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Eruptive Behaviour of Forest Fires

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Abstract:

A critical review of the mechanisms that are described in literature to explain the onset and development of eruption or blow up in forest fires is presented, given their great relevance for fire safety, particularly in canyons. The various processes described in the literature that are considered as potential causes of fire eruption are discussed. Some of them seem more likely to cause the phenomenon and the others seem to have a complementary role in some conditions. The current review highlights that more research is required to create a classification of Fire Eruption types and to allow the development of specific Fire Safety procedures for fire fighters to minimize accidents.

Keywords: Fire behaviour; eruptive fire; blow up; extreme fire; fire modelling; fire safety.

Introduction

In certain conditions forest fires can exhibit an extreme behaviour that is characterized by very large rates of spread and energy release. We consider the following types of extreme fire behaviour: (i) Eruptive fires, (ii) crown fires and (iii) spot fires. In this paper we analyse the eruptive fire behaviour given its relevance for fire safety because it has been associated to a large number of fatal accidents in many parts of the World, like for example all those that are mentioned in Table 1 below.

The designation of fire eruption was proposed in Viegas [1] given the similarity between the convection column that is produced by a volcanic eruption and that created by a forest fire that experiences a sudden acceleration of its rate of spread that is a characteristic property of this type of fire behaviour. These fires are also referred to blowups or flashovers in literature. Analysis of past accidents shows that in many cases the fire erupted modifying its previous behaviour and surprised the fire fighters that were in its vicinity and caused their death. An analysis of past accidents in which multiple fatalities occurred led us to the conclusion that the main part where related to eruptive fire behaviour [2-17].

Table 1

Some accidents with multiple fatalities associated to extreme fire behaviour in canyons

Case	Year	Place	Country	Victims	Biblio. Reference
1	1949	Mann Gulch	USA	13	Rothermel [2]
2	1953	Rattlesnake	USA	15	Cliff *et al.* [3]
3	1966	Sintra	Portugal	25	Viegas [4]
4	1984	La Gomera	Spain	20	Viegas *et al.* [5]
5	1985	Armamar	Portugal	14	Viegas [4]
6	1986	Águeda	Portugal	16	Viegas [4]
7	1990	Dude	USA	6	Goens and Andrews [6]
8	1994	Storm King	USA	14	Butler *et al.* [7]
9	1996	Loop	USA	12	Countryman *et al.* [8]
10	1999	Alajar	Spain	4	Silva [9]
11	1999	Tabuaço	Portugal	2	Viegas *et al.* [10]
12	2000	Palasca	France	2	Raffalli *et al.* [11], Dold *et al.* [12]
13	2000	Mação	Portugal	2	Viegas *et al.* [10]
14	2003	Cramer	USA	2	Donoghue *et al.* [13]
15	2003	Freixo	Portugal	2	Viegas [1]
16	2005	Guadalajara	Spain	11	Viegas and Caballero [14]
17	2005	Mortágua	Portugal	4	Viegas [15]
18	2006	Famalicão	Portugal	6	Viegas [15], Viegas *et al.* [16]
19	2007	Kornati Island	Croatia	11	Viegas *et al.* [17]

Fire eruptions and especially those associated to canyons are not rare, but without a clear understanding of their causes and possible consequences even experienced operational persons tend to ignore or minimize their importance. Human losses like those shown in Table 1 cannot be neglected but even the occasional occurrence of accidents in some countries has not been sufficient to allow practitioners to develop an empirical knowledge about the phenomenon.

The similarity between different accidents, like for example the Mann Gulch, the Storm King and the Cramer fires, has been noted in The Situational Awareness poster developed by the Boise National Forest with help from Missoula Technology and Development Center (MTDC) [18]. In all these cases a group of fire fighters was attempting to suppress a fire that was spreading down slope on steep hills or canyons when suddenly fire developed below them are erupted uphill and killed a large part of the group. In the first two cases the fire at the bottom of the slope or canyon was caused by spot fires. The issue of the similarity between Mann Gulch and Storm King was also addressed, but from a broader perspective, by Weick [19]. We found other similarities notably between the Palasca [11] and the Kornati [17] accidents, both in the shape of the canyon and in the fire development.

In this article the authors present the concept of eruptive fire and discuss critically some of the existing models or explanations of the phenomenon that can be found in the literature.

