The trench effect and eruptive wildfires: lessons from the King's Cross Underground disaster.

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Abstract

Fire eruption (also known as 'blow-up' or 'flare-up') is a very dangerous aspect of wildland fire behaviour. It poses a significant threat to the safety of wildland fire-fighters and complicates the broader problem of wildfire risk management in complex terrain. Despite the seriousness of eruptive fire events, operational wildland fire spread models generally do not account for the possibility of these events occurring and there is little in the literature devoted to obtaining a model that consistently describes the phenomenon. To address this situation international researchers have recently proposed models that account for eruptive fire behaviour as a feedback process, with possible mediation by other factors. One such factor is flame attachment to steep slopes.

The concept of flame attachment is also of interest in the structural fire-fighting context. For example, it is a key component of the so-called 'trench effect' which is a well established mechanism for fire propagation on enclosed slopes such as escalators or stairwells in building structures. Studies into structural fires have revealed that the trench effect can produce extreme fire behaviour and rapid fire spread, as was apparent in the 1987 Kings Cross (London) Underground fire disaster, for example. Despite the well known implications of the trench effect in the structural fire context it has received little attention in the wildfire context.

We therefore consider the trench effect in a wildfire context as a possible trigger for eruptive fire behaviour. In particular we consider the findings of a number of inquiries into fatal and near-fatal incidents apparently involving eruptive fire behaviour and discuss the possible involvement of a landscape-scale trench effect in these incidents.

1. Introduction

It is well known that a wildfire will spread more rapidly up a slope than it will on flat terrain (McArthur, 1967; Van Wagner, 1977; Noble et al, 1980). Indeed, it is common lore amongst Australian bushfire-fighters that the rate of spread of a fire will double for every 10° increase in topographic slope. This rule-of-thumb is well entrenched in wildland fire-fighting training materials where, for example, it is included on the back of the circular slide rules used to calculate expected fire behaviour characteristics based on the McArthur Forest Fire Danger Rating System (McArthur, 1967). Implicit in such rules is the notion that constant environmental and topographic conditions (e.g. fuel, weather and slope) will result in a roughly constant rate of fire spread: significant changes in rate of spread arise only through changes in the underlying conditions. In particular, on a slope of constant gradient a fire is expected to spread at a well-defined, constant rate of spread. However, there are now many documented cases from around the globe where wildfires have violated this expectation (Viegas, 2009).

Analyses of fire behaviour in both laboratory and wildfire settings have indicated that in some circumstances a fire can accelerate significantly up a slope of constant gradient (Viegas, 2006). This type of fire behaviour has recently been termed ‘eruptive’, though ‘blow-up’ or ‘flare-up’ may have been traditionally used to describe the same phenomenon. In the wildland fire setting, instances of eruptive fire behaviour pose significant dangers and are commonly associated with serious injuries to fire-fighters. In the worst cases they have resulted in multiple fatalities.

Understanding the physical mechanisms that result in eruptive fire behaviour is thus an important aspect of wildfire risk management, but until recently this problem had received little concerted attention amongst wildfire researchers. While a number of models have been devised to successfully account for eruptive fire behaviour (Viegas, 2005; Dold & Zinoviev, 2009), they are not widely known amongst fire management practitioners, nor are they definitive in explaining the phenomenon. For example, a majority of eruptive fire incidents have been observed to occur in connection with steep slopes or canyons (Viegas, 2006), yet topographic attributes have not been explicitly included in eruptive fire behaviour models. Instead topographic effects are considered *a priori* to modulate the initial conditions required as input to these models (Viegas, 2009; personal communication).

The intent of this article is to discuss the possible role that topography has in the incidence of eruptive fire behaviour. In particular, the ‘trench effect’ is introduced and discussed as a potential trigger for eruptive behaviour of wildfires. The ‘trench effect’ refers to a specific interaction between the buoyant plume of a fire and an inclined trench, and became known through investigation into the tragic King’s Cross Underground fire in London, 1987 (Crossland, 1992). This fire, which started as an innocuously small fire in an escalator trench, took fire-fighters by surprise as it rapidly escalated in intensity and ultimately claimed the lives of 31 people and caused extensive damage to the Underground railway station.

