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**Euro-Mediterranean Wildland Fire Laboratory,
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in the Euro-Mediterranean Region**

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**Behaviour Modelling of Wildland Fires:
a State of the Art**

**Dominique MORVAN, Michel LARINI, Jean Luc DUPUY,
Paulo FERNANDES, Ana Isabel MIRANDA, Jorge ANDRE
Olivier SERO-GUILLAUME, Didier CALOGINE, Pedro CUIÑAS**

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SUMMARY

In this document, the authors summarise the two main approaches for modelling the behaviour of wildland fire classically followed by the scientific community.

Concerning the empirical modelling, the authors analyse the models developed in Australia since the 1960's in the different type of ecosystems concerned by wildland fire: mainly grassland and eucalypt stands, and, more recently in moorlands and shrublands.

Then analyse also the models developed in Canada related to the Canadian Forest Fire Rating System in constant evolution since the 1920's.

The authors pay attention to the required input data of these empirical models and the empirical functional relationships established between parameters like damping effect of the moisture content, wind and slope effects on wildland fire dynamic, or flame length and height and wildland fire intensity.

Afterwards, they analyse the empirical approach for modelling the wildland fire behaviour in Europe, in fact in the Euro-Mediterranean countries.

They add considerations about research priorities in the domain of the empirical approach in relation with the current state of the art.

Concerning the physical modelling, the authors compare the different physical models, which take into account one or several processes of energy transfer from the burning zone to the unburned fuel.

None of the reviewed models takes into account basic phenomena explaining the wildland fire behaviour.

The authors describe largely the detailed physical and multiphase approach, indicating the nature of the equations, which are solved.

Before developing some future prospects, they analyse the interest of approximate models.

The third part of the document is dedicated to a complete review of the smoke dispersion models used world-wide.

The authors classify them in three groups: research models, planning models and screening models.

They underline the interest of fire assessment systems and expert systems in this domain.

At the end of each part, the authors provide a very large list of bibliographical references concerning the items developed in the three chapters of the document.

GLOSSARY

None

LIST OF ASSOCIATED DOCUMENTS

None

1 EMPIRICAL MODELLING OF WILDLAND FIRE BEHAVIOUR: A SHORT REVIEW

1.1 INTRODUCTION

Reviews of fire behaviour models (BEER 1991a; BURROWS 1994; PERRY 1998; DUPUY 1999; ANDRÉ and VIEGAS 2001; WEBER 2001; PASTOR et al. 2003) usually recognize three categories, respectively empirical (or statistical), semi-empirical (semi-physical or laboratory models), and physical (theoretical or analytical).

The physical modelling of fire behaviour seeks mathematical solutions for the complex mechanisms involved in fire propagation.

A theoretical formulation capable of a direct, practical, and truly predictive response to the entire fire behaviour variability that can naturally occur is quite distant (ALEXANDER et al. 1998), and will depend on the nature of its inputs (can they be readily acquired in the real world?) as well as on the availability of powerful computing resources.

Consequently, fire modelling for operational applications is currently restricted to semi-empirical or empirical models.

Empirical fire behaviour models are based on data collected in experimental fires or in well documented wildfires or prescribed fires.

Although containing an element of uncertainty, the former are frequently used to expand the range of environmental conditions and fire characteristics.

Empirical models are built by correlating the observed fire characteristics with easily measured variables which describe the so-called fire environment (fuel, weather and slope).

The process is guided by observational evidences and statistical criteria, but the functional relationships employed in contemporary models try to be consistent with theoretical knowledge.

Empirical models should not be extrapolated beyond the data range used for their development, but this basic rule is seldom respected: it is better to use a (probably) poor model than no model at all.

This is not the sole weakness of empirical models, as environmental factors cannot be controlled in the field.

As a result, natural or circumstantial correlation between variables can hide their true effects and complicate the detection and quantification of relationships with the dependent variable, e.g. CHENEY et al. (1993).

