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Burgers Program and Combustion Institute
Summer School on Fire Safety Science –
Wildland/WUI Fire Behaviour

Extreme Fire Behaviour

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Foto L: M. Ribeiro

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Contents

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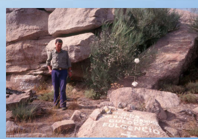
1 Introduction

- In this lecture I will review some basic aspects of forest fire behaviour, paying particular attention to what we designate by **Extreme Fire Behaviour** (EFB). This lecture is based on my research activity with my research Group in this area since 1985.
- I was motivated to study forest fires by an accident that occurred in Portugal on the 8th of September of 1985, in which fourteen fire fighters were killed by the fire.

Accident of Armamar

8 September 1985
14 fatalities



J. M. Fulgêncio (sobrevivente)

- At that time the circumstances of this accident were not well explained to the public. It was said that the wind or a change of the wind had modified the fire behaviour and caught the fire fighters by surprise.
- When I visited the site of the accident a few years later I understood that whatever had happened it must have been very quick and sudden, because the site was not that large and, in spite of their attempts, most of the fire fighters in the Group did not survive.

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a. Background

- I decided to study these problems to understand fire spread and why these accidents happen, with the purpose of avoiding them.
- Knowing the importance of wind on fire spread and given my scientific training as a wind engineering specialist I started to study the role of wind on fire behaviour.
- Given my preference to experimental work I started to build a fire laboratory to analyze systematically the effect of wind on the development of the fire front. Soon I had to include the role of terrain as well, initially just with slope but later with hills and canyons.

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- I started to pay much more attention to the role of topography, particularly in the context of fire safety, as I realized that the majority of fatal accidents and in particular those in which groups of fire fighters were involved happened in canyons.

- From the beginning, like so many of us did since 1972, I used the Rothermel model, but at the same time challenged it. I learned a lot from it but found that it was not the end of the line as it had several limitations. I will refer later to some of these limitations and how I proposed to overcome them.

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Team of the *Centro de Estudos sobre Incêndios Florestais* (CEIF)

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Methodologies employed

- Mathematical modelling
- Laboratory Experiments
- Field Experiments
- Observation of real fires

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Canyon Table

Combustion Tunnel

Dihedral table

Wind ans Slope table

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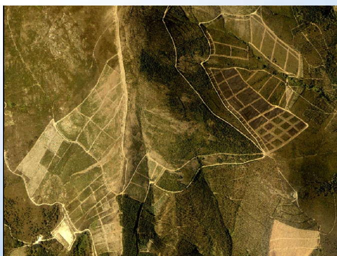
Field Experiments



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Observation of real fires

b. Extreme Wildfire Events

- When we speak about **Extreme Fires** it is important to define better what we mean by this and in particular distinguish between **Extreme Wildfire Events** (EWE) and **Extreme Fire Behaviour** (EFB). I will use two texts which I co-authored to deal with these definitions and to present you my points of view on these two subjects.

- The expression "extreme" has a sense of comparative or relative assessment. Statistically it corresponds to the limit of the probability distribution, either around the maximum or near the minimum values. Thus we have to retain that what is considered as "extreme" in a certain context or environment may not be so in others. Although we may not be speaking about absolute quantities we will try to establish some common ground for what we can consider as an out of normal process in fire behaviour.

- Tedim *et al.* (2018) proposed the term EWE to designate what is currently referred in the literature as large fires, megafires, or similar terms, based on different metrics to asses the fire behaviour, fire size or duration or the fire impacts of events that are out of normal and therefore cause concern to the society and to fire managers in particular.
- A set of criteria to evaluate EWE is presented in a Table, considering different metrics of fire and smoke spread and their effects. It is interesting to notice the mention to "Fire behaviour sudden changes", referring to "unpredictable variations of fire intensity, erratic ROS direction, spotting".

- A definition of EWE is proposed using multiple criteria:

"A pyro-convective phenomenon overwhelming the capacity of control (fireline intensity currently assumed ≥ 10,000 kWm⁻¹; rate of spread >50 m/min), exhibiting spotting distance > 1 km, and erratic and unpredictable fire behavior and spread. It represents a heightened threat to crews, population, assets, and natural values, and likely causes relevant negative socio-economic and environmental impacts."

Tedim, F. *et al.* (2018) 'Defining Extreme Wildfire Events: Difficulties, Challenges, and Impacts', *Fire*, 1(1), p. 9. doi: 10.3390/fire1010009.

Table 2. Criteria for the definition of EWE and their social implications and outcomes.

Criteria	Indicators		Social Implications and Outcomes
Fire behavior	FLI	≥10,000 kWm⁻¹	**DURING FIRE SPREAD AND SUPPRESSION** **Increase of the area of intervention:** (i) Requires more fire suppression resources; (ii) Increases the threatened area and potential losses and damages. **Response capacity of suppression crews:** (i) Reorganization of suppression activities is made difficult by the increasing ROS; (ii) Deployed crews are rapidly overwhelmed. **Capacity of reaction of people and displacement capacity** is overwhelmed by ROS and massive spotting. **Impacts:** (i) Smoke problems: increased hospital admissions during and immediately after the fires; poor visibility; impacts on displacement and on the use of firefighting aircraft; (ii) Loss of lives. **AFTER SUPPRESSION** **Short -term and long-term impacts:** (i) Loss of lives and injured people; (ii) Economic damages; (iii) High severity.
	Plume dominated event with EFB	Possible pyroCb with downdrafts	
	FL	≥ 10 m	
	ROS	≥ 50 m/min	
	Spotting	Activity Distance	
	Fire behavior sudden changes	Unpredictable variations of fire intensity Erratic ROS direction Spotting	
Capacity of control	Difficulty of control	Fire behavior overwhelms capacity of control Fire spreads unchecked, as suppression operations are either not attempted or ineffective	**DURING SUPPRESSION** **Immediate consequences:** (i) Entrapments and fire overruns; (ii) Unplanned last moment evacuations; (iii) Entrapments with multiple fatalities and near misses; (iv) Fatal fire overruns.

Note: The criteria to define EWE are only contained in the first and second column. The integration in the table of social implications and outcomes (fourth column) has the purpose to show the interplay of fire behavior and capacity of control with several social issues. The implications and outcomes are not exhaustively listed and they are not exclusive and specific for EWEs but certainly they can be magnified in case of EWEs occurrence.

Table 3. Wildfire events classification based on fire behavior and capacity of control.

	Fire Category	Real Time Measurable Behavior Parameters			Real Time Observable Manifestations of EFB				Type of Fire and Capacity of Control *
		FLI* (kWm^{-1})	ROS (m/min)	FL (m)	PyroCb	Downdrafts	Spotting Activity	Spotting Distance (m)	
Normal Fires	1	<500	<5 [a] <15 [b]	<1.5	Absent	Absent	Absent	0	Surface fire Fairly easy
Normal Fires	2	500–2000	<15 [a] <30 [b]	<2.5	Absent	Absent	Low	<100	Surface fire Moderately difficult
Normal Fires	3	2000–4000	<20 [c] <50 [d]	2.5–3.5	Absent	Absent	High	≥100	Surface fire, torching possible Very difficult
Normal Fires	4	4000–10,000	<50 [c] <100 [d]	3.5–10	Unlikely	In some localized cases	Prolific	500–1000	Surface fire, crowning likely depending on vegetation type and stand structure Extremely difficult
Extreme Wildfire Events	5	10,000–30,000	<150 [c] <250 [d]	10–50	Possible	Present	Prolific	>1000	Crown fire, either wind- or plume-driven Spotting plays a relevant role in fire growth Possible fire breaching across an extended obstacle to local spread Chaotic and unpredictable fire spread Virtually impossible
Extreme Wildfire Events	6	30,000–100,000	<300	50–100	Probable	Present	Massive Spotting	>2000	Plume-driven, highly turbulent fire Chaotic and unpredictable fire spread Spotting, including long distance, plays a relevant role in fire growth Possible fire breaching across an extended obstacle to local spread Impossible
Extreme Wildfire Events	7	>100,000 (possible)	>300 (possible)	>100 (possible)	Present	Present	Massive Spotting	>5000	Plume-driven, highly turbulent fire Area-wide ignition and firestorm development non-organized flame fronts because of extreme turbulence/vorticity and massive spotting Impossible

Note: [a] Forest and shrubland; [b] grassland; [c] forest; [d] shrubland and grassland; *FLI classes 1–4 follow the classification by Alexander and Lanoville [125].

- The other work is Viegas, 2012, a book chapter that I entitled Extreme Fire Behaviour, in which I propose the following definition of EFB:

*"**Extreme Fire Behaviour** is the set of forest fire spread characteristics and properties that preclude the possibility of controlling it safely using available present day technical resources and knowledge"*

Viegas, D.X., 2012. Extreme Fire Behaviour. In: Armando C. Bonilla Cruz and Ramona E. Guzman Correa (Ed.), *Forest Management: Technology, Practices and Impact*. Nova Science Publishers, Inc. ISBN 978-1-62081-359-1.pp: 1-56.