In what follows the characteristics of fire behaviour driven by the trench effect are described along with some of the most important findings of the King’s Cross fire investigation. Implications of the trench effect for wildland fire behaviour are then discussed. In particular, two serious burn-over incidents, one in Australia and one in the United States, are considered with the trench effect in mind. It is hoped that this will stimulate interest, discussion and better collaboration amongst Australian fire researchers and practitioners, and promote better communication between the structural/urban and wildland fire-fighting fraternities.

2. Wildland fires and topographic slope

Topographic slope has a strong effect on the rate of spread of a wildfire. The slope of the terrain essentially brings the ground, and hence the fuel upon it, into closer proximity with the flames ahead of the fire. This in turn extends the preheating range and allows for faster rates of spread. In practice there are a number of methods for incorporating the effects of topographic slope into wildfire rate of spread calculations (Sharples, 2008). Of particular importance in the Australian context is the method introduced by McArthur (1967). In his fire behaviour guide McArthur noted that the rate of spread of a fire doubles for each 10° increase in slope. This can be expressed mathematically as (Noble et al., 1980):

$$R_S = R_0 \exp(0.069\,S) \qquad (1)$$

where R_S is the slope-induced rate of spread, R_0 is the corresponding rate of spread on level ground and S is the topographic slope in degrees.

While equation (1) is accurate in expressing McArthur’s ideas, it may not be the best formulation for describing the effect of slope on rate of spread. In fact, it indicates that the rate of spread will increase to an implausible extent as topographic slope increases to 90°. This is inconsequential for practical use of the model within an appropriate data domain but suggests that the model should be considered with some caution when applied to steep slopes. Indeed, McArthur (1967) only considers slopes below 20°. Despite its limitations, equation (1) is the most common method currently used in fire behaviour calculations in Australia and, in the absence of more appropriate methods, is often used to account for fire behaviour on slopes exceeding 20° (e.g. Newnham et al., 2007).

3. Eruptive fire behaviour

In a series of articles (Viegas, 2002, 2004; 2006; Viegas and Pita, 2004; Viegas et al., 2005; Viegas et al., 2006) Viegas and his co-workers demonstrate and discuss the variable nature of fire spread, even when wind and topographic conditions are unchanging. Such behaviour contradicts traditional slope correction methods such as equation (1), which imply that a fire on a uniform slope will spread at a constant rate, assuming homogeneity in all other factors (Sharples, 2008). Of particular concern in the context of fire-fighter safety is the phenomenon of eruptive fire behaviour, whereby a fire can exhibit a continually increasing rate of spread, with associated increases in intensity, flame height and flame depth. Eruptive fire behaviour has been linked with many fatal incidents in the past, the majority of which occur in connection with steep slopes and canyons (Viegas et al., 2005; Viegas et al., 2006; Viegas, 2009).

Viegas and Pita (2004) provided confirmation of the existence of eruptive fire behaviour in the laboratory by considering a number of symmetrical canyon-like configurations. The experimental results indicated an apparent dichotomy in the observed rates of spread. For canyons inclined at 0° and 10° the rates of spread remained relatively constant, with only small variations over time. On the other hand, for canyons inclined at 30° and 40° the fire fronts were observed to accelerate significantly. For inclinations of 20° different dynamic behaviour was observed depending on how closed the canyon was; for more closed canyons a distinct acceleration in spread was observed, while for fairly open canyons the acceleration was not as pronounced.

Viegas (2005; 2006) introduced and discussed a mathematical model designed to account for eruptive fire behaviour. In this model heat produced by the flames induces air movement that acts to intensify the combustion process and the rate of spread. The increase in intensity further enhances the induced air movement leading to a feedback effect, which results in accelerated fire growth.

Dold & Zinoviev (2009) also derived a mathematical model that predicts eruptive fire spread under certain circumstances. In this model, the predicted rate of spread is critically dependent on a parameter v. For $v < 1$ the model predicts a stable, constant rate of spread, while for $v \geq 1$ the model can exhibit accelerated fire growth. Dold & Zinoviev (2009) argue that the case $v \geq 1$ corresponds to a situation where the buoyant fire plume attaches to the surface over which the fire is spreading. The hypothesised role of plume attachment was supported in a series of laboratory experiments and also in a field experiment.

