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Effect of canyons on a fire propagating laterally over slopes

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Abstract

Forest fires often cause fatal losses, human lives and resources in wildfire-prone regions. Several accidents were registered in canyons with a scenario in which the fire propagates laterally over a slope then enters the canyon causing a rapid increase in the fire's rate of spread (Viegas, 2004; Lahaye et al. 2018; Pimont et al. 2012). This behaviour is known as eruptive fire behaviour (blow-up) – Viegas et al. 2011 – which usually happens over slopes or in canyon configurations (Viegas, 2005; Viegas, 2006; Viegas and Simeoni, 2011). The behaviour surprised fire management teams in several recorded events and caused loss of lives in some of them. In 2013, at Serra do Caramulo, two firefighters died on a sloped terrain when a flank fire entered a canyon (Viegas et al. 2013). This particular accident motivated us to study the change in the flank fire behaviour over slopes when it enters canyons with the aim of improving the safety of the personnel involved in the combat of wildfires.

In this study, we analyse results of laboratory-scale experiments that model a fire spreading latterly over a slope then enters a canyon from its base. We considered various conditions of terrain slope, canyon's axis angle along with altered canyon configurations. Also, we tested a number of fire approaching angle scenarios. Based on the analysis, we are proposing a mathematical model for predicting the fire's rate of spread in this configuration along with suggested personnel safety measures under these conditions.

Keywords: Forest Fires; Fire safety; Extreme Fire Behaviour; Eruptive Behaviour; Fire in canyons.

1. Introduction

The knowledge on fire behaviour is an essential tool to fire suppression and increase the personnel safety. Thus, research has contributed to the advancement of the scientific knowledge on forest fires. According to Viegas et al. (2011), the fire behaviour can be classified as normal and extreme. Accidents related to forest fires are often due to insufficient knowledge about fire and its behaviour (Viegas, 2006), especially in the case of Extreme Fire Behaviour (EFB).

Most of the behaviour models are based on the assumption that the fire propagation properties are almost static and can be determined by considering three essential factors: topography, fuel and meteorology, which is called the "fire triangle" (Byram, 1959). However, Viegas (2006) proposed, as an alternative to this classic concept, the concept of "fire square", adding a fourth factor: time.

A low and little time-dependent rate of spread is a characteristic of Normal Fire Behaviour. This type of behaviour doesn't pose a great risk to the operational, instead that happens with the Extreme Fire Behaviour. In Extreme Fire Behaviour there is a dynamic change of the characteristics of the fire over time, as shown by the studies on slopes of Dold and Zionviev (2009) and in canyons of Viegas and Pita (2004). According to Viegas et al. (2011), the Extreme Fire Behaviour is defined as the set of characteristics of propagation and properties that call into question the possibility the control in safety using the available technology and knowledge. One of the examples of Extreme Fire Behaviour is the fire spread in canyons. The rate of spread of the fire front has a dynamic behaviour and its properties depend on the canyon's geometry and the fire spread, suffering this acceleration by the variation of rate of spread and energy release rate (Viegas, 2005, 2006; Viegas *et al.*, 2017). The induced fire convection becomes stronger due to the specific topography of the terrain which promotes the occurrence of the eruptive fire behaviour (Velez, 2000; Raposo et al., 2018). The rate of spread of the fire front increases steadily, even in the absence of wind or any other feature (Pyne et al., 1996; Dold, 2010). Canyons are associated with a large percentage of fatal accidents during forest fires worldwide (Viegas, 2005; Schemel et al., 2008; Lahaye et al., 2018). The eruptive effect created by this topographical configuration induces a spreading of increased velocity surprising experienced firefighters causing death (Viegas and Pita, 2004). In 2013 at Serra do Caramulo two firefighters died on a slope when the fire reached the canyon (Viegas *et al.*, 2013).

The main objective of this paper is a detailed and exhaustive analysis on the phenomenon of the interaction on lateral spread of fire on a slope with a canyon. The intent to understand the variation of fire propagation velocity and direction and the values of the energy release rate, contributing towards the increase of scientific knowledge in this case of EFB. Fuel moisture, relative humidity and air temperature will be taken into account. Different ignition modes will be tested to evaluate their influence on the development in the forest fires. The acquisition of images in the visible range and infrared range to determine the velocity and direction of fire propagation, the flame geometry and the energy release rate is the purpose of this work. This study also aims to propose behaviour models and operation rules in safety in the fight against forest fires on slopes with canyons, based on previous studies and in the research that will be carried out.