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- I would like to stress that EWE and EFB are not the same.
- In an EWE we will certainly have what we call manifestations of EFB, but we do not need a very large fire or EWE to have some form of EFB. This means that even in a relatively small fire (in terms of size and duration) we may have manifestations of EFB.

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c. Fire behaviour properties

- There are many parameters that can be used to describe and characterize the spread of a fire. For scientific and operational purposes it is important to determine the location of the fire at given time periods, which we call the fire isochrones. From these lines we can derive a large number of data namely the rate of advance of the fire between two periods of time at any point in the area of fire.
- In extreme or very intense fires there is usually a main direction of fire spread that drives the fire. The knowledge of the spread of the fire the along this direction in the course of time is of particular importance. We shall use the rate of spread (ROS) of the fire as a main descriptor of fire behaviour.

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Rate of Spread

The ROS is a vector that in the general case is given by its two components on the surface of the ground:

$$\overrightarrow{R(x,y,t)} = \overrightarrow{R_x} + \overrightarrow{R_y}$$

In some conditions in which there is a main spread direction we can consider just one component of the ROS and treat it is as a scalar quantity.

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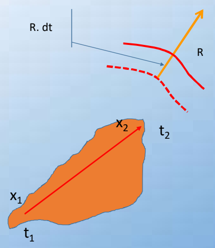
We must distinguish the instantaneous value of ***R*** and its average value.

Instantaneous value

$$R = \lim_{dt=0} \frac{dx}{dt}$$

Average value

$$R = \frac{x_2 - x_1}{t_2 - t_1}$$



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Fireline Intensity

A very important property that is related to the ROS is the Fireline intensity (FLI) first proposed by Byram, which is defined by:

$$I = R.Q.M_c$$

In this equation ***I*** is the fireline intensity (W/m) that gives the energy released by the fire front per unit of time and of length.

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- R ROS m/s [0.001 to 10 m/s]
- Q Calorific power J/kg [17 to 23 MJ/kg for wood]
- M^*_c Effective fuel load kg/m² [0.3 to 6 kg/m²].

It is easy to see that the ROS is the parameter that varies more and therefore has a major role in determining the order of magnitude of the FLI. The effective fuel load is a fraction of the total fuel load that actually takes part in the propagation phase. If the vegetation is very fine and dry the value of this fraction will be closer to one.

The FLI is associated to the length of the flames and to the capacity of suppressing the fire according to the available means. From this table we can recognize that in the current state of the art in fire suppression technology, we cannot expect to attack directly a fire with an intensity greater than 10MW/m.

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Fire suppression perspective

- It must be realized that there are physical limits to the capacity of extinguishing a forest fire.
- Depending on the resources available the thresholds of fire line intensity that can be addressed by direct attack can change.

Year	I (kW/m)	Available Resources
1900	<350	Hand tools
1930	<1700	Water and fire trucks
1960	<3500	Light aerial means
2000	<10000	Heavy aerial means

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2 – Fire Behaviour
a. Types and Modes of FB

- I would like to present here a quick background on fundamental aspects of fire behaviour, in order to propose a set a of definitions and to introduce the terminology that I use currently in my work. You will notice that some of the concepts and definitions may not coincide with the concepts that are used in some works.
- In this lecture I assume that you are familiar with the main chemical and physical processes associated to FB so in the benefit of time I will not go deeper in most of them.
- Let us look at the classification of **types of FB**.

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a 1. Types of fire spread

- According to the level or layer of the fuel bed that is supporting the spread of a fire we can consider the following ***types of fire spread***:
- Ground fires – those that spread, usually with non-flaming combustion, under the surface of the soil, consuming the organic material that exists in the duff or in the peat layers.
- Surface fires – those that spread, usually with a flaming fire front, consuming the fuels that are above the ground, like litter, grass, shrubs and small trees.
- Crown fires – those that spread consuming the foliage of the tree crowns, usually with the support of the surface fire below the canopies and propagating from one tree to another.
- Spot fires – those that spread by burning particles or embers, released by some of the previous types of fire, that are carried out by the atmospheric or fire induced wind, when landing on burnable material may start new ignitions.

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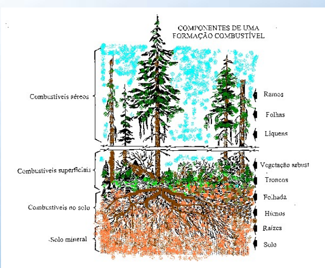
- Spot fires
- Crown fires
- Surface fires
- Ground fires



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a2. Modes of fire behaviour

- This lecture deals mostly with surface fires that exist in practically all fires and correspond to a large majority of the burned area in the World.
- In surface fires we can distinguish the following ***modes of fire behaviour***:
  - **Marginal Fire behaviour**
  - **Static Fire Behaviour**
  - **Dynamic Fire Behaviour**

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1. **Marginal Behaviour** - It corresponds to the situations of an initiating fire or to a fire in the extinction phase, when the fire may or may not go.

- It occurs when ignition or spreading conditions are not good, for example because the fuels have a large moisture content or are very sparsely distributed in space.
- This mode is important to analyze the efficiency of extinction agents like water or retardants, and to the eventual process of rekindling.
- The fire suppression requirements (minimum amount of water or a fire retardant to suppress a fire) fall in this type of fire behaviour.
- Some fuel treatment techniques (modifying the fuel bed compactness or the creation of fire breaks) also fall in this type of fire behaviour.

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- The conditions required for a prescribed fire to ignite and run demand for a specific research.
- The conditions for rekindling of a nominally extinct fire correspond to Marginal FB.
- Peat fires that burn with smoldering combustion – without flame – can be considered in this mode of Marginal FB.

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2. Static Behaviour – It corresponds to fire spread regime in which the properties of propagation are assumed to be constant in the course of time. If the boundary conditions do not change during a period of time the fire spread properties, namely the ROS, remain constant.

In this case the usual procedure of estimating average properties of fire spread in a given period of time is acceptable, as they correspond to the actual values of that property in the entire period.

In this approach we assume that the fire behaviour depends on the three common factors described below (topography, vegetation, and meteorology) or more common mode of fire behaviour.

As we shall see this mode of fire behaviour is very particular and it occurs only in very restricted conditions. In spite of that this is the usual or more common mode of fire behaviour that is considered in the majority of studies.

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3. Dynamic Behaviour – In the general case the interaction of the fire with its surrounding environment, modifies the fire spread properties in the course of time, even if the boundary conditions (topography, vegetation, and meteorology) remain constant or uniform.

The description of fire properties involves explicitly the variable time and the process of taking average values of the fire spread properties may not be valid.

This mode of fire behaviour is actually the one that occurs in the large majority of situations and it is particularly relevant in large fires and in the analysis of accidents.

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b. Factors affecting fire spread

- A well-known concept in wildfire science and practice is the so called "triangle of fire factors" that include the three sets of factors that affect fire ignition, spread and extinction:
  - (1) Topography;
  - (2) Meteorology and
  - (3) Vegetation.
- These three sets of factors are not independent, as for example topography may affect vegetation type and growth and modify the wind field near the ground, but for the sake of our analysis we shall assume that we can consider their role separately from each other.

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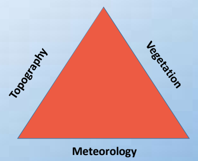
- In the analysis of Static FB it is usual to consider that the factors that affect FB form the so called "Triangle of Fire Factors":



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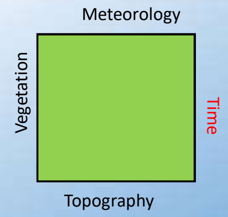
The square of fire factors



Topography

It is well known that topography has a very important role in fire spread. From the various parameters that we can use to describe and define the shape of the terrain we shall retain the two following:

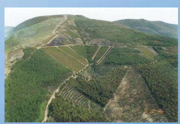
- **Terrain slope** – that we can measured by the maximum angle inclination (αº) or slope of the terrain in relation to the horizontal reference; it can also be expressed as a percentage of the value of tg (α).
- **Terrain curvature** – that is characterized by the radius of curvature of the terrain as it can be either convex (the center of curvature is below the ground) or concave (the radius of curvature is above the ground). A case of particular interest of concave ground is the canyon given its relevance for EFB and fire safety. This parameter is often overlooked in the literature.

We shall retain two parameters in particular:

- Slope

Characterized by slope angle αº

- Curvature or concavity



Vegetation

For us all vegetation is a potential fuel and it is characterized by a wide set of parameters which are usually standardized in the classical fuel models to predict surface fire behaviour. The surface layer fuel bed can be characterized, among other by the following parameters:

- H_f Fuel depth (m)
- M_c Fuels load (kg/m²)
- β Compactness (-)
- x,y,z Composition of the fuel bed in species, dead and live fuels, size classes
- σ Equivalent surface to volume ratio (m^{-1})
- m_f Equivalent fuel moisture content (%).