While the models of Viegas and Dold & Zinoviev do both predict eruptive fire behaviour under certain circumstances, they do not have an explicit dependence on topographic attributes such as slope. As such they do not provide any direct explanation as to why incidences of eruptive fire behaviour are so commonly observed to occur on steep slopes or in canyons. Similarly they do not offer any direct insight into why the geometric properties of the terrain, such as how closed a canyon is, should have any effect on the incidence of eruptive fire spread.

4. The King’s Cross Underground fire and the trench effect

The King’s Cross Underground (railway) fire occurred on the 18th of November 1987. It exhibited behaviour that was both unexpected and disastrous, resulting in 31 deaths and the grievous injury of many people including commuters, public transport workers and fire-fighters. The fire had ignited within a wooden escalator trench and burnt for approximately 15 minutes, during which time fire-fighters had assessed its size and behaviour and concluded that although it was a significant fire, there was nothing to suggest that it would rapidly develop (Crossland, 1992). However, within an unexpectedly short amount of time the fire spread with extreme ferocity up the escalator trench and into the ticket hall and surrounding areas with tragic consequences. Photographs taken immediately after the incident attest to the extreme intensity of the fire. For example, see the photograph at http://en.wikipedia.org/wiki/File:King's_Cross_Fire1.jpg

Investigations into the King's Cross fire revealed that the extreme fire growth was primarily caused by a distinct phenomenon, which caused the flames and combustion products to be confined and concentrated within the escalator trench below the balustrades. This phenomenon was called the 'trench effect'. The scientific aspect of the investigation involved both experimental and theoretical research into fire spread in trench-like configurations. The experimental work focused on scale models of the escalator trench (Moodie & Jagger, 1992; Drysdale et al., 1992), while the theoretical work mainly concerned computer simulations of the flow of hot gases within the escalator shaft (Simcox et al., 1992).

Experiments using scale models of the King's Cross escalator shaft and ticket hall found that the flame front from a fully developed fire across the escalator trench remained virtually within the channel and spread upwards at an exponentially increasing rate. As in the King's Cross fire a sustained jet of flame was observed to emerge from the top of the channel. As such the experiments confirmed the existence of a mechanism for accelerated fire spread that occurs primarily within the confines of a trench. Subsequent experiments found similar effects in various trench configurations, even in trenches with only one side-wall (Drysdale et al., 1992). Similarly, the main feature of the theoretical simulations was the way that the hot gases in the buoyant plume lay along the trench floor.

Subsequent experiments and simulations with trenches of various inclinations and geometries found that flames would attach to a surface inclined above a critical gradient of around 24°-27° (Drysdale & Macmillan, 1992; Smith, 1992; Wu and Drysdale, 1996; Wu et al., 2000). The effect was found to be independent of the amount of heat released and surface conditions, and was observed even when the trench side-walls were removed. Thus, the term 'trench effect' is actually a misnomer; while a trench-like configuration will cause the particular behaviour more readily, the essential requirements are a slope of sufficient gradient and the inhibition of lateral entrainment of air into the plume. This can occur with long line fires on flat, inclined surfaces or by restricting lateral entrainment with a trench-like configuration (Smith, 1992). This suggests that the terms 'plume attachment' or 'flame attachment' are perhaps more appropriate to describe the phenomenon.

Simcox et al. (1992) concluded that flame attachment is the result of two separate effects: a significant chimney (Venturi) effect caused by the heat source, and the Coandă effect, which causes the buoyant plume to attach to the floor of the trench. Once flame attachment is established the enhanced preheating and pyrolysis of the fuel above the fire leads to accelerated fire spread. The Coandă effect is a response to the pressure differential induced by differences in the capacity for entrainment of air upslope and down-slope of the fire plume. It is named after aerodynamics pioneer Henri Coandă (1886-1972), who patented a number of devices based on the effect, but appears to have been known of much earlier (Young, 1800).