Concept of Eruptive Fire

In the context of the present article we apply the definition of eruptive fires to those in which a sudden change of the rate of spread of the head fire occurs in a very short lapse of time with or without the influence of any changes of the fire temporal or spatial boundary conditions (fuel properties, meteorological or topographical conditions). In our perspective this definition is applied strictly to fires that occur with uniform and permanent overall boundary conditions, but we will generalize it to other situations in order to include the role of other factors that are mentioned in literature. Eruptive fires are also known in literature as blowup or flashover. These last terms should be used with caution as they can be misleading. Indeed, eruptive fires do not correspond to the specific definition used in Fire Safety science for flashover in the built environment, as we are not dealing with fires in an enclosed space. Eruptive fires are characterized by a sudden change of the rate of spread and therefore of energy release. In Butler [7] one can find the following definition of blowup "a rapid transition from a surface fire exhibiting relatively low intensity, to a fire burning in the whole vegetation complex, surface to canopy and demonstrating dramatically larger flame heights, higher energy release rates, and faster rates of spread". This definition invokes the participation of both surface and canopy fuels in the blowup although blowups or fire eruptions may occur in single layer fuels [2], [11] and [17]. Eruptive fire behaviour can also occur in wind induced fires when the wind direction is constant and the wind velocity is relatively high during a long period of time [20]. Fire eruptions are more likely to occur in steep slopes and especially in canyons because topography plays the role of a constant and strong constrain to the fire, which is similar to the role of a strong wind with a constant direction [1], [21]. The effect of topography does not vary in time whereas wind in the field is rarely constant in amplitude and direction.

Classical fire behaviour modelling considers that the rate of spread of a fire depends on the following three sets of factors: (i) fuel bed properties, (ii) topography and (iii) meteorological conditions [22]. It is commonly assumed that if the parameters that characterize each set of factors are fixed there is a unique value of the rate of spread. In particular it is assumed that for a given fuel bed if one knows the terrain slope or the ambient wind velocity it is possible to determine the value of the rate of spread and to predict the behaviour of the fire. This assumption is referred in the literature as the concept triangle of the factors of fire. The effect of the dramatic increase in the fire rate of spread for high values of slope or wind has been observed many times for laboratory experiments [23-27] but it has been analyzed only in terms of steady regime that considers the average rate of spread.

Previous studies on fire blow up being based on the concept of fire triangle tended to consider the existence of a sudden change of some of one or more of the above mentioned factors to justify the rapid change of fire behaviour. As topography in the general case could not be invoked as a factor that changed suddenly it was overlooked in the analysis of the phenomenon; changes of fuel bed properties or meteorological conditions were more frequently assumed as the cause of fire acceleration. This is the reason why in many studies of incidents and accidents associated to fire eruptions a very detailed analysis of prevailing meteorological conditions tends to exist in order to find an explanation for fire acceleration, quite often without coming to positive conclusions [7], [4], [13], [8], [6], [28], [29]. Several studies [7], [9], [12] propose more than one possible explanation based of different arguments or interpretations of the facts. These studies invoke the occurrence of various atmospheric processes as the passage of a cold front above the fire, the presence of a thermal belt around vegetation and an atmospheric instability, among others.

In Viegas [30], it was shown that this assumption is not correct in the general case, particularly in the presence of strong wind or steep slopes. The alternative concept of square of the factors of fire was proposed in Viegas [31] in which the factor of chronological time was added to the set of factors to illustrate the dynamic behaviour of forest fires, particularly in the case of eruptive fires. It corresponds to the accumulation of energy of the growing fire over time due to the feedback between that fire and its environment, leading to an extreme behaviour when the accumulated energy is enough to accelerate dramatically the fire rate of spread. This process is similar to flashovers, not in the physical sense but in the sense of being a self induced and dramatic evolution of the fire without any possibility of control. It should be noticed that the concept of the fire behaviour at a given time depending on the fire behaviour in the past has been introduced earlier by Albini [32] for classical fire behaviour.

In the literature we can find diverse interpretations about the mechanism of fire acceleration that is associated to an eruption. The first kind of explanations is mainly based on a variation of the external conditions and the second kind is mainly based on the own properties of the spreading fire. The first kind includes the variation in external conditions as a change in wind intensity or direction, the development of a thermal belt around vegetation and the existence of atmospheric instabilities above the fire. The second one includes self-induced fire behaviour as a convective feed-back from the fire, a flow attachment, a gas accumulation or spotting. As the fire by itself involves strongly coupled phenomena and factors, it is difficult to separate the mechanisms causing eruptive behaviour from the conditions that favour its initiation. The authors consider that it is one of the reasons of the large diversity in interpretations that can be found in literature. This distinction is very important in the author’s viewpoint and will be developed in the following.