Among these parameters the fuel moisture content plays a very important role, so we will mention it frequently.

- In the analysis of fire dynamics a very relevant parameter is the Residence time t_o of the flaming combustion in the fuelbed.
- We assume that all these parameters are known and fixed in a given area. If the fuel bed properties change from one place to another we assume that fire spread properties will change and adapt to the new situation after a relatively short period of transition.

Meteorology

We can divide the set of meteorological parameters in two groups:

The conditioning parameters - that influence the availability of fuel and its moisture content; these are the following:

- Precipitation or ground moisture
- Solar exposure
- Air temperature
- Relative humidity m_a

<u>The determining parameters</u> – that influence directly the spread of the fire; these are:

- Wind velocity, direction and gustiness;
- Vertical stability of the atmosphere.

In the present study we shall assume that the fuel bed properties are defined and therefore we shall retain only the wind velocity and direction as a factor to affect fire spread.

Atmospheric winds and fire induced winds

- When we speak it is important to distinguish between the atmospheric or ambient wind, U_o, that would exist in the absence of fire, and the fire induced wind, U_f.
- The local wind at the fire will be:

$$\vec{U} = \vec{U}_o + \vec{U}_f$$

- Sometimes U_f may be much superior than U_o.

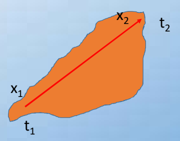
Summary of fire factors

- In summary we consider initially the following simplified set of parameters that affect fire spread:
  - Terrain slope a and curvature γ
  - Fuel moisture content m_f
  - Wind velocity U (m/s).

c. Static Fire Behaviour

- As defined above in the "static fire behaviour mode" we consider that during a period of time between t_1 and t_2, for which we wish to estimate the propagation of the fire, all the boundary conditions and the fire spread properties remain invariable in the course of time.
- Therefore, we can take average values of the ROS and of the other fire spread properties. This is the domain of Rothermel 1972 model and of all fire simulation tools that are derived from it.

- If we consider that the properties of fire spread, namely its Rate of Spread – ***ROS*** – do not change in the course of time, we have a Static Fire Behaviour.
- We take average values of the spread properties and time is not considered explicitly in the problem.



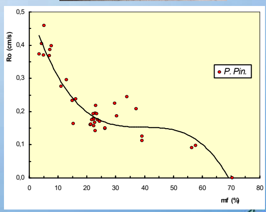
$$R = \frac{x_2 - x_1}{t_2 - t_1}$$

Basic ROS

- A characteristic property of a fuel bed is its rate of spread in the absence of slope or wind. We designate this ROS of a linear fire in the case of α=0 and U=0 as the <u>Basic ROS</u>, R_o.
- The case of zero slope and zero wind is relatively rare in fire behaviour but it must be noted that the ROS of backfires (against the wind or slope) and flank fires is very close to R_o.

Role of moisture content

- Laboratory experiments for the evaluation of the basic ROS for dead needles of *Pinus pinaster* provided the results that are illustrated in the following figure.
- As we can see for high values of m_f we may not even have fire spread, while for low values the ROS increases with decreasing values of m_f. The same behaviour is found for all the fuels that we studied.



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Local ROS

- According to the Rothermel Model the local ROS at a given point of the fire front is given by the local properties of the determining factors.

$$R = f(\sigma, \alpha, U).R_o = (1 + \phi_s + \phi_w).R_o$$

- The function *f* depends on:
  - Meteorology (Wind)
  - Topography (Slope)
  - Fuel properties (σ, β, m_f, ...)

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Non-dimensional ROS

- We define the non-dimensional ROS R' by:

$$R' = \frac{R}{R_o}$$

- The non-dimensional ROS is useful in modelling and when we perform experiments with similar fuel beds that have small variations of R_o – due to moisture content variations – as for the same boundary conditions (a and U), the value of R' will remain fixed.

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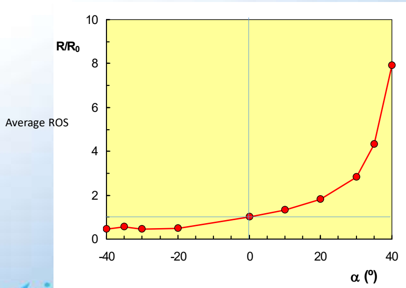
Effect of Terrain Slope on the Average ROS



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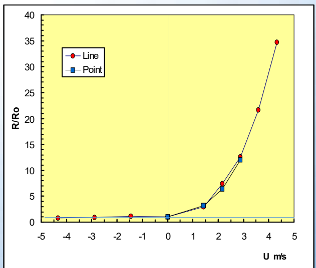
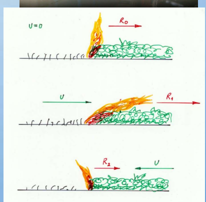
Effect of Wind Velocity on the Average ROS





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Joint role of wind and slope

- It is assumed that slope and wind affect ROS independently and usually a vectorial sum is considered:

$$\vec{R} = \vec{R}_w + \vec{R}_s$$

- According to Rothermel model and in many fire simulators it is assumed that a point ignition fire spread as a simple or a double ellipse with its axis defined by the relative magnitude of slope of wind velocity. The Huygens principle of wave propagation is invoked to formulate mathematical models of fire perimeter growth. A previous study by Viegas mm showed that the problem is much more complex than this.

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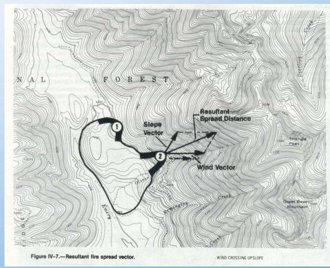
- Rothermel's Model of 1972 which is the basis of many fire behaviour simulators provides empirical formulations for *f* for a wide range of fuel bed properties as a function of positive wind or positive slope.
- This model has many restrictions which are not considered in many applications.
- It is assumed that either wind or slope gradient vectors are aligned with the ROS.
- It assumes that the ROS depends only on the local conditions and properties and does not take into account the interaction between the fire and the environment.

Non-aligned wind or slope

- Additive effect postulated of the wind and slope factors.

Fire behaviour prediction

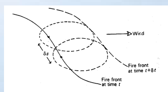
Prediction of the global Evolution of the fire front

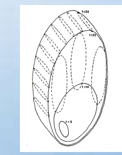


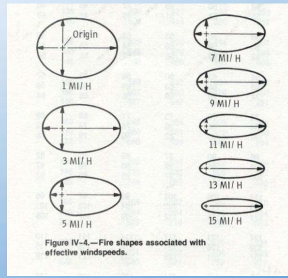
Rothermel (1983)

Elliptical Growth hypothesis

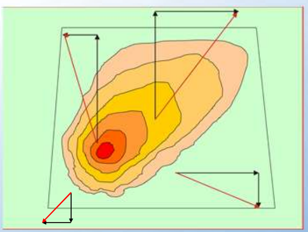
Some models assume that the fire starting from a point grows as an ellipse







- Joint effect of slope and wind

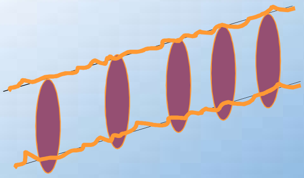


Viegas DX, 2004. Slope and Wind Effects on Fire Spread. Int. J. Wildland Fire. 13:143-156.

Lack of meaning of Local ROS

- As was said above, Rothermel model assumes that the ROS at a given point of the fire can be estimated by the local and instantaneous properties of the relevant set of basic parameters. This is not correct as the properties of the fire are influenced by the its overall conditions and specially with what happens in its immediate vicinity.
- This can be illustrated by the very simple but common case of a non-horizontal linear fire in a slope. According to the Rothermel model all points of this line should have the same ROS and the line would travel remaining parallel to itself. In Viegas mm it was shown that this is not case and that the fire line rotates at the same time that it translates. The rotational movement is induced by the transport of heat from the lower part of the fire line to its upper parts which modify the ROS at adjacent points in a process that evolves with time.

The application of Huyghens principle is in error!



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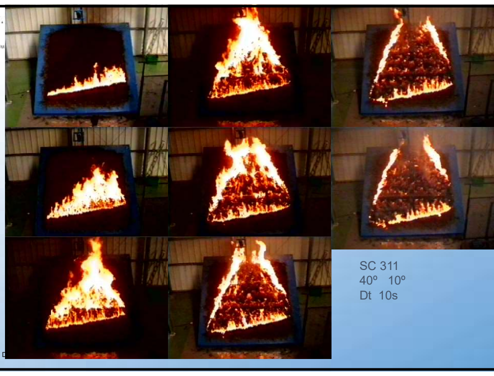

d. Dynamic Fire Behaviour

- We must realize that a fire is a place where important convective processes occur due to the very high temperatures associated to the combustion process. Interaction between these convective flows and the surrounding ambient modify the spread conditions of the fire, even if the remaining conditions remain constant. In Viegas, 2004, it was shown that in the general case the ROS depends explicitly on time. This is why we consider that time is a factor of FB.
- What the fire is doing now may be very different from what it will do in a few minutes.