2. Conceptual Model

For the experimental study a test table was built, which allows to change the inclination and rotation of the slope, the angle and the geometry of the canyon. The testing table (figure 1) allows to change the angle of inclination of the slope between 0º and 45º and the angle of rotation between 0º and 360º. Various canyon configurations (figure 2) will be studied by changing their opening angle, width and depth.

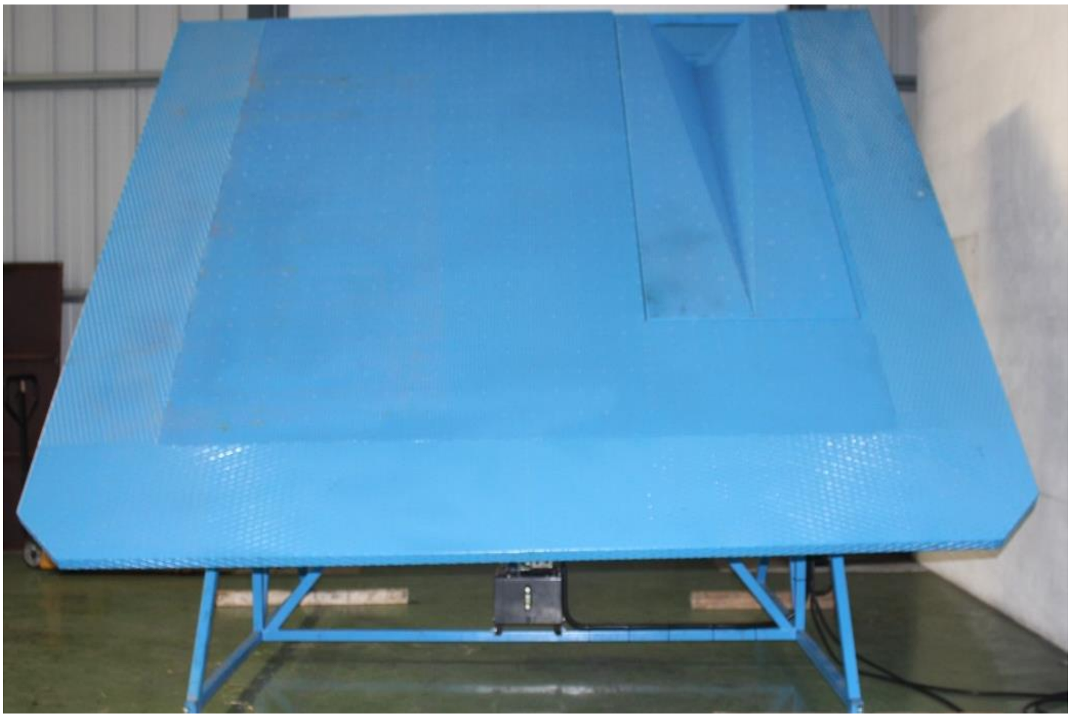


Figure 1 - Table of laboratory tests.

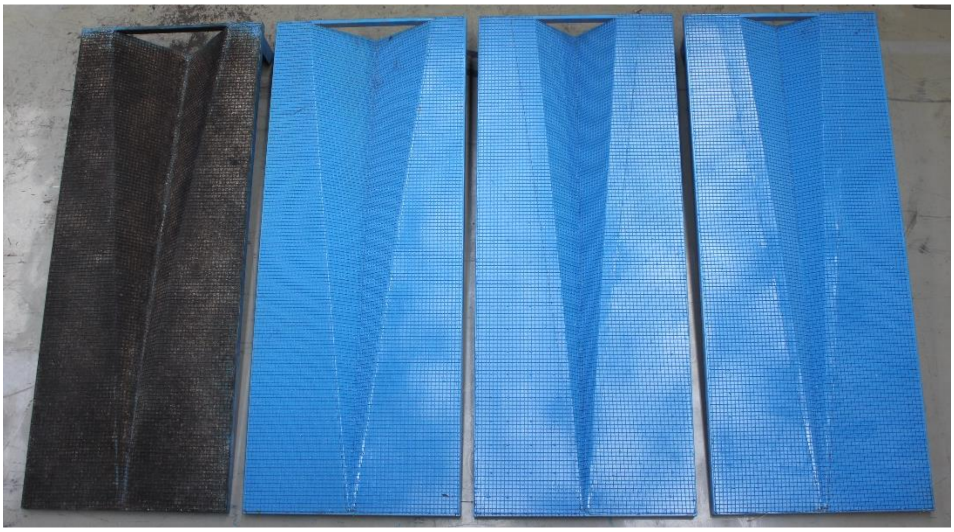


Figure 2 - Various canyon configurations, changing their opening angle, width and depth.