Mechanisms contributing to fire acceleration

In this section, the different mechanisms proposed in literature are detailed and discussed. Before developing them, a link is established with flame spread theory.

Self-accelerating fires in flame spread theory

The closest definition in flame spread theory to eruptive fires is self-accelerating fires. These fires can occur during flame spread over the surface of either thermally thin or thermally thick solids. Flame spread theory for concurrent flame spread suggests that under specific conditions there is no steady state solution and that flame spread can be self-acceleratory [33]. A simple application of the energy conservation leads to the following expression of the flame spread rate [33]:

$$V_f = \frac{dx_p}{dt} = \frac{\Delta}{t_{ig}} \quad (1)$$

where V_f is the flame spread velocity, x_p is the pyrolysis front position, D is a preheating length, and t_{ig} is the ignition time associated to the flame heat flux.

Fundamental studies have given some limited results to predict flame spread [33] and a simple expression of the flame speed can be derived by stating that delta is proportional to the flame length, which is in turn proportional to the length of the pyrolysis area. This leads to the following empirical formula:

$$\Delta \propto \text{flame length} \propto = \left(x_p - x_b\right)^n \quad (2)$$

where x_b is the position of the burnout front and n is approximately 2/3 but may vary between 0.5 and 1 [33]. Combining Equations (1) and (2) gives:

$$V_{\mathrm{f}} \propto = \left(x_p - x_b\right)^n \quad (3)$$

It can be seen from Equation (3) that if the pyrolysis front (x_p) moves faster than the burnout front (x_b), then ($x_p - x_b$) increases and the flame spread rate accelerates, meaning a steady-state flame spread rate does not exist. An exponential growth is achieved if $x_b = 0$ and $n = 1$. This expression is similar to equation (1) and suggests that an extension of Δ can lead to a self-accelerating fire.

However, even if this model could apply to small scale fires, the assumption that the preheat length is proportional to the flame length, which is in turn proportional to the length of the pyrolysis area is difficult to verify in wildfires. Indeed, due to their large scale, wildland fires exhibit flame structures which are very different from the laboratory flames used to describe flame spread over solid surfaces [34]. Some physical explanations for self-accelerating wildfires are either proposed in [1] or in [35] and are discussed later in the paper.

Positive feedback from the fire

This interpretation was proposed by Viegas [1] and it consists essentially in considering the feedback effect caused by the convective flow induced by the existence of the fire front in the presence of wind or positive slope. Considering the case of wind it is reasoned that its presence transports oxygen to the reaction zone enhancing the combustion process and causing an increase of the flame length and of the rate of spread in a given time lapse; this increase of the flame will therefore entrain more ambient air and cause a further increase of the rate of spread in the following time lapse. If this feedback process is not inhibited by some external mechanism the rate of spread of the fire front will increase continuously in the course of time having the potential of reaching very high values.

Based on these considerations, Viegas proposed a mathematical model to predict the rate of spread of the head of an eruptive fire. For convenience a non dimensional rate of spread $R'=R/R_o$, where R_o is the so called basic rate of spread for a given fuel bed, under no wind and no slope conditions, is used. The rate of change of R' is given by the following differential equation:

$$\frac{dR'}{dt} = a_1^{1/b_1}.b_1.a_2.(R'-1)^{(1-1/b_1)}.R'^{b_2} \qquad (4)$$

The parameters a_1, a_2, b_1 and b_2, in equation (4) are related to the rate of spread change with wind velocity and to the reaction time of the fuel bed. They were measured experimentally at laboratory and field scales and checked against real fire cases for several fuel beds [1, 31]. It was shown that after a finite interval of time the rate of spread starts to increase very rapidly as it is observed in fire eruptions. Experimental data obtained in the analysis of real cases [1, 2, 7, 14] and in a field experiment performed by the first author in 2001 (unpublished) show that for shrub fuels the time lag for the initiation of eruption is of the order of 15 to 20 minutes which is consistent with the predictions of this model for this type of fuels.