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- The previous case is already an example of dynamic fire behaviour in the sense that a fire line spreading in permanent conditions without the change of the external conditions modifies continuously is spread properties. But let us look at some more fundamental cases of fire spread to identify that interaction between the fire and its surroundings also modifies the spread properties in the course of time.
- Let us consider a point ignition fire in a slope under the controlled conditions of a laboratory for different values of the slope angle α. The results of figure show that the instantaneous value of the ROS is not constant, it oscillates but tends to increase in the course of the experiment. If we take an average value of the ROS this will correspond to a test made in a given table. Possibly if the table was longer, we would obtain a higher value of the ROS and this explains the discrepancy that we find among results from different sources.

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Instantaneous and average ROS

- In FB analysis it is common to consider only average values of the ROS.
- The fire behaves in a variable form and important errors can be made if we only consider average values.

Viegas DX, 2004. On the existence of a steady state regime for slope and wind driven fires. Int. J. Wildland Fire. 13:101-117.

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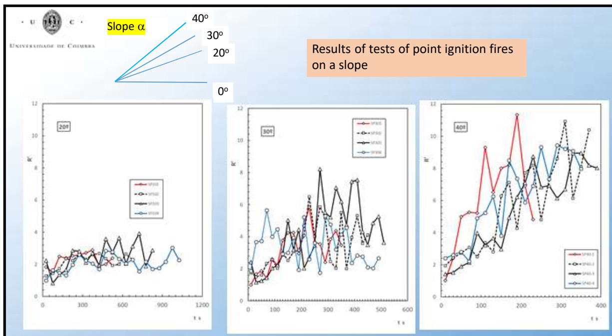
Results of tests of point ignition fires on a slope



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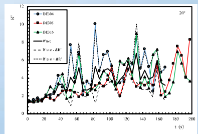
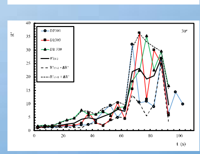
- This effect is even more pronounced in tests with canyons, in which we have a very large difference between the ROS values at the beginning and at the end of the test. In this case a mean or average value of the ROS will be a very poor representation of the fire properties; it may provide an accurate estimate of the time of arrival of the fire from the bottom of the canyon to its top but will not indicate its accelerating behaviour with all its implications for fire safety.

α=20º
δ=30º

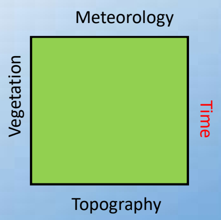


α=30º
δ=30º



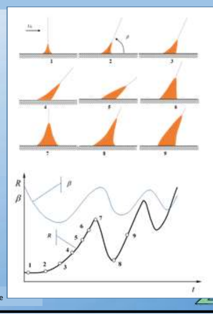
The square of fire factors

- For the above reasons we proposed that the widely considered of "triangle of fire factors" is replaced by the concept of "square of fire factors" to describe the main physical parameters that affect fire spread.
- We may of course add other dimensions to the problem, including the role of human intervention that can modify drastically the development of a fire, but this component is out of the Physical factors.

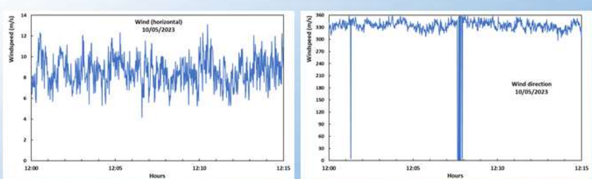


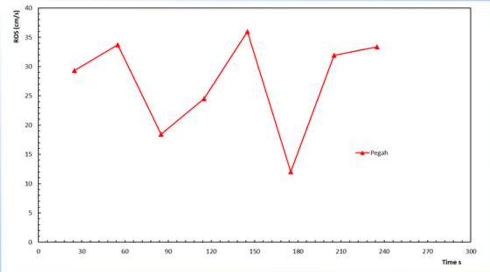
e. Intermittent or oscillatory fire behaviour

- In Viegas et al, 2021 it was shown that the behaviour of a fire is oscillatory and intermittent, in the sense that its ROS may increase but then the convective flow induced by the fire counteracts the acceleration tendency and decreases the ROS value; if the boundary conditions remain the same the fire will undergo another cycle of ROS increase and decrease as it is observed in various carefully documented laboratory and field experiments and in real fires as well.



Viegas DX, et al., 2021. On the non-monotonic Behavior of Fire Spread, Int. J. Wildland Fire. https://doi.org/10.1071/WF21016.





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- In Viegas et al. (2022), we studied the amplitude and frequency of oscillations of the ROS in the course of time for a set of fires ranging from small scale laboratory tests to field experiments and large-scale real fires, covering four orders of magnitude of the average ROS. We found that the amplitude of the oscillations of the ROS – given by the difference between the maximum and the minimum value of the ROS in a given cycle - for a given set of fires is proportional to its average value – given by the arithmetic mean of the minimum and maximum values.

Viegas DX, et al., 2022. On the intermittent nature of forest fire spread-Part 2, Int. J. Wildland Fire. https://doi.org/10.1071/WF21098.

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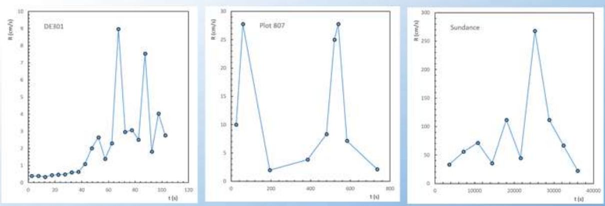

Lab Test | Field experiment | Sundance Fire

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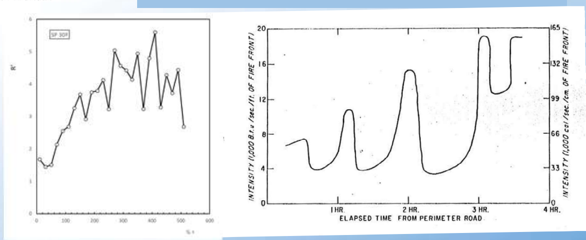
Oscillatory behaviour of fire



Lab. experiment (Slope 30º) | Bomb Range Fire

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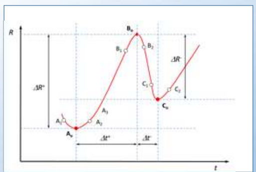
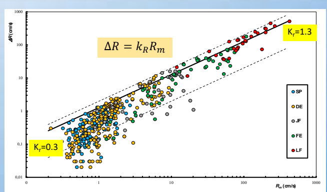
R(t) during fire evolution in two semi-periods



$$R_m = \frac{R_1 + R_2}{2}$$

Amplitude of fluctuations of the ROS as a function of the average value of R_m for all cases



Laboratory | Field | Real Fires

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- The analysis of these data for large fires shows that the amplitude of oscillation of the ROS may be so large that the maximum value of the ROS can be four or five times larger than the minimum value. This fact explains the intrinsic difficulty in predicting the ROS of large fires without considering the convective effects induced by the fire.
- This analysis also shows that the corresponding oscillations for laboratory and for field experiments are much smaller both in absolute and in relative terms therefore we cannot expect to predict the behaviour of large fires based on the results of laboratory and field experiments, which is the case of Rothermel model.
- This was probably the reason why in his report Rothermel, 1991, when attempting to use his model to predict the average ROS of some very large fires, he had to use a multiplying factor of 3.34 to adjust the results.

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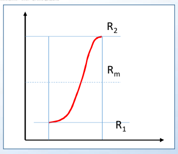

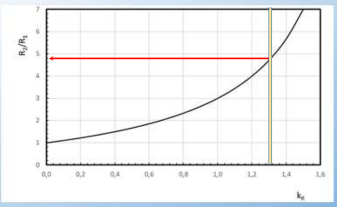

$$\Delta R = k_R R_m = k_R \frac{R_1 + R_2}{2}$$

$$\frac{R_2}{R_1} = \frac{2 + k_R}{2 - k_R}$$

$$k_R = 1.3 \rightarrow \frac{R_2}{R_1} \approx 5$$

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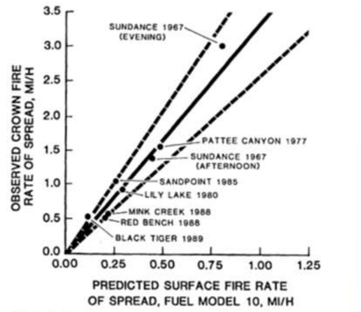

Figure 4—Correlation between observed crown fire spread rates of wind-driven fires and predictions with the fire spread model using fuel model 10.

