sci. 11 (2014) 1312–1325.
[81] A. Abbud-Madrid, M.C. Branch, T.J. Feiereisen, J.W. Daily, Ignition of Bulk Metals by a Continuous Radiation Source in Pure Oxygen Atmosphere (Flammability and Sensitivity of Materials in Oxygen Enriched Atmospheres) ASTM STP 1197), ASTM, Philadelphia, 1993.
[82] C. Fernandez-Pello, C. Lautenberger, D. Rich, Wildland Fire Spotting Ignition and Propagation, in: Proceedings of 6th Annual Wildland Fire Litigation Conference, Sacramento, CA, April 20-22, 2012.
[83] S.L. Manzello, T.G. Cleary, J.R. Shields, J.C. Yang, On the ignition of fuel beds by firebrands, Fire Mater. 30 (2006) 77–87.
[84] S.L. Manzello, T.G. Cleary, J.R. Shields, J.C. Yang, Ignition of vegetation and mulch by firebrands in wildland-urban interface fires, Int. J. Wildland Fire 15 (2006) 427–431.
[85] S.L. Manzello, S. Suzuki, Y. Hayashi, Exposing siding treatments, walls fitted with aves, and glazing assemblies to firebrand showers, Fire Saf. J. 50 (2012) 25–34.
[86] S.L. Manzello, S. Suzuki, Y. Hayashi, Enabling the study of structure vulnerability to ignition from wind-driven firebrand showers: a summary of experimental results, Fire Saf. J. 54 (2012) 181–196.
[87] S.L. Manzello, S. Suzuki, D. Nii, Full-scale experimental investigation to quantify building components ignition vulnerability to mulch beds attacked by firebrand showers, Fire Technol. Online (2017).
[88] L. ManzelloS, S.L. Quarles, Special section on structure Ignition in Wildland Urban Interface (WUI) Fires, Fire Technol. (2017).
[89] A. Filkov, S. Prohanov, E. Mueller, Kasymov, P. Martynov, M. El Houssami, J. Thomas, N. Skowronski, B. Butler, M. Gallagher, K. Clark, W. MelD, R. Kremens, R.M. Hadden, A. Simeoni, Investigation of firebrand production during prescribed fires conducted in a pine forest, Proc. Combust. Inst. 36 (2) (2017) 3263–3270 ISSN 1540-7489 https://doi.org/10.1016/j.proci.2016.06.125.
[90] S. Fereres, C. Lautenberger, C. Fernandez-Pello, Preliminary Study of the Ignition of Vegetation Bed by a Firebrand, in: Proceedings of Workshop on Mathematical Modeling and Numerical Simulation of Forest Fire Propagation, Vigo, Spain November 29–30, 2008.
[91] C. Lautenberger, S. Fereres, S. Scott, R. Hadden, C. Fernandez-Pello, Ignition of Combustible Fuel Beds by Embers and Heated Particles, in: Proceedings of Fall Technical Meeting, Western States Section/Combustion Institute, U.C. Irvine, CA, October 26-27, paper 09F-26F, 2009.
[92] J.L. Urban, J. Song, N. Liu, C. Fernandez-Pello, Effect of Fuel Moisture Content on Smoldering Spot Ignition by Firebrands in: Proceedings of the 10th US National Combustion Meeting, University of Maryland (Submitted for publication), 2017.
[93] G. Rowntree, A. Stokes, Fire ignition of aluminum particles of controlled size, J. Electr. Electron. Eng. (1994) 117–123.
[94] R. Hadden, S. Scott, C. Lautenberger, C. Fernandez-Pello, Ignition of combustible fuel beds by hot particles: an experimental and theoretical study, Fire Technol. 47 (2011) 341–355.
[95] C. Zak, E. Tjahjono, D. Rich, C. Fernandez-Pello, Ignition of Powdered Fuels by Hot Particles: An Experimental Study, Forest Fires 2012, New Forest, UK, May 22–24 (2012) .