The mathematical model described by (4) is very robust and has been checked in various situations. One case that provided valuable data to validate this model and the convective feedback mechanism that it proposes was the accident of Freixo de Espada-a-Cinta that occurred in Portugal in August 2003 [1]. In this case a fire front erupted in a slope killing two persons. An automatic meteorological station placed above the slope recorded the meteorological parameters every ten minutes before, during and after it was reached by the very hot gases produced by the fire eruption. It registered a wind direction change of 180º from a down slope wind with an average 17 km/h to an upslope wind of 56 km/h when the fire erupted with gusts of 96 km/h. The time lag and the wind velocity increase are consistent with this model's predictions. The Portuguese Meteorological Institute confirmed that in this case no changes in the synoptic conditions before or after the accident occurred.

The solution of equation (4) indicates that the rate of spread of the fire can become many times larger than its value R_o, for horizontal terrain without wind, in the limit it tends to infinity. There are certainly physical limits in the process that should bind this limit to some finite value. It is interesting to note that according to Butler [7] the rate of spread of the erupting fire was one thousand times greater than R_o, as it is predicted by the model. To our knowledge no other fire spread models explain such a large order of magnitude variation on the rate of spread of a given fire in the same fuel bed and basically in the same topography without invoking changes in the overall boundary conditions.

Although the parameters of the model can be determined from experiments there is not sufficient knowledge about the role of various factors, namely terrain configuration, fuel properties, presence of wind, type of ignition on these parameters, therefore more research is needed to explicitly include the different factors in the model.

Gas accumulation

This potential explanation is quite popular among fire fighters, despite the fact that very few studies provide elements to support it. This is mainly due to the feeling of surviving fire fighters reported after a fire eruption that the fire looked like a pool fire or a hydrocarbon fire [11, 35]. In some cases it is described as a "fire ball" [29]. This empirical explanation, in spite of coming from situations of maximal stress, has become quite wide spread and it has to be taken into consideration. Butler *et al.* discarded it in their report of the South Canyon Fire [7].

Two explanations are proposed for gas accumulation:

(i) The first one assumes the existence of an accumulation of unburned products coming from the fire plume - or coming from unburned pyrolysis gases produced elsewhere in the fire - and accumulating ahead of the fire in closed geometries like deep canyons. The created flammable mixture would then ignite when reached by the fire. This effect has been cited early as a potential source of fire eruption among others but without offering any scientific proof [29]. Dold *et al.* [36], report a similar phenomenon occurred in 2003 during a severe fire near Canberra, Australia. Fire fighters were engulfed in high flames while positioned far from the fire front on a flat parcel with very scarce vegetation. The authors deduce that this fire was due to an accumulation of unburned gases coming from the fire plume. A study on the Palasca incident, which occurred in Corsica (France) in 2000, mentions a possible gas accumulation in a canyon [12]. According to the testimony of surviving fire fighters [11], the head of the fire almost extinguished before the occurrence of a fire eruption; the presence of remaining vegetation with leaves that seemed to be caramelised and not totally burned are other indicators of unusual fire behaviour. It is proposed that the extinction of the head by fire fighters could have been only partially successful leading to the generation of pyrolysis gases that would otherwise have burnt in the head fire and these pyrolysis gases may have developed into flammable proportions upper in the canyon, causing what the authors call a 'flashover' when the flank fires reached the pool of flammable gases. One problem with the assumption of a flashover through the pyrolysis gases is that premixed flames can only propagate through relatively high concentrations of the combustible gases. For a premixed flame to propagate along such a large area - the phenomenon was estimated to have covered approximately 6 hectares - there should have been a build-up of combustible volatile organic compounds above the lower flammability limit over much of the area. But even if the flammability limit was not reached everywhere and if the mixture zone was not very deep inside or above vegetation, the overall effect could have been to enhance greatly the flame spread over the area. The development of this first flame could have initiated the widespread diffusion flame in a very flammable vegetation cover, which has been described by the crews as a lake of fire.