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The spread rate data in table 1b were correlated with predictions of the surface fire spread model developed by Rothermel (1972), adjusted by Albini (1976), and packaged in the BEHAVE fire behavior prediction and fuel modeling system by Andrews (1986). Fuel model 10, timber litter and understory (Anderson 1982), was used to represent the surface fuels in all cases. The correlation is shown in figure 4. The average rate of spread for the crown fires listed in table 1 was 3.34 times faster than predicted for surface fire, with a standard deviation of 0.59. Figure 4 also shows the 75 percent confidence interval for predicting the observed value. Although there are fewer data on maximum spread rate, for five wind-driven fires spread rate was 1.7 times faster than average, with a standard deviation of 0.28.

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Frequency of oscillations

- The analysis of the frequency of fluctuations indicates that it can change also by orders of magnitude from relatively high values 0.05Hz (T=20s) for small scale laboratory experiments, to 0.005Hz (T=200s≈3min) for field scale experimental fires and 0.0001Hz (T=10000s≈2.7hours) or less for large fires.
- For each type of fires the frequency of the fluctuations seems to increase with the average value of the ROS.

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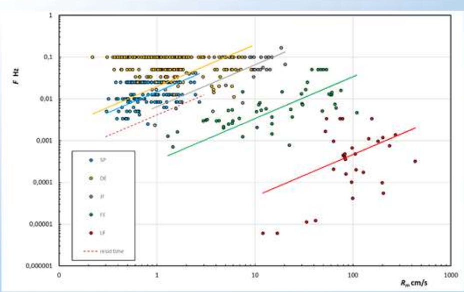

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- The concepts of "convective fire", "topographic fire" or "wind induced fire" as "types of fires" are erroneous, as wind and topography may be always present as well as convection.

(Mount Carmel, 2010)

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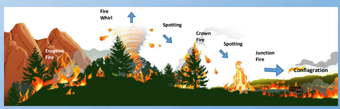
3. Extreme Fire Behaviour

a. Manifestations of EFB

We can identify several modes or manifestations of EFB. Without being exhaustive we list the following examples of manifestations of EFB:

- Conflagrations
- Eruptive fires
- Junction Fires
- Crown fires
- Spot fires
- Fire whirls
- Horizontal vortices.

We shall study some of them briefly.



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b. Conflagrations

- Conflagrations are those fires that occur under strong meteorological wind conditions lasting for relatively long time – hours or days – in large areas, leading to widespread of fire propagation with high values of the ROS and other manifestations of EFB like crown fires, spot fires and other, even on relatively flat ground.
- The fires that occurred in Portugal on the 15th October of 2017 were an example of a conflagration. In this day there were more than 400 fire ignitions and from these we had nine major fires that burned a total of more than 200kHa and caused the death of 52 persons.

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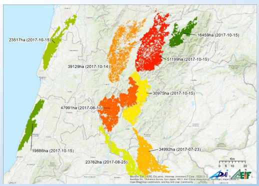
Fires of 15 de October 2017 in Portugal



Vieira de Leiria

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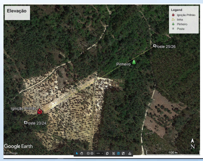
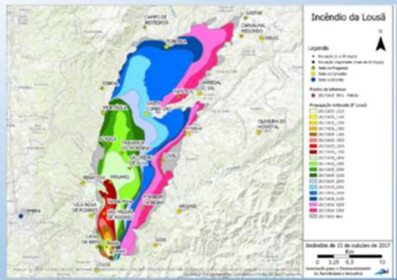
The fire of Lousã on the 15th October

Started near Prilhão near a 15 kV electric line managed by EDP.



54407 ha
15 Vitimas



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c. Eruptive fires

- It is a type of behaviour that is associated to a very high acceleration of the fire, which can be assimilated to an eruption. The destructive power of these eruptions is very high and it can surprise the people. The majority of accidents in fires are associated to this type of FB. This type of behaviour is very much linked to canyons and to steep slopes but the physical processes that are involved happen even in much normal situations.
- This type of EFB was studied systematically for the first time by Viegas and Pita, 2002 who found that this behaviour was associated to the fire induced flow which is enhanced by the concave shape of the terrain of a canyon. In the laboratory experiments we used a canyon table composed by two inclinable plane surfaces. The shape of the canyon was determined by the slope angles d of the two faces of combustion table and the overall angle α of its base.

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Eruptive Processes in Nature

Vulcanos

Mount Saint Helens

Wildfires

Thirtymile, 10 July 2001

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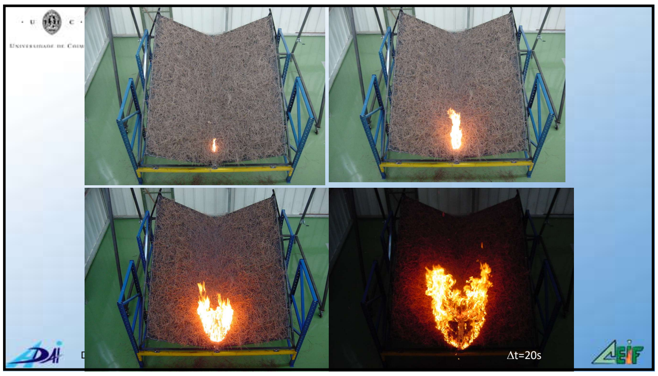

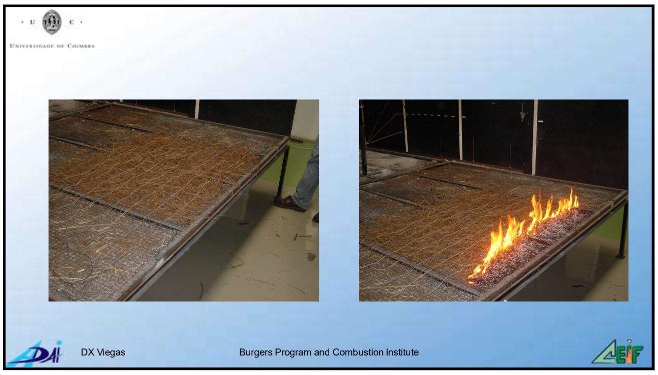

- In Viegas et al, 2005 a semi-empirical model to describe the increase of the ROS in the course of time was proposed. This model assumes that for a given value of the local wind velocity there is a single instantaneous value of the ROS; a second assumption is that the presence of the combustion modifies the local wind field inducing an increase of the local wind. The increase of local wind velocity produces an increase of the ROS in a feedback process.
- This mechanism is illustrated in the figure in which the increase of the flame length and the corresponding increase of the ROS during a short period of time.

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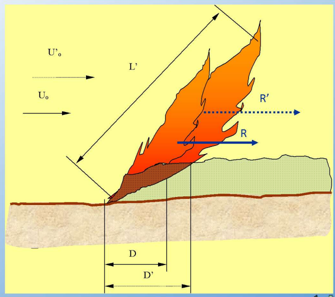
Horizontal fuelbed with wind



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- The rate of variation of the ROS is given by the following differential equation:

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

- All the parameters in this equation can be determined from experiments and depend on the fuel bed properties, namely on its time of residence t_o which is a measure of the inertia of the combustion processes in a given fuel bed and therefore to the changes of the spread properties in that fuel bed. In the table we can see some typical values of the residence time for some common fuels.
- According to this equation we see that whenever R'≠1 we will have a non-zero derivative of the ROS and therefore a change of the ROS in the course of time.

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Differential equation of the eruptive fire (non-dimensional form):

$$\frac{dR'}{dt'} = a'_1{}^{\frac{1}{b_1}}a'_2 b_1(R'-1)^{1-\frac{1}{b_1}}R'^{b_2}$$

$$R' = \frac{R}{R_o} \qquad t' = \frac{t}{t_o}$$

R_o is the basic ROS (No Slope and No wind)
t_o is the residence time of the flame in the fuel

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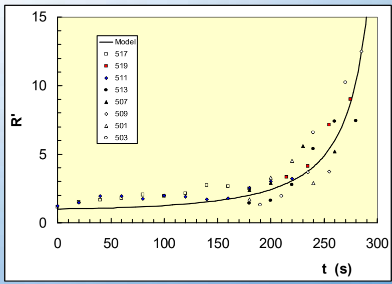
In this figure we can see a numerical solution of the differential equation for the case of pine needles, in comparison with experimental results.



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- In the following figures we can see tests with two different fuels, straw and pine needles. The processes are very similar but everything happens faster with the straw fuel bed because the residence time is smaller.