3. Methodology

A testing table was prepared as a flat surface with a canyon structure inserted within this surface. The table has an allowance to change its inclination (α), its rotation (γ) and the opening angle of the canyon (δ), according to figure 3.

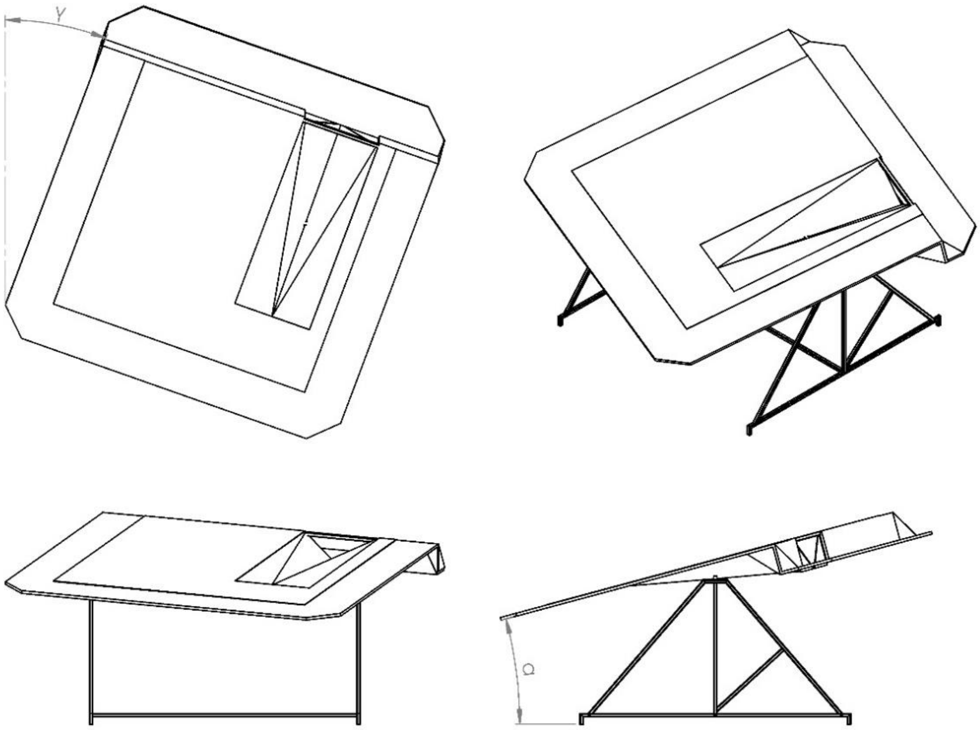
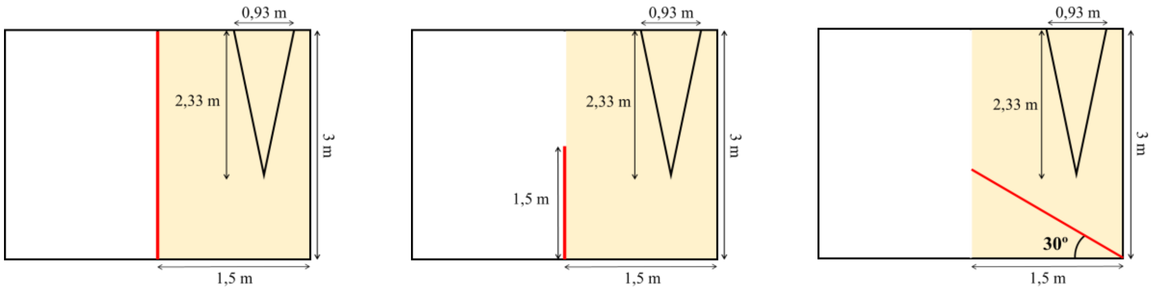


Figure 3 - The table and the variation of its geometry.