(ii) The second explanation is related to the production of Volatile Organic Compounds (VOC) by vegetation at temperatures below the ignition point. When heated, some Mediterranean plants produce and emit VOC related to their secondary metabolism [37, 38]. These compounds possess a low ignition temperature [39]. As the density of VOC is higher than the density of air when vegetation is heated by the sun or by an approaching fire, the emitted VOC would be released and could accumulate near the ground and below the vegetation layer or flow down slope to the bottom of a canyon. In the two cases, they would create a flammable mixture [35]. This explanation is supported by the empirical knowledge of fire fighters. They associate the strong odour of volatiles in vegetation with high risk, particularly in relatively confined geometries like canyons. The scientific aspect of the problem is to know if this accumulation of volatiles is sufficient enough to generate a flammable mixture with air or if it is only an indicator of vegetation stress due to heat impact or to dryness that are certainly related to high risk conditions. The paper by Raffalli *et al.* [11] cites clearly a VOC accumulation as a potential cause for several fire accidents occurred in France [11]. The authors described these accidents and deduced that they were linked to gas accumulation because of several factors like a sudden ignition of a large area of vegetation and smoke accumulation. For this reason these authors decided to study the emission of VOC of one Mediterranean plant species (*Rosmarinus officinalis*), which is known to release a substantial amount of VOC. The experiments showed that the plant was producing a lot of flammable gases but at temperatures over 90°C (the peak being around 170°C). This VOC emission has been confirmed also in Ormeño *et al.* [40] for lower temperatures. However, no concentration studies were conducted to check if any flammable mixture could be encountered in the field. Some laboratory-scale experiments were also conducted but no link between the full-scale phenomenon, the small-scale tests and the VOC production measured with plant powders in the laboratory was established. However, the main advantage of this study was to point out that plants can release highly flammable gases at relatively low temperatures. Some other studies show that the flammability of vegetation increases with the presence of VOC in plants [41, 42].

To our knowledge the only study considering VOC emissions by heated plants and the flammability of the mixture of the released gas in air is the one presented in Chetehouna *et al.* [43]. This study used a hermetic enclosure and a radiant panel to heat different *Rosmarinus officinalis* plants by radiation (as a fire approaching would supposedly do). The 30 cm high plants were placed at the centre of the small enclosure and had a moisture content of 70%, which is close to the one expected for average summer conditions. The plants were heated during 30 minutes with radiative fluxes ranging from 0.5 to 20.5 kW/m^2. The emitted gases trapped into the enclosure were sampled thanks to adsorbent tubes and analysed by gas chromatography and gas spectrometry. Then, the lower flammability limit was estimated as a function of the temperature of the enclosure [39]. The study showed that generally the VOC concentrations were under the flammability limit, except for heat fluxes over 15 kW/m^2 and enclosure temperatures above 170°C. These values are consistent with the temperature of maximal VOC emission found in Raffalli *et al.* [11]. This study did not show a clear VOC accumulation that could create flammable mixtures in the field because the tested laboratory conditions are very unlikely to occur in other places than very close to the fire where no accumulation would have time to take place. However, this study represents a first evaluation of VOCs emitted by vegetation and two conclusions arise: the VOC emitted by the plant could play a role on plant flammability close to the fire and it is worth investigating further the potential accumulation of these gases for very peculiar and extreme conditions in the field (as high temperature, long exposure to sun radiation, low air humidity, condensation of the products near the ground, among others). The first conclusions lead to the question of the existence of species prone to support fire eruption by high rates of VOC emission either by increasing the plant flammability or creating VOC accumulation in air.

Because wildfires are occurring in open spaces a gas accumulation seems to be unlikely to occur and even more to lead to large pockets of flammable mixtures. However, it is impossible to exclude that this phenomenon can occur under very specific conditions and could initiate or create a fire eruption. It is therefore necessary to further investigate this potential cause and to obtain data to demonstrate and understand the creation of flammable gas mixtures by accumulated smoke of VOC.

Flow attachment

This interpretation has been proposed recently by Dold and Zinoviev [44]. Their model is not formally linked to flow attachment in confined slopes but the authors refer to this notion to interpret the eruptive behaviour described by the model. This work proposes that the flow-field around a fire can change from a usual steady-state spreading of the fire into an eruptive fire behaviour for which the spread rate and the intensity of the fire can grow infinitely. The model is developed based on a previous work by Albini [32], which considers that the fire behaviour at a given time is influenced by the fire behaviour in the past of the fire. This quite intuitive feature cannot be included by essence in steady-state models as Rothermel's model [22], which is the most used fire spread model for operational purposes [45, 46]. Except for the work by Viegas [1], this paper represents to our knowledge the only other attempt to model eruptive fire behaviour. In Dold and Zinoviev [44], the final representation of the model is the classical formulation of fire rate of spread and intensity but including a non-steady rate of spread. The non-steady rate of spread is assumed to vary as a power-law of the fire-line intensity. The behaviour of the fire is discussed for different values of the power law exponent: if the exponent is less than 1, the spread rate will tend towards the steady rate of spread and if the exponent is greater than or equal to 1, the fire will erupt. The power-law dependence between the rate of spread and the fire-line intensity is not directly supported by experimental evidences given by the authors. In [47], the fire intensity of a burner is linked to the height of flame following the classical analysis of Cox and Chitty [48] and can be considered as an indirect justification of a power-law relationship between the fire rate of spread and the fire intensity. The model is also indirectly related to the self-accelerating fires described previously as the fire-intensity is related to the length of the pyrolysis zone. However, as stated before, these links are less straightforward for wildfire than for flame spread theory, due to the scale of the phenomenon.