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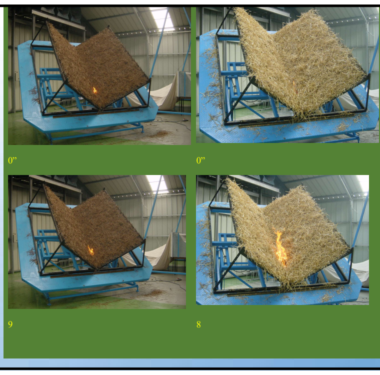

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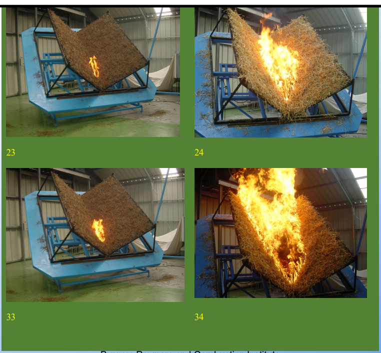

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- In 2001 we performed a fire experiment in a canyon with a length of the order of 120m.
- After the ignition it took around 20 or 22 minutes for the fire to "blow-up". In the following ten minutes the remaining two thirds of the canyon were burned with great intensity.

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Field experimente 2001

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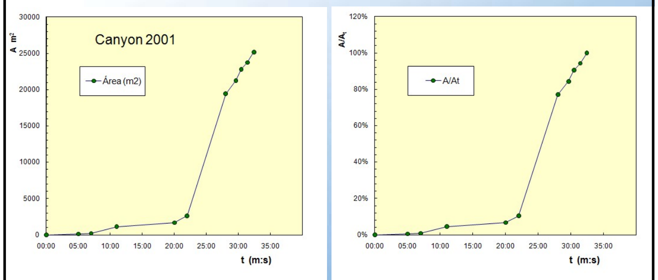

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- Evaluating the parameters of the model for each fuel we can obtain the curves that are shown in the figure for herbaceous, litter and shrub vegetation.
- In the figure we can see that herbaceous fuels have a very low residence time and therefore the eruptive process may start in less than one minute; for litter composed by foliage like dead pine needles the eruption will occur in few minutes; for shrub vegetation which is common the field the time for eruption is of the order of 20 to 30 minutes.
- These curves were computed starting with the initial condition of R'=1.1 for t=0, which correspond to a certain terrain or canyon configuration with very low values of d and a. In a steeper canyon or slope the initial value of R' can be much higher and therefore the time left for the eruption may be much less.

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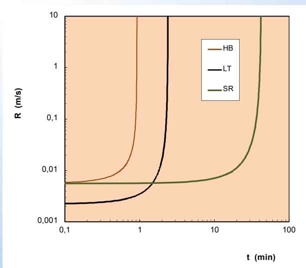

HB	Herbaceous
LT	Litter
SR	Shrub

Viegas DX, 2006. Parametric Study of an Eruptive Fire Behaviour Model. Int. J. Wildland Fire. 15(2):169-177.

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Case study

- We could present dozens of cases of fire eruption in canyons, most of them associated to accidents with multiple fatalities.
- I will mention the case of Freixo de Espada à Cinta that occurred in Portugal on the 5th of August of 2005, causing the death of two persons.

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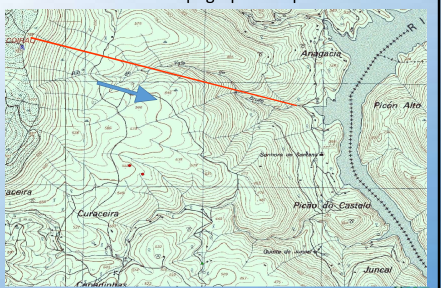
Accident of Freixo de Espada à Cinta

- 5 August 2003
- 2 victims

Topographic Map



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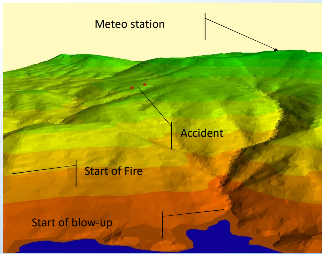

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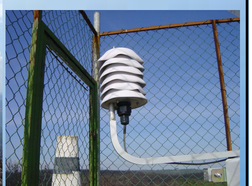
Meteo Station



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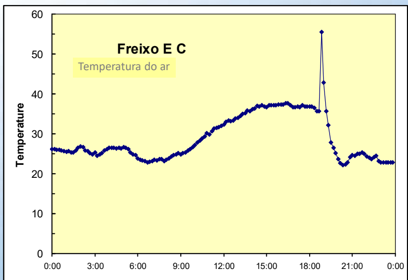

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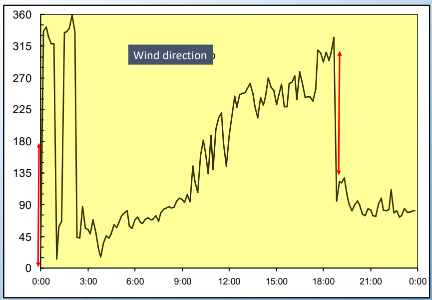

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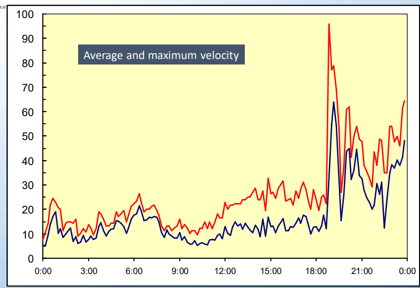

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- This case is reported in Viegas, 2005 and it deserves a remark here. When I submitted this paper to the CST Journal it was criticized by one of the Reviewers arguing that my model was based in small scale laboratory experiments which had very little relationship with the reality. This was said in spite of the fact that I had mentioned the field experiment that had a much larger scale in comparison to the laboratory experiments.
- When I received the reply from the Reviewers I had the data from this accident and included it in my reply and revision. The article was immediately accepted.

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3.2 Junction Fires

- The merging of two fire fronts involves very important convective processes.

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Motivation

- This process of EFB occurs when two fires with their fire lines making a relatively small angle between them, merge. In the photos we can see a field experiment in which two fire fronts merge in an inclined plot.
- The problem was first raised to me when I was studying the fire that occurred in the vicinity of Canberra on the 18th January 2003, by invitation of the New South Wales Government. There were two large fires started some days before, one was the McIntyre that had started in the NSW territory, and the other was the Bendora fire that had started in the Canberra Capital State Territory. Both fires were not controlled when on the early afternoon of the 18th a strong wind from West pushed both fires towards Canberra causing great destruction and four deaths. In the fire a third fire appeared between the other two with the shape of a tongue. This fire spread very rapidly (27km/h) and very violent convective processes (tornadoes) were observed in the area where it spread.

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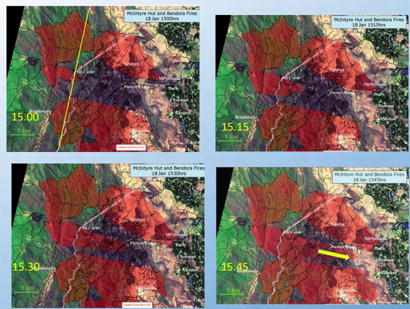
- Evolution of McIntyres Hut and Bendora fires on the 18th January between 15.00h and 15.45h.
- The ROS observed in this fire (27 km/h) is still one of the highest registered in FF in the entire World.

Plates from Cheney (2004).



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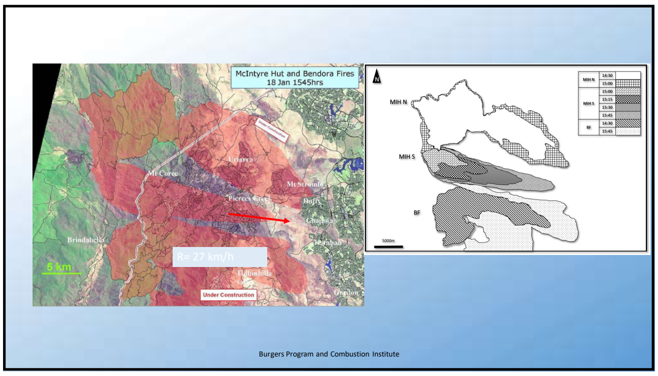

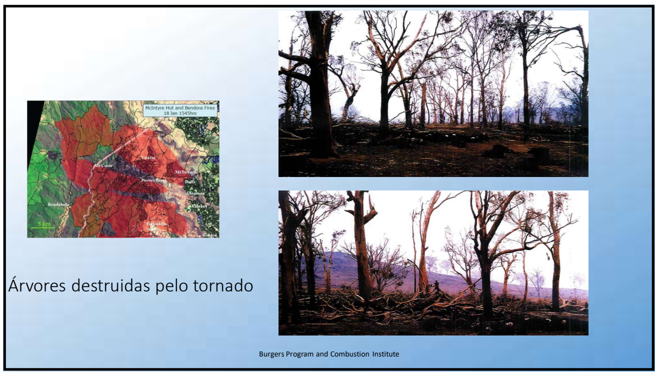

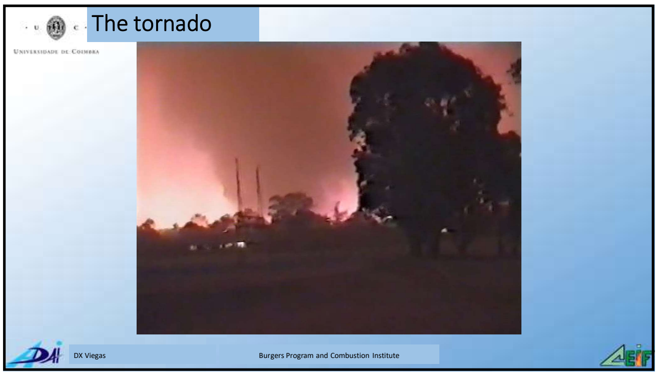

- In the Fire Laboratory we created a set of experiments attempting to mimic this case and rapidly we realized that the configuration of two lines making a small angle between them produced a fire spread similar to what was observed in Canberra.
- We performed also field experiments to check the scale effects of the problem. The experiments were very similar and very strong convective processes including the formation of fire whirls were observed.