The flat surface of the table and the canyon covered with a fuel bed. A linear ignition is applied with different angles and locations, which are: A Total Ignition, which is a lateral ignition line with the full width of the fuel bed (parallel to the axis of the canyon); Partial Ignition, which is similar to the Total Ignition but the ignition line extends over only half of the width; finally, a Diagonal Ignition, which is a line forming an angle with the base side of the fuel bed. In the first experimental tests only half of the table (shaded area) was used. The figure 4 shows the different ignition modes and the shaded area. For the diagonal ignition an angle of 30º was used.



(a) (b) (c)

Figure 4 - Ignition modes: (a) total linear; (b) partial linear; (c) diagonal.

The conditions of fuel moisture, relative humidity, air temperature and the fuel loading were controlled. The objective of this study is to determine the fire's rate of spread and the propagation behaviour of the fire. The tests were monitored using a photographic camera, two video cameras – one in the frontal plane and one in the lateral plane – and an infrared camera. Data such as the time of preparation of the test, air temperature, relative humidity, fuel bed moisture and height were collected. In the carried out tests, the fuel used was *Pinus Pinaster*, with a load of 0.6 kg/m^2.

We analysed the infrared recorded frames and obtained the fire's rate of spread and propagation contours; the frames were taken from the recording with time intervals determined for each test, in order to follow the evolution of the fire front, following the methodology referred in Raposo (2016).

4. Results and conclusions

Pre-tests were performed with a slope angle (α) of 30º, a canyon opening angle of 45º and three rotation angle of the table, which are: -20º, 0º and 20º. For each angle of rotation of the table, the three types of ignition described above were tested.

Table 2 - Data of the tests performed.

Ref.	Designation	mf*1 %	R0*2 cm.s-1	□ o	Ignition
1	AVE_01	17.23	0.36	0	Total
2	AVE_02	9.82	0.35	0	Partial
3	AVE_03	12.36	0.33	20	Total
4	AVE_04	12.11	0.31	20	Partial
5	AVE_05	13.38	0.38	-20	Total
6	AVE_06	13.77	0.34	-20	Partial
7	AVE_07	12.49	0.34	-20	Diagonal
8	AVE_08	10.74	0.25	20	Diagonal
9	AVE_09	10.74	0.55	0	Diagonal

[1] **mf – Fuel moisture Content; *[2] **R_0** – Basic rate of spread of linear fire in the absence of slope and wind.*

In figure 5, we can observe the test "AVE_08" recorded using the infrared camera with frames every 30 seconds, from instant 0s to 270s.