The laboratory experiments presented in the paper demonstrate the change in the mechanism of fire spread when the slope angle is above a threshold value. Early studies depicted flow and more specifically flame deflection towards a plane slope for positive tilt angles above 20° [49, 50]. For trench configurations, the effect is greatly enhanced by the restriction of air entrainment [51, 52]. This effect is called the 'Trench Effect' [53]. In trench fires, the flames attach to the fuel when the slope angle is above a threshold value [51]. The flame attachment increases dramatically the heat transfer to the unburned fuel and consequently the fire rate of spread. The laboratory experiments described in the paper reproduce the configuration depicted in [51, 52], which were conducted to study the lethal fire that occurred in an escalator of King's Cross subway station in 1987 in London. The main difference is the use of wild land fuels at the lower side of the trench. The authors cite a paper on flame length and inclination, which was published in the same special issue dedicated to the fire at King's Cross Station [47] but the study would have gained in power if a comparison was conducted between the two sets of experiments and particularly the ones with fire spread [51, 52].Then, the authors show that when the slope angle is above a threshold value, the flow at the top of the trench is reversing from backward to upward. These features have already been described by Atkinson *et al.* [54] for fires on inclined surfaces.

As a whole, the main strength of the paper is to propose a new mathematical model based on simple assumptions to describe eruptive behaviour. More research is certainly essential to justify or validate the assumptions of the model. For instance, the model and experiments describe a linear fire front but past accidents show clearly that many eruptions occur for non linear fronts [15, 55]. The work would also merit a better link with existing fire science literature.

Change in wind direction or velocity

Wind is by far the factor that is invoked more frequently, given its great influence on the rate of spread of the fire front and its natural variability and apparent unpredictability in the short term. Very often an incident or an accident is described as being associated to a sudden wind change, whatever could have been the cause of such a change. In some cases this wind change is said to be caused by the passage of a meteorological front. In Byram [56] wind turbulence is associated to erratic fire behaviour, namely the onset of fire blowup and fire whirls.

An example of the use of this explanation is given in the Loop Fire accident report [8] in which the authors admit that the fire was being blown down slope by a very strong and dry (the so called Santa Anna) wind. In order to adjust this fact with the reality that the fire that was burning in the lower part of the canyon actually blew up and spread very rapidly against the prevailing wind - killing eleven fire fighters in its run - the authors make the following surprising statement "*Wind direction may switch 180 degrees and back again only in few seconds. Dense smoke clings to the ground and the winds drive a hail of burning embers into the unburned fuel ahead of the fire*". In the same report the authors admitted that careful observation of the wind pattern on the site in conditions similar to those of the accident did not evidence any wind shift.

Another example is given by the Storm King Mountain accident report [7] in which a spot fire that ignited at the bottom of a very steep slope blew up burning it entirely in less than 20 minutes killing 14 fire fighters that were working on its flank trying to suppress it. In order to justify the sudden change in fire behaviour the authors of that report invoke complex interactions between the general wind and local winds induced by the topography including a Venturi effect to explain the flow acceleration near the top of the slope. In the case of this accident a change of wind direction that was caused by the passage of a weather front actually occurred sometime before the accident. One of the consequences of this change was a modification of the general behaviour of the fire but in our opinion the key factor to produce the fire eruption was the already mentioned spot fire at the bottom of the slope where the group of fire fighters was working. According to [7] the area burned during around 20 minutes in the eruption that resulted from this spot was much larger than the area burned by the initial ignition during three days.