5. Flame attachment and wildfires: two case-studies

The trench effect, or more properly flame attachment, arises through the interaction between a fire's buoyant plume and the terrain geometry. The physics underlying the phenomenon applies over a wide range of geometries and scales. As such it is natural to consider flame attachment as a potential trigger for eruptive fire behaviour in landscape-scale wildfires. Indeed, such a consideration is entirely consistent with the observations and analyses of Dold & Zinoviev (2009). Moreover, the fact that confined slopes of over about 25° are the most prone to flame attachment provides a physical rationale as to why eruptive wildfire behaviour is more prevalent on steep

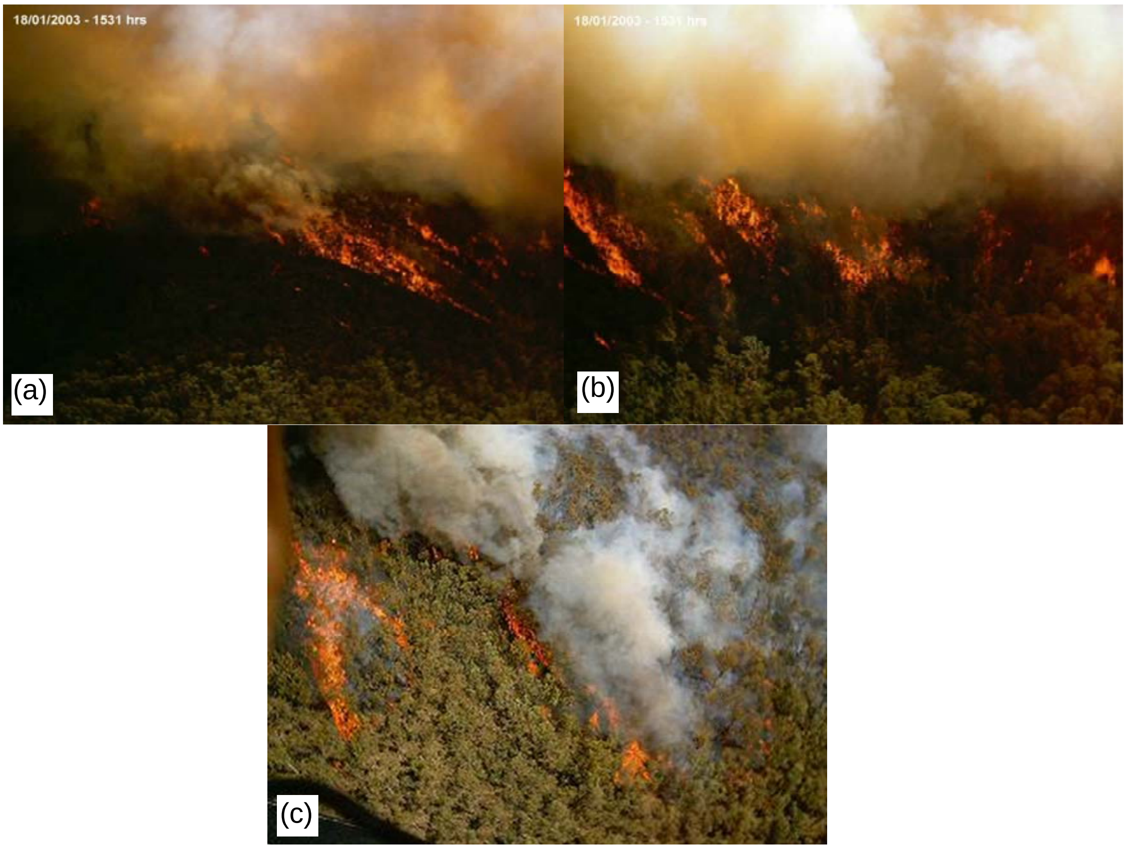

Figure 1. Wildfires burning on steep slopes and in montane forest fuels (approx. 30m tall eucalypts) to the west of Canberra on 18 January 2003. The slopes in (a) and (b) are approximately 30° and the slope in panel (c) is approximately 40°. Photographs taken by Stephen Wilkes (NSW Rural Fire Service Air Observer).

slopes and in canyons. In this section this rationale will be applied to two case-studies of burn-over incidents. In particular, the similarities between the extreme fire behaviour resulting in the burn-overs and that observed in the King's Cross fire will be discussed.