Last but not least, various practical, economical and legal matters strongly restrain the number and size of field trials and the range of experimental burning conditions which are acceptable, which poses constraints on the performance of the resulting models.

E.g., despite its long tradition of experimental wildland fires, it was only by the end of the 1990's that a vast and well-funded research program focused on high-intensity crown fires was undertaken in Australia.

Some of the advantages of empirical fire models are readily apparent, namely:

- the absence of artificiality and scale problems (present in the lab experiments associated to physically-based models), and
- the integration of numerous factors which operate in the real world, such as wind and moisture profiles (impossible to reproduce in the lab) and fuel heterogeneity.

This is probably why an empirical model developed for a given vegetation type usually performs better than ROTHERMEL's semi-physical model (LINDENMUTH and DAVIS 1973; MARSDEN-SMEDLEY and CATCHPOLE 1995; FERNANDES 1998; VEGA et al. 1998; BURROWS 1999; HÉLY et al. 2001).

Therefore, an empirical model can be viewed as a fast (and intrinsically incomplete) answer to a specific problem of fire behaviour prediction.

The future will hopefully bring more fundamental solutions but, for the time being, the most apparent benefit of a physical approach to fire modelling is its contribution to understand fire propagation mechanisms, therefore helping the experimental design and interpretation of field trials (BURROWS 1994).

1.2 EMPIRICAL FIRE BEHAVIOUR MODELLING IN AUSTRALIA AND CANADA

1.2.1 Australian models

Fire behaviour research in Australia is pragmatic: the objective is to derive relationships which are consistent with management necessities (fire danger rating and accurate prediction of prescribed fire behaviour, essentially) and are immediately usable, based in easily acquirable variables.

The existing diversity of climates and vegetation types has led to a variety of regional models (BURROWS 1994), which classically have been provided to end users in the form of circular meters (e.g. MCARTHUR 1967) or sequenced tables and graphs (e.g. SNEEUWJAGT and PEET 1985).

The fire behaviour relationships underlying the first generation of fire behaviour guides were the product of experimental fires lit by point ignition in specific fuel types and mild fire weather, with additional data collected in wildfires in order to make the predictions more respondent to severe conditions (CHENEY 1981; BURROWS 1994).

Fire spread in grassland (MCARTHUR 1966) and dry eucalypt forest (MCARTHUR 1962, 1967) in south-eastern Australia was predicted from dead fuel moisture content and wind speed, and then adjusted for slope.

Forest situations considered also the fine fuel load and fuel availability (MCARTHUR 1962) or a drought factor (MCARTHUR 1967).

The importance of other fuel characteristics, namely the fuel bed compactness and particle size has been recognised, but their effects were disregarded, probably due to difficulties in obtaining exact measurements and the high field variability or simply because their effects were not quantifiable (CHENEY 1981; TOLHURST and CHENEY 1999).

The Forest Fire Behaviour Tables (FFBT) (SNEEUWJAGT and PEET 1985) were developed in the south-west of Australia by similar methods.

The *Red Book*, as its is often called, applies to 11 fuel complexes one of two models, respectively for dry eucalypt forest of *Eucalyptus marginata* with sparse and low understorey, and for humid eucalypt forest of *Eucalyptus diversicolor* with dense and tall understorey.

A basic spread rate is calculated from dead fuel moisture content and wind speed for a standard fuel type, and subsequently is adjusted for the amount of available fuel and terrain slope.

The above-mentioned predictive schemes are currently available as equations, which were fit to the original tables, graphs and meters by NOBLE et al. (1980), GOULD (1993), BECK (1995) and GRIFFITHS (1999) to facilitate calculation and comparison between systems.

Given their solid data background, these models perform well when applied to the situations for which they were developed (CHENEY 1981), but the agreement between observations and predictions is usually deficient outside the original range (UNDERWOOD et al. 1985; TOLHURST and CHATTO 1998; BURROWS et al. 2000).