Byram [57] considered that the vertical wind velocity profile, associated to other factors, was of great importance in the development of a blowup. In particular he considered that the existence of a low level jet was determinant for the occurrence of a blowup. Dieterich [58] also considers the existence of a low level jet to explain the differences in fire behaviour between Willow fire and Dudley Lake fires. This same idea is followed also by Aronovitch [59] several years later but concluding that it is only a possible explanation for some of the cases that were analysed.

The effect of the wind on the fire spread is obvious and it seems that it can provoke fire acceleration in steep slopes as during the field experiment conducted at ADAI described in [44]. However, many fire eruptions occurred under no or low wind conditions as has been observed in their laboratory experiments that are performed in the quiescent air conditions of an enclosed laboratory. Let us assume that wind flow exists and that it is parallel to the slope gradient or to the canyon water line and blowing upwards. In this case it will certainly favour the occurrence of fire eruption in conjunction with steep slopes or canyon topographies. We nevertheless remark that even in the presence of contrary wind, like in [8] a fire eruption in a canyon can occur.

A concept that is commonly accepted in the literature is that of the existence of a “potential rate of spread” that is the results of a fire accelerating in given boundary conditions to reach a steady state of spread [60-63]. According to this assumption for a given fuel bed, an ignition pattern and boundary terrain and meteorological conditions there is a well defined “potential rate of spread”. This concept is clearly in contradiction with flame spread theory and the different models developed to represent fire eruptions. Furthermore it was shown in [30] that a condition of a steady state does not exist in a fire spreading in a forest. In that study it was shown that a steady state of fire spread does not exist in the controlled conditions of a laboratory test even in some permanent and uniform boundary conditions. Besides this our experiments show that there is not a defined limit to the rate of spread [1, 64] and field observations [1], [7] confirm this statement. If for example we analyse the results of field experiments of Mc Alpine and Wakimoto (figure 3 of [61]) and of Mc Rae (figures 4 and 5 of [60]) it is difficult to establish that there is a limit to the rate of spread from those experiments.

Thermal belt and Atmospheric instability

The first explanation is based on an assumed change of the third factor: fuel bed properties. It is observed that in certain atmospheric and topographic conditions the temperature and relative humidity diurnal cycle between intervals of altitudes in mountainous terrain is such that the moisture content of the fuel between those altitudes remains lower than that below or above these altitudes.

According to this explanation a fire that started in a given slope below this “thermal belt” would accelerate because it would reach a fuel with lower moisture content. This fact was invoked by some authors (cf. Butler *et al.* [7], Donoghue *et al.* [13]) to justify the change in fire behaviour once the fire front enters the dryer fuel.

Regarding the second explanation, it is well known that when the vertical structure of the atmosphere is unstable hot gases produced by combustion can raise much more easily inducing more air entrainment at ground level and facilitating fire growth. This explanation is followed by several authors namely Byram[57], Aronovitch[59], Schroeder[65], Goens [6]. Interestingly Byram [57] proposes a Unifying Concept associated to the energy conversion that in his opinion can be reduced to three groups of factors: (i) Stability conditions in the atmosphere, (ii) Wind speed and wind shear in the atmosphere and (iii) Fuel (and stand) conditions. To this he adds the following phrase: “Strangely enough, topography as such does not appear directly in the above groups of factors; its major effects can be handled most simply by letting them operate through groups 1 and 2”. We disagree with this point of view as we have found that topography alone can be a major factor of a fire eruption or blowup, without requiring any of the other factors of groups (1) and (2) that Byram considers.

Although these factors may have contributed in some cases they do not explain at all the occurrence of fire eruptions in the absence of such thermal belts or unstable atmospheres. And like previous potential causes, they are not likely to explain alone a fire eruption even if they contribute to the onset of the event.

Spot fires

Some authors, Butler *et al.* [7] and Countryman *et al* [8], refer that the increase of the rate of spread of the fire front, is due to a process of short distance spotting ahead of the main fire. The present authors have observed many situations of fire eruptions without the occurrence of spotting or at least when this could be indicated as being the main process of fire advance [1]. Actually this is observed in all laboratory experiments in canyons where fire eruptions occur without the presence of spot fires ahead of the fire front.

It is normal that given the very large increase of the fire line intensity with the creation of strong convective winds above and ahead of the fire burning particles are launched as spot fires at small or even large distance of the main fire front, but as we have remarked above that fire eruptions can occur even without spotting, in many cases this mechanism should be regarded as a consequence rather than a cause of rapid fire spread.