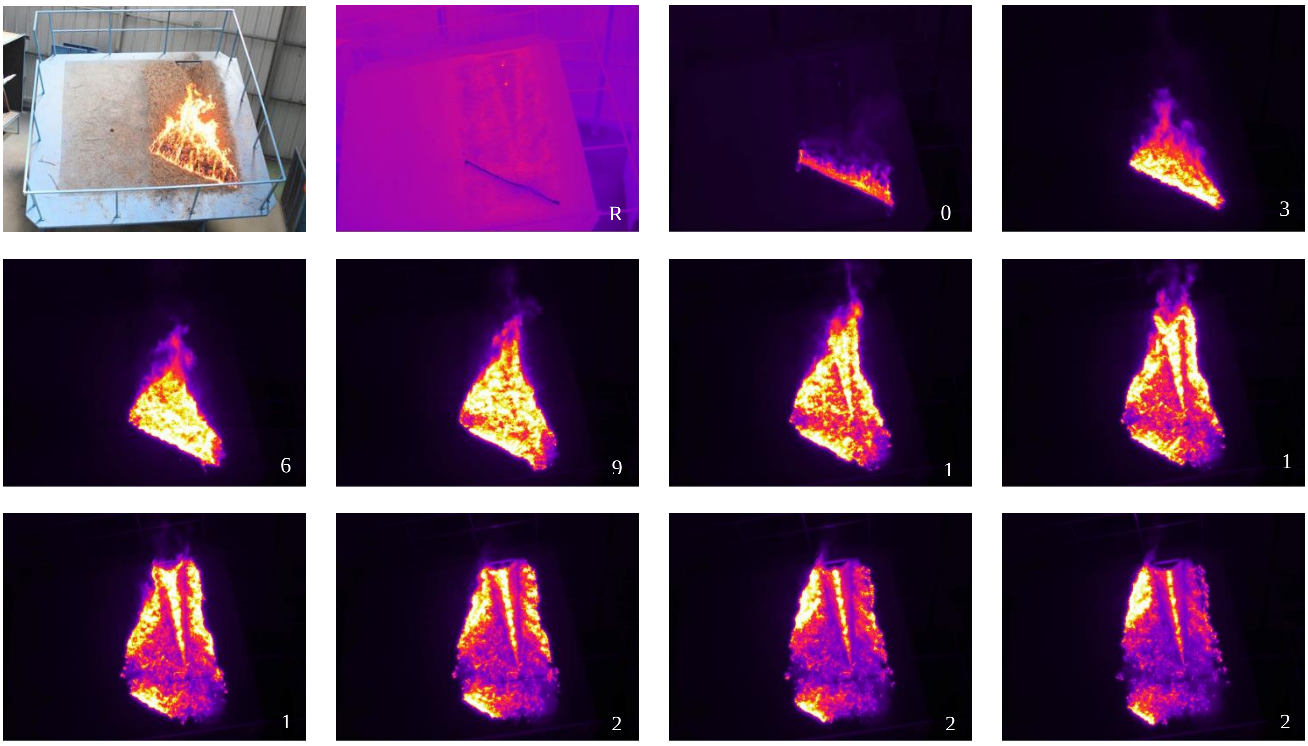


***Figure 5** - Test AVE08 (α=30º; γ=20º; δ=45º): visible picture of the table, reference frame and frames every 30 seconds, from instant 0s to 270s.*

In figure 6, we can observe the propagation contours of the fire front as a function of time for one of the tests with a Diagonal Ignition. It should be noted that, initially, the fire propagation isochronous are mostly parallel to the ignition line (red line in the figure). With the evolution of the time, it is observed that the direction of propagation changes from this initial direction to align with the maximum slope direction on the left of the canyon. However, the canyon also interferes with the direction of the propagation where the fire spreads with a higher rate of spread in the direction of the canyon's waterline affecting the adjacent points.

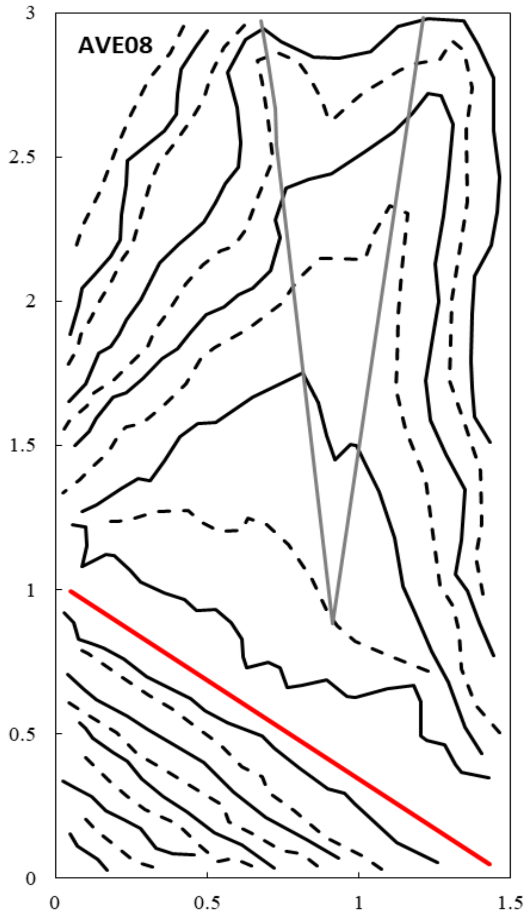


***Figure 6** - Fire spread propagation contours of the AVE 08 test (α =30º; γ=20º; δ=45º) as a function of time (interval between 30-second contours).*

In figures 7 and 8, we can find the resultant rate of spread of the fire along the axis of the canyon (the waterline) for AVE07 (α=30°, γ=-20°, δ=45°), AVE08 (α=30°, γ=20°, δ=45°) and AVE09 (α=30°, γ=0°, δ=45º). On these three tests, we used a Diagonal Ignition, and we changed only the rotation angle (γ).