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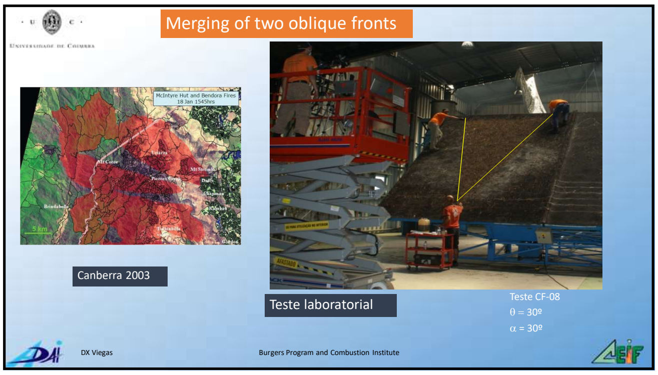

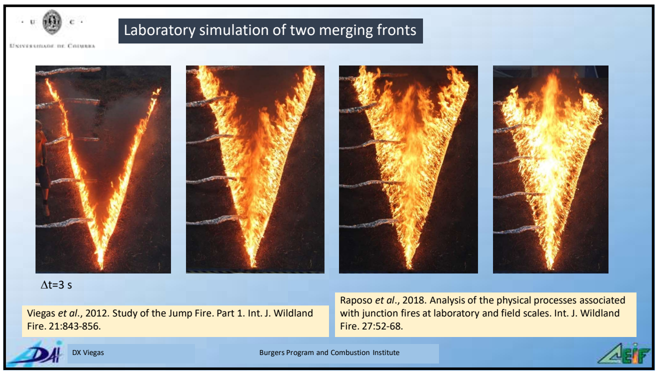

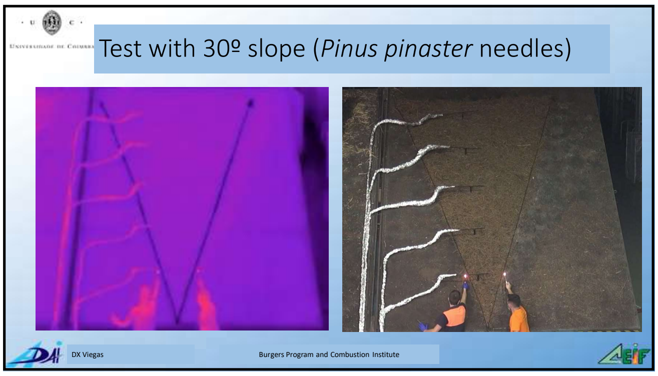
Test with 30º slope (Pinus pinaster needles)
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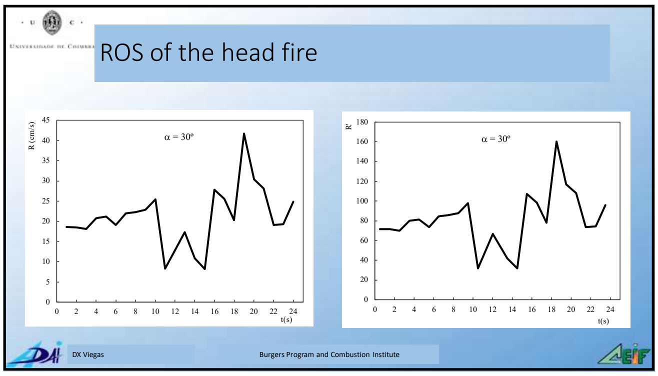
ROS of the head fire
R (cm/s)
α = 30º
t(s)
R'
α = 30º
t(s)
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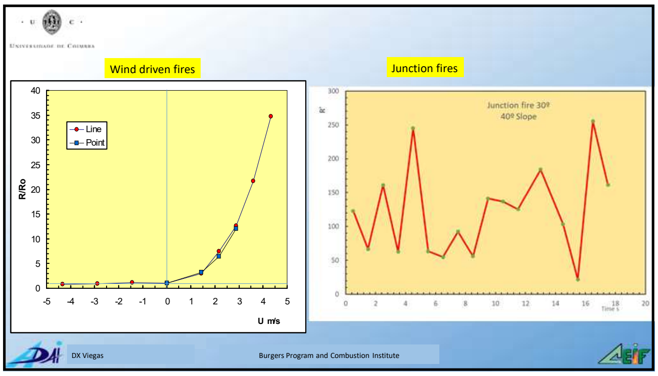
Wind driven fires
Junction fires
Line
Point
R/Ro
U m/s
Junction fire 30º
40º Slope
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Gestosa 2011
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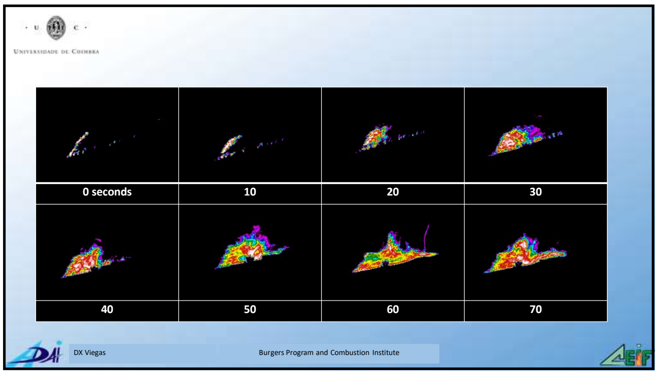
0 seconds
10
20
30
40
50
60
70
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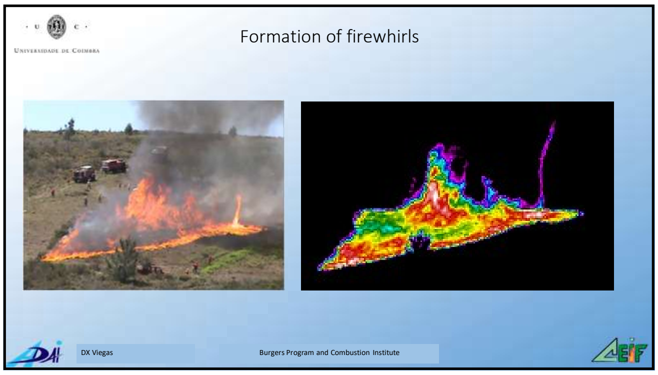
Formation of firewhirls
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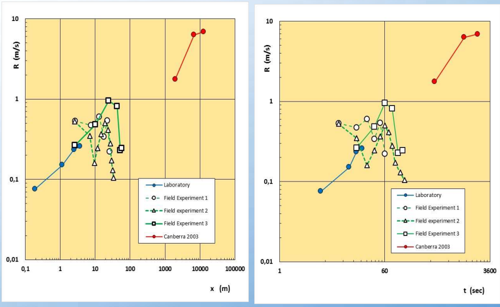
The ROS of the Junction fires for the laboratory and field experiments and the Canberra fires are shown in the figure.



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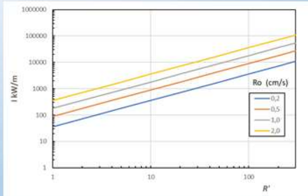
$$I = R.Q.M_c$$

$R = R' \times R_o$

$M_c = 1kg/m^2$



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Case study

- The fire of Pedrógão Grande that occurred on the 17th June 2017 in Portugal and caused 66 fatalities was actually an example of a junction fire. This large fire was started by two separate ignitions caused by an electrical line (15kV). These two fires were not suppressed on time due to the lack of resources.
- After 18.00h an overhead thunderstorm modified the behaviour of both fires that became impossible to stop and started to spread without control.
- After 19.30h due to their proximity they started to merge producing the very important convective processes associated to fire merging.