In some cases, like for example in the accident of Guadalajara [14], spotting at the bottom of a canyon seems to have started a new fire that developed quickly as an eruptive fire before the fire fighters could even notice the existence of a new fire under them and feel any increase in danger. In this case, spotting appears clearly to have created a supplementary risk of fire eruption but only as an ignition source of new fires in the canyon. A similar event happened in the South Canyon fire in which a set of spot fires that fell on a place designated as the “Bowl” actually started the fire eruption on the West Drainage slope that ultimately killed the fire-fighters [7].

There are some reported fires like Sundance [20] and Bomb Range [66] that spread under a constant direction wind that had an increasing rate of spread in spite of the fact that the wind velocity did not increase as well. Although the terrain was not flat in all these cases topography did not seem to play a major role as the fire spread very rapidly both upslope and down slope. In these major fires in which a wind induced eruption occurred it is interesting to observe that the rate of spread does not increase continuously but in an oscillatory form. This is clearly reported in [20] and [66] in which we see that short distance spot fires can play an important role to promote an increase of the rate of spread by burning a large area ahead of the main fire front in a relatively short time. While this area is burning a high plume is formed, blocking wind action and slowing down the fire. Then more spot fires are produced and the rate of spread increases another step. It is very probable that in some of the fires that occurred in Australia, on the 7th of February 2009 [67] a similar effect must have occurred. These fires include clearly acceleration and they could also be considered in the category of wind induced fire eruptions, but more research is needed to include all the involved factors.

General discussion and conclusion

The scientific studies on eruptive fire behaviour are quite scarce and recent. Among the different contributors, the ADAI team developed a systematic way to reproduce fire eruptions in the laboratory for steep slope and canyon shaped configurations under constant external conditions besides proposing a simple and consistent semi-empirical model that provides a general explanation for it. Some other explanations as flame attachment, gas accumulation or spotting also try to describe mechanisms involved in the fire.

Many of the explanations due to a variation of the external factors do not provide a direct explanation of the mechanism of fire eruption but provide more explanations about the onset of the phenomenon. Furthermore, they invoke the occurrence of some rare atmospheric processes that can give the dangerous feeling of extremely rare and unavoidable events. Some interpretations (cf. [68]) mention the “alignment of factors” meaning that when some factors occur simultaneously under given conditions, then a blow up will occur. The probability of the occurrence of most of these factors either isolated or connected, as some interpretations of this phenomenon require, can be assumed to be very small. Thus, the message that is conveyed by the literature is that fire eruptions should occur rarely and by surprise.

In the opinion of the present authors the various explanations that were presented to explain the process of fire eruption do not have the same generality. Some of them can play some role in certain cases but in some of them more research is required to validate their relevance to real cases.

Even if some phenomena can favour the onset of an eruptive fire, the concept of “alignment of factors” or other explanations that are based on the occurrence of some conditions like atmospheric instability, a wind change, a thermal belt and others, should be avoided in fire fighters training because they can induce the dangerous idea that fire eruptions occur rarely and by surprise and can lead to the development of some fatalism. In our opinion these interpretations do not contribute for the development of sound Fire Safety procedures for fire-fighting aiming to decrease the number of accidents and fatalities.

Fire eruptions in canyons can no longer be considered as a surprising or rare event. Actually they are both frequent and predictable. Fortunately not all cases result in accidents or fatalities. The analysis of past situations shows that experience alone is not sufficient to avoid this type of accidents, as many of the victims of the reported accidents were experienced fire fighters.

For all these reasons, the authors really trust that more research is necessary in order to complete the current state of the art and to develop a network of specialists who could investigate each case in a systematic and rigorous way. In parallel, more experimental and field experiments, as well as more modelling have to be conducted in order to better understand the set of parameters driving eruptive fire behaviour. This would lead to the classification of Fire Eruption types with their favourable conditions of occurrence, allowing the development of risk indexes for canyons and the creation of specific Fire Safety procedures for fire fighters.

In our opinion it is necessary to promote more research on this process of eruptive fires and then disseminate the message clearly to fire fighters and population in general to increase awareness, avoid misconceptions or erroneous concepts and consequently reduce the chances for the repetition of this type of accidents.

A breakthrough in this topic would be to obtain a classification of the different mechanisms involved in eruptive fires combined with the conditions that would increase the risk of occurrence. This objective can be reached only by increasing the research in this field. A good way to do it would be to include more fire science in the study of extreme wildfires.

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