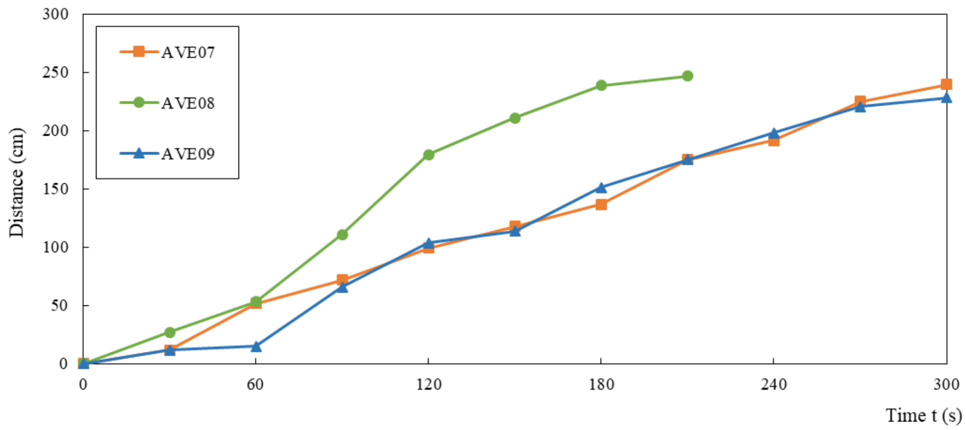


Figure 7 - Distance travelled by the fire front of the tests AVE07 (α=30°, γ=-20°, δ=45°), AVE08 (α=30°, γ=20°, δ=45°) and AVE09 (α=30°, γ=0 °, δ=45º) as a function of time.

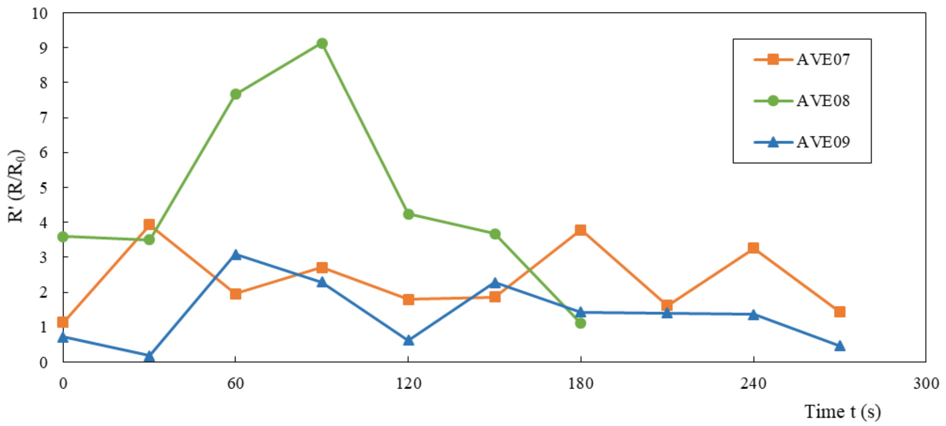


Figure 8 - Non-dimensional rate of spread along the axis of the canyon of the tests AVE07 (α=30 °, γ=-20 °, δ=45 °), AVE08 (α=30°, γ= 20°, δ= 45°) and AVE09 (α=30 °, γ=0º, δ=45º) as a function of time.

Based on the previous figures, it is concluded that the test AVE08 (α=30º; γ= 20º; δ= 45º) shows a higher fire front propagation velocity than the other two tests. This result is due to the fact that this test is performed with a table rotation angle of +20°. On this test, the fire has entered the canyon from its base initially while the fire front tends to align with the maximum slope direction. After the fire has entered the canyon, an evident eruptive behaviour takes place, which is a common behaviour associated with this type of terrain configuration. In the other two tests, the fire's rate of spread was lower as the fire front entered the canyon from its left side and the eruptive behaviour did not occur intensity as on AVE08.

The tests carried out with total and partial ignition did not reveal the Extreme Fire Behaviour because the fire enters the canyon laterally, which does not lead to the eruptive behaviour, as it happens when the fire reach the canyon at the base.

The greater or less inclination of the slope has a decisive influence on the propagation of forest fires, since the more inclined it is the greater the effect of the convection that heats the fuel above the fire, increasing the upward propagation velocity. Thus on a slope the fire spread is much faster in the ascending than in the descending direction. Another very important aspect of the topography is manifested in the canyon. On an inclined slope with a canyon the Extreme Fire Behaviour is to be expected. Thus, it's important to note that the fight against forest fires in this configuration (slope with canyon) must have rules, such as: not to fight the fire by the top of the slope or the half slope; to have someone watching to see if there is fire below the position of the operational that can progress quickly and surprise them; to anchor the fire and make its fight from the rear, going through the flanks until it reaches the head; to establish a communications plan for all operational so that dangerous situations can be anticipated; before the fight define more than an escape route that everyone knows; to define a safety zone that can protect the operational in case of need.

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