The models for eucalypt forest tend to underestimate the rate of spread of fires initiated by a line, especially when wind is stronger and shrubs are taller (GOULD et al. 2001).

According to BURROWS (1994), the explanation lies not just in the original range of data but also in the methodology used to establish the relationships: some were inferred rather than derived directly, and there's a lack of descriptive and statistic information concerning the process of model development.

Fire management requirements are increasingly demanding and, consequently, more accurate and exact fire behaviour predictions are required.

A second generation of Australian fire models appeared in the 1990's, carefully examining the existing assumptions, enlarging the spatial scale and the meteorological range of experimental conditions, and based on sophisticated statistical analysis.

Some previously ignored influences were experimentally addressed, such as the effect of the ignition line length (CHENEY and GOULD 1995).

CHENEY et al. (1992) and BUCKLEY (1993) presented equations for eucalypt stands with an important shrub component.

CHENEY et al. (1993, 1998) qualitatively individualised two pasture types and introduced considerable modifications in the wind speed function, which has resulted in a new meter for grassland (CSIRO 1997).

The model of BURROWS (1999) for SW Australia eucalypt forest is much simpler than the cumbersome *Red Book* and, in the same forest environment, the VESTA project has expanded the weather conditions of experimentation to extreme fire danger levels, as well as examining in detail the polemic effects of fuel load, age and structure on spread rate (GOULD et al. 2001).

Fire behaviour models are now available for other Australian environments, namely discontinuous vegetation types in arid (BURROWS et al. 1991) and semi-arid (MCCAW 1991, 1998) regions, buttongrass moorland (MARDEN-SMEDLEY and CATCHPOLE 1995) and shrublands (CATCHPOLE et al. 1998).

1.2.2 Canadian models

The Canadian Forest Fire Behaviour Prediction System (FBP) is part of the Canadian Forest Fire Danger Rating System, whose concept has continuously evolved during the 1920's – 1990's period.

The system estimates fire behaviour as a function of indexes belonging to the FWI (Fire Weather Index) sub-system.

So, and contrarily to the Australian approach, there are no direct functional relationships between the descriptors of fire behaviour and the fire environment.

The FWI sub-system has temperature, relative humidity, precipitation and wind speed as inputs, variables which allow the calculation of six components (VAN WAGNER 1987; STOCKS et al. 1989):

- Fuel moisture content indexes: Fine Fuel Moisture Code (FFMC), Duff Moisture Code (DMC) and Drought Code (DC);
- Fire behaviour indexes: Initial Spread Index (ISI), Buildup Index (BUI) and Fire Weather Index (FWI), respectively representing rate of fire spread, available fuel, and fireline intensity.

The FBP sub-system includes 89 equations, derived statistically (but with some theoretical background) from the analysis of an extensive quantitative data base of experimental fires and wildfires (Forestry Canada Fire Danger Group 1992).

Data from wildfires (e.g. Stocks 1988) is more general and less reliable, but is important as it represents extreme events.

Fire behaviour predictions (which include crown fire propagation) are provided for 16 specific fuel types but, differently to other empirical models, structural variation within a vegetation type is not accounted for.

The ISI is the basic input for rate of spread estimation on each fuel type, followed by corrections for the BUI and terrain slope.

The FWI sub-system is increasingly being used in fire danger rating in several countries.

Because of its structure the FBP system allows adaptation to fuel types outside Canada, e.g. FOGARTY et al. (1998).

The FBP data base was analysed by CRUZ et al. (2002) in order to derive a model for the rate of spread of crown fires in conifer forest.

The independent variables in the equation are wind speed, canopy bulk density and dead fuel moisture content.

1.2.3 Input data and functional relationships

A particular type of models tries to describe the conditions under which an ignition succeeds, i.e. the environmental thresholds for sustained fire propagation.

This is because the moisture of extinction (ROTHERMEL 1972) in a given fuel type is not constant, and is affected by wind speed and the characteristics of the fuel complex.