[96] C.D. Zak, D.C. Murphy, A.C. Fernandez-Pello, Understanding ignition of natural fuels by heated particles, Safety and Security Engineering V 134, WIT Press, 2013, pp. 607–614 WIT Transactions on The Built Environment.
[97] C.D. Zak, J. Urban, C. Fernandez-Pello, Characterizing the ignition of cellulose fuel beds by hot steel spheres, Combust. Sci. Technol. 186 (10–11) (2014) 1618–1631 (2014).
[98] C. Zak, J. Urban, V. Tran, C. Fernandez-Pello, Flaming Ignition behavior of hot steel and aluminum spheres landing in cellulose fuel beds, in: Proceedings of the 11th International Symposium on Fire Safety Science, Canterbury University, Christchurch, N.Z., 2014, pp. 9–44.
[99] A.C. Fernandez-Pello, C. Lautenberger, D. Rich, C. Zak, J. Urban, R. Hadden, S. Scott, S. Fereres, Spot fire ignition of natural fuel beds by hot metal particles, embers and sparks, Combust. Sci. Technol. 187 (1–2) (2014) 269–295.
[100] J. Urban, C. Zak, C. Fernandez-Pello, Cellulose spot fire ignition by hot metal particles, Proc. Combust. Inst. 35 (3) (2015) 2707–2714.
[101] J.L. Urban, C. Zak, C. Fernandez-Pello, "The effect of fuel bed composition on the spot fire ignition of natural fuels by hot aluminum particles" AOFST10, Tsukuba, Japan, October, 2015.
[102] J.L. Urban, C.D. Zak, J. Song, A.C. Fernandez-Pello, Smolder spot ignition of natural fuels by a hot metal particle, Proc. Combust. Inst. 36 (2) (2017) 3211–3218 ISSN 1540-7489 https://doi.org/10.1016/j.proci.2016.09.014.
[103] W. Pitts, Ignition of Cellulosic Fuels by Heated and Radiative Surfaces, NIST Technical Note 1481, March 2007.
[104] S. Wang, X. Huang, H. Chen, N. Liu, Interaction between flaming and smoldering in hot-particle ignition of forest DFuels and effects of moisture and wind, Int. J. Wildland Fire 26 (2017) 71–81.
[105] P.H. Thomas, A comparison of some hot spot theories, in: Proceedings of the Tenth Symposium (International) on Combustion, The Combustion Institute, Pitsgburgh, PA, 1965, pp. 369-372.
[106] J.C. Jones, Improved calculations concerning the ignition of forest litter by hot particle ingress, J. Fire Sci. 13 (1995) 350–356.
[107] C. Zak, The Effect of Particle Properties on Hot Particle Spot Fire Ignition (PhD Dissertation), Department of Mechanical Engineering, University of California, Berkeley, 2015.
[108] C. Lautenberger, A.C. Fernandez-Pello, Spotting ignition of fuel beds by firebrands, in: C.A. Brebia, G.M. Carlomagno (Eds.), Computational Methods and Experimental Measurements XIV, WIT Press, 2009, pp. 603–612.
[109] C. Lautenberger, A.C. Fernandez-Pello, Generalized pyrolysis model for combustible solids, Fire Saf. J. 44 (2009) 819–839.
[110] C. Lautenberger GPyro Code. [Online] ⟨http://code.google.com/p/gpyro⟩.
[111] C. Lautenberger, A.C. Fernandez-Pello, Model for the oxidative pyrolysis of wood, Combust. Flame 156 (2009) 1503–1513.
[112] K. McGrattan, S. Hostikka, J. Floyd, H. Baum, R. Rehm, Fire Dynamics Simulator (Version 5) Technical Reference Guide, NIST Special Publication 1018-5, 2007.
[113] C. Lautenberger, D. Rich, M. Kramer, S. Stephens, C. Fernandez-Pello, CommunicationInfrastructure Provider Assets in the Wildland Setting: CIP Fire Threat Map, June 9, 2010.