Before discussing the case-studies, it is interesting to note that Rothermel (1985) mentions the possibility of flame attachment in a wildland setting. In particular he refers to steep slopes over 50%. It is remarkable that a slope of 50% equates to 26.5°, which is about the same figure derived from the investigations into the King's Cross fire. It is also remarkable that Rothermel reported this figure two years *before* the King's Cross disaster and suggests that the wildfire and structural/urban fire-fighting fraternities might benefit from closer communication and collaboration on research matters. Moreover, Van Wagner (1977) notes that on slopes of 60-70% (30-35°) flames tend to bathe the slope directly, leading to intense and unstable fire behaviour, while Cheney and Sullivan (1997) note that under very strong winds the convection column may not lift away from the surface of steep slopes and result in very high rates of spread. Cheney and Sullivan (1997) make no mention of the possibility of such an occurrence under conditions of light or no wind, however. Alexander et al. (2009) also mention the possible role that flame attachment played in the development of the escape fire used by fire-fighters to survive the Mann Gulch fire.

There is also strong evidence of flame attachment playing a role in the extreme fire behaviour during the 2003 Canberra fires and the recent Black Saturday fires of 7 February 2009. Figure 1

shows photographs taken by Stephen Wilkes, an air observer with NSW Rural Fire Service. Figures 1a and 1b show entire slopes involved with flame with very little smoke directly above them. Similarly, figure 1c shows flames on a steep slope that appear to be attached to the terrain-vegetation surface. The slopes depicted in the photographs are approximately 30-40°. Photographs taken on 7 February 2009 also indicate flame attachment on slopes of around 20°-30°. For example, see the photograph at:
http://www.worldweatherpost.com/2009/02/13/greenies-blamed-for-victoria-bushfires-scale/

5.1 Tuolomne Fire, California 2004.

The Tuolumne Fire occurred on 12 September 2004 in California. A Helitack crew from the California Department of Forestry and Fire Protection were tasked with constructing a control line with hand tools near the back of the fire. The terrain was very steep, with slopes of 80-120% (approx. 38°-50°). During the initial stages of control line construction fire behaviour was reported as relatively benign: the crew was working near a portion of the fireline that was backing slowly across-slope against a steady, light up-canyon wind with surface flame lengths of 6 to 12 inches. However, with an abrupt wind shift of approximately 90° the rate of spread and flame lengths increased dramatically and the fire rapidly burnt upslope, emitting a loud roaring sound and over-running the crew within 8-30 seconds (Cole and Edgar, 2005). Three fire-fighters sustained minor burns and other injuries, while one fire-fighter was entrapped and killed.

The report into the burn-over incident indicates that, as in other fatal wildfire accidents, an unexpected wind shift was a primary causal factor. The wind shift was supposed to be part of a localised weather pattern created by the interaction of the ambient up-canyon winds with the complex topography, but no similar wind shift was observed for over thirty minutes before the burn-over, nor was one observed in the remainder of the day or in the next several days. Cole and Edgar (2005) concluded that the cause of the wind shift was not apparent.

As part of the investigation into this incident an analysis of the fire behaviour using the BEHAVE system (Andrews, 1986) was conducted. The analysis indicated that with the assumption of a moderate increase in wind strength associated with the change in direction, the fire would have exhibited a rate of spread of approximately 2-3 km h^{-1}. At this rate, one would expect to be able to outrun the fire, even after considering the effects of a 40° slope on maximum running speed (Minetti et al., 2002). It therefore seems likely that the fire was propagating much faster than the modelling suggests.

Testimony of fire-fighters that survived the incident appears to favour fire spread driven by attachment of the buoyant plume to the terrain-vegetation surface. Indeed, one fire-fighter describes seeing the fire "sheeting" in association with the wind change. Specifically, the sheeting behaviour was described as "fire about 8 to 12 inches tall and 10 to 15 feet deep, spreading 10 to 15 feet into the green with intense heat". Another fire-fighter describes feeling heat at his back as he scrambled up the hill and rolled over the lip of the road within the flame front. The incident occurred at a location with a slope of approximately 42°, which is sufficient to enable flame attachment via the Coandă effect, even without the shift in wind. In fact in this light it seems plausible that the upslope wind, which unexpectedly occurred and is cited as the cause of the escalation in fire behaviour, was actually the flow within the buoyant plume itself, attached to the terrain surface. Based on the evidence presented in Cole and Edgar (2005) it is difficult to rule out this possibility.