The most common modelling approach is logistic regression, whose outcome is a probability of fire sustainability (LAWSON et al. 1994; MARSDEN-SMEDLEY et al. 2001).

Crown fire initiation models also rely on logistic models, with wind speed, fuel strata gap, surface fuel consumption class and dead fuel moisture content as independent variables (CRUZ et al. 2002) or, alternatively (CRUZ et al. 2003), with wind speed, crown base height and combinations of indexes from the FWI as predictors.

Models for fire spread typically combine in a multiplicative way functions for the individual effects of wind speed, fuel moisture and a fuel complex descriptor, with a subsequent correction for slope.

Wind speed measured or estimated at heights of 10m in open terrain is required for fire spread prediction by the Canadian system and a few other models (MCARTHUR 1966, 1967; CHENEY et al. 1998).

The remaining empirical models use surface wind speed, at the height of 1-2 m.

Wind speeds from weather forecasts (6 or 10 m height) can be converted to surface wind speed according to a logarithmic profile (ALBINI and BAUGHMAN 1979) or with specific simple equations (SNEEUWJAGT and PEET 1985; CHENEY et al. 1992; GOULD 1993; MARSDEN-SMEDLEY et al. 1999).

Most wind functions describe the wind influence on rate of spread by power or exponential curves.

The difference is unimportant (BEER 1991b), except at high wind velocities, where the option for an exponential equation tends to produce unrealistic high predictions, e.g. BURROWS (1999).

In the FBP system the wind component of the ISI is exponential, but rate of fire spread has an upper limit, usually based in wildfire data.

Few empirical functions are available to describe the effect of slope terrain in fire propagation (MCARTHUR 1962; VAN WAGNER 1977; CHENEY et al. 1992), possibly because experiments in flat terrain are prevalent.

All are exponential and provide similar results.

The available information for shrubland suggests a weaker effect of slope on rate of spread (GREEN 1981; CATCHPOLE et al. 1999).

The damping effect of dead fuel moisture on fire spread takes the form of an exponential function in most models (e.g. CHENEY et al. 1993; MARSDEN-SMEDLEY and CATCHPOLE 1995; MCCAW 1998; BURROWS 1999) which is well supported by theory and combustion experiments in controlled environments, but some Australian equations assume a linear effect.

It is difficult to quantify, under field conditions, the effect of fuel characteristics on fire spread, and nearly impossible to distinguish between the influences of different descriptors without manipulation of the fuel complex.

The dominant role of wind, slope and moisture, and natural heterogeneity and correlation between fuel properties are the main reasons for this problem.

Inputs concerning the physical properties of the fuel complex generally resort to variables with an apparent important variation within a fuel type and easily assessed at the management level.

Rate of spread increases linearly with available fuel quantity in the FBP system (Forestry Canada Fire Danger Group 1992) as well as in the eastern Australia models for eucalypt forest (MCARTHUR 1962, 1967; CHENEY 1978).

Other models use fuel age (MARSDEN-SMEDLEY and CATCHPOLE 1995), vegetation height (CHENEY et al. 1992; CATCHPOLE et al. 1998), a fuel factor calculated from vegetation cover and patchiness (BURROWS et al. 1991), or a qualitative indicator of compactness (CHENEY et al. 1993).

Models for flame length or height and fire intensity are equally important, because these variables are directly related with fire suppression difficulty and fire effects.

BYRAM (1959) was the first to estimate flame length from a power function in fireline intensity, which by definition is the product of rate of spread, fuel available for flaming combustion and fuel heat content.

Various equations fit the model for different fuel types.

In Australia, flame height is generally preferred to flame length, and is predicted from fireline intensity (MARSDEN-SMEDLEY and CATCHPOLE 1995) or from the combination of rate of spread and fuel load in various linear and non-linear forms (NOBLE et al. 1980; CHENEY et al. 1992; GOULD 1993; BURROWS 1999).

1.3 EMPIRICAL FIRE BEHAVIOUR MODELLING IN EUROPE

1.