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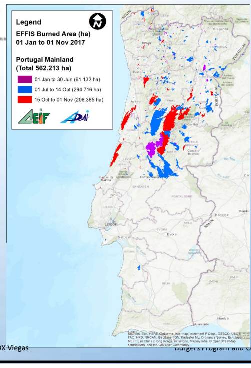

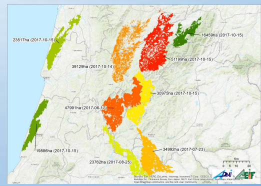

The nine major fires of 2017

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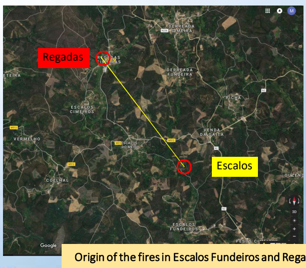
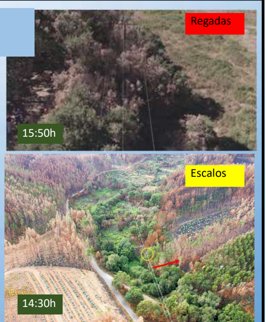
The fire of Pedrógão Grande
16 de junho de 2017





Origin of the fires in Escalos Fundeiros and Regadas

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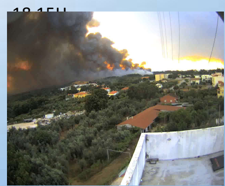
Interação com a trovoada



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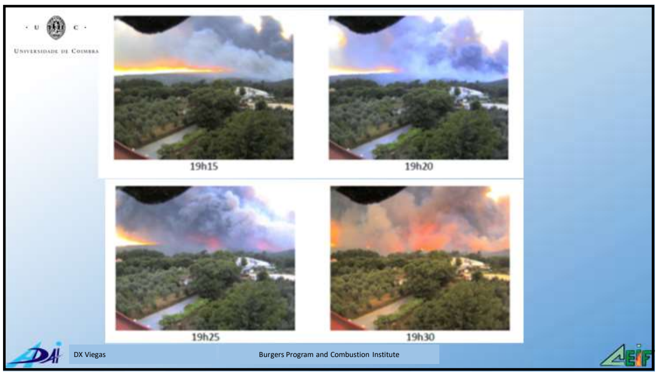
19h15
19h20
19h25
19h30
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19h35
19h40
19h45
20h00
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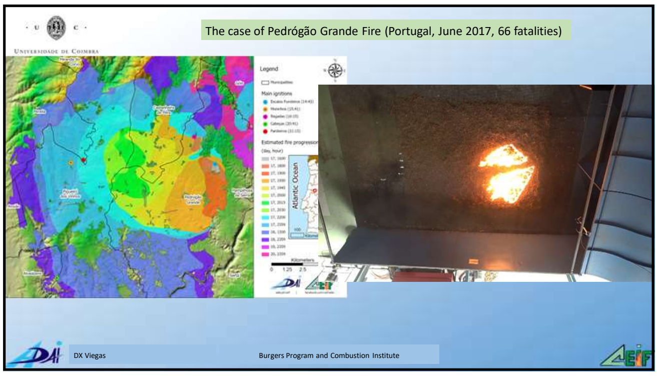
The case of Pedrógão Grande Fire (Portugal, June 2017, 66 fatalities)
Legend
Atlantic Ocean
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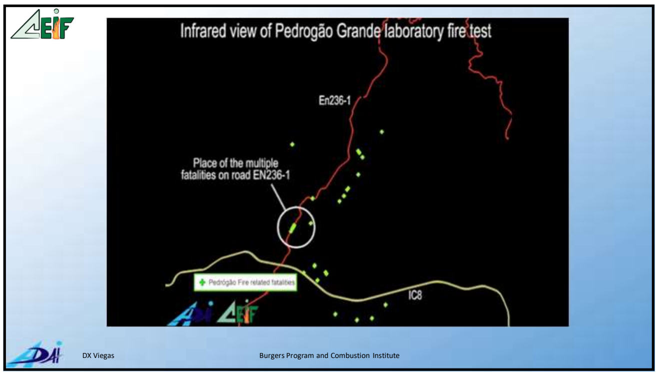
Infrared view of Pedrogão Grande laboratory fire test
En236-1
Place of the multiple fatalities on road EN236-1
Pedrógão Fire related fatalities
IC8
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S.JOÃO
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Troço da EN 236-1

18 de junho

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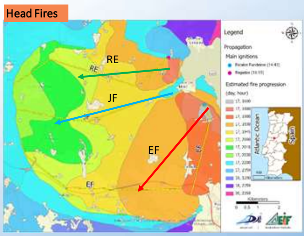
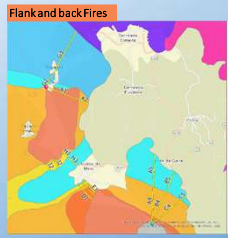
Pedrogão Grande Fire - Results and discussion

Head Fires



Flank and back Fires



R_{or}=5.37 cm/s

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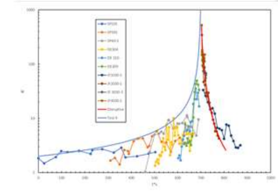
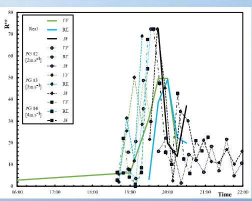
Acceleration and deceleration of the head fire

Joint analysis of the acceleration and the deceleration of the fire

$$\frac{dR'}{dt'} = a'^{\frac{1}{b_1}}_1 b_1 a'_2 (R' - 1)^{1-\frac{1}{b_1}} R'^{b_2}$$



Laboratory experiments



Fire of Pedrógão Grande

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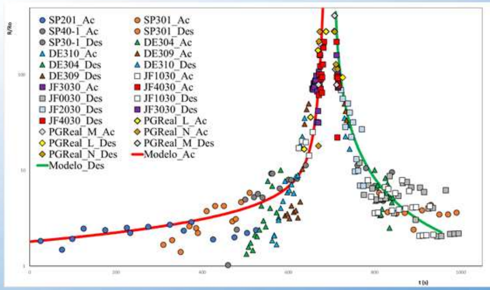
Mathematical model of acceleration and deceleration



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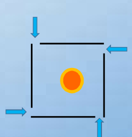
e. Fire whirls

- Fire whirls are very dangerous processes and not well studied yet. As they burn vegetation very efficiently they release large amounts of energy per unit of time. They can produce spot fires at unexpected places and as they move randomly they can burn nearby vegetation and cause great destruction.



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f. Horizontal vortices

- Near the ridges of hills wind flow may separate and create flow conditions for the formation of horizontal axis vortices that promote the lateral growth of the fire.
- In collaboration with Australian colleagues we are studying a phenomenon that although observed in some fires is still poorly studied.
- It is the lateral growth of a fire near the ridge of a hill in the presence of wind.
- This growth is induced by the flow separation associated to the strong vorticity that is created.

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Horizontal Vortices

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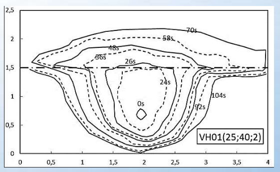

Sa Costa, Sardenha

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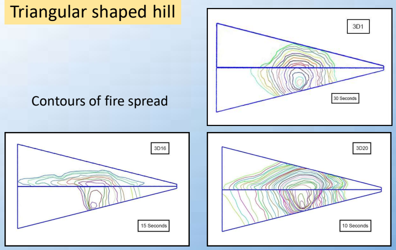
Triangular shaped hill

Contours of fire spread



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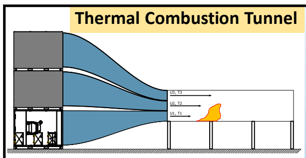
Thermal Combustion Tunnel



- Three layers of air flow with independently controled values of velocity and temperature.
- Stable, neutral and unstable vertical profiles.

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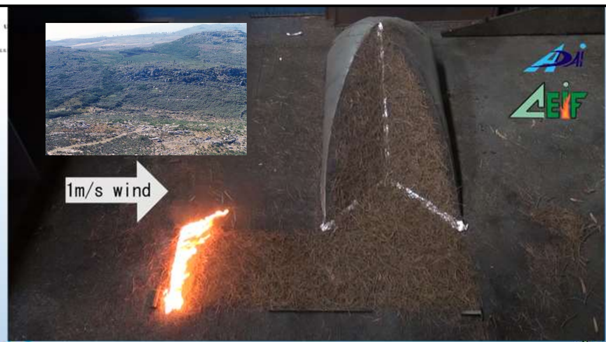

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Yarnell Mountain June 2013

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18 victims

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4 - Conclusion

- The study of fire behaviour is central to understand all processes associated to wildfires.
- The behaviour of a fire is dynamic due to the interaction between the hot gases produced by the fire and the environment.
- Recent studies of our Team show that the fire behaviour is oscillatory, which induces a prediction error that is proportional to the average ROS.
- Sometimes the fire may assume conditions of Extreme Fire Behaviour, which are the most challenging for those who have to manage and investigate wildfires.

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- Extreme Fire Behaviour is not synonymous of very large fires. EFB may occur even in relatively small fires, but it is more likely to occur in very large fires.
- Accidents and large fires involve usually EFB processes, some of which are not yet well studied.
- With scientific research we have to improve our knowledge on these processes.

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2002

2018

Alvoco das Várzeas

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