5.2 Mansfield Fire, Victoria 2006

A more recent example, in which fire eruption driven by flame attachment may have been a contributory factor, occurred during the Great Divide Fires of 2006/07 in Australia, southeast of Mansfield, Victoria. A team of New Zealand fire-fighters assisting in the suppression efforts were constructing control lines just above a side-cut road near the top of a hill, with a 25° slope above them and a 30-36° slope below. Both slopes contained unburnt fuel but weather conditions were benign and observed fire behaviour was relatively mild (Newnham et al., 2007). The majority of the crew felt comfortable with their position. However, within seconds the fire-fighters became aware that there was an escalation in fire behaviour in the gully below them and that they were in danger. Witnesses reported hearing the fire before seeing it, with the sound described as the roar of a jet engine or freight train. Those members of the crew that didn't escape in time were burnt-over, with eleven fire-fighters suffering burns and other injuries.

An investigation into the burn-over incident (Newnham et al., 2007) concluded that the escalation in fire behaviour was mainly due to the effects of slope on the rate of spread of the fire, as described by equation (1). The predicted rate of spread on level ground was estimated as 0.27 km h^{-1}, and so equation (1) suggests that on a 35° slope the fire would have been travelling at a little over 3 km h^{-1}. This implies that the fire would have traversed the 180 m slope in approximately 3.5 minutes. However, given that the length of the road impacted by the fire was around 250-300m with a maximum incline of less than 10°, and that the fire-fighters were physically fit, they should have been able to reach safety within 3.0 minutes[1], or even less given that they would have been running. This combined with the details of the burn-over incident contained in Newnham et al. (2007) indicates that the fire spread much more quickly than the steady rate obtained from equation (1). Indeed, it seems unlikely that experienced remote area fire-fighters would be surprised by a fire spreading up a slope at 3 km h^{-1}, which corresponds to a moderate walking pace. Eruptive fire spread induced by flame attachment again offers a plausible explanation for the rapid spread upslope. Even without any wind the slope of 30-36° would enable the effect.

6. Discussion and Conclusions

The characteristics of fire behaviour driven by the 'trench effect', such as in the King's Cross escalator fire, bear a strong resemblance to the fire behaviour described in many 'blow-up' fires and burn-over incidents. In particular, the rapid rates of spread and blasts of superheated air described in burn-overs such as those discussed above and in other fatal incidents (for example, see Butler et al., 1998; Viegas, 2009) are consistent with the results of experimental and numerical work that lead to the discovery of the 'trench effect' or flame attachment phenomenon. Flame attachment driven by the Coandă effect on the buoyant plume applies at a multitude of scales and so it is entirely plausible that such an effect could play a role in these eruptive occurrences. Indeed, the fact that eruptive fire incidents tend to occur almost exclusively in landforms that satisfy the geometric prerequisites for flame attachment, supports the hypothesis that it is a key aspect of eruptive fire behaviour in these cases. Furthermore, the rapidity of the transition from a relatively low-intensity, slow spreading fire to a high-intensity, fast moving fire that is associated with the flame attachment phenomenon is consistent with the fact that in many burn-over incidents experienced fire-fighters are caught as if by surprise, with little time to reach safety. The sudden 'upslope wind change' that is often reported as a main causal factor in such occurrences is also consistent with what would be experienced in the initial stages of plume attachment.

The presence of various types of vegetation, the intricacies of the terrain and the impacts of highly variable winds in a wildland setting will undoubtedly affect whether or not flame attachment, and hence eruptive fire behaviour, can occur. For example, in cases where the topography doesn't quite possess the required geometric properties, the conditions necessary for flame attachment might be met with the assistance of relatively mild upslope winds. Fuel structure can also be expected to have

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[1] A standard fitness test for fire-fighters in Australia requires them to carry a 20 kg weight over 4.8km within 45 minutes (without running). This implies an average walking pace of 6.4 km h^{-1}. Moreover, remote area fire-fighters are required to complete the 4.8 km in 40 minutes or less, implying an average walking pace of 7.2 km h^{-1}.

an influence on any resultant fire behaviour (Gould et al., 2008). Further research is clearly indicated and will be pursued by the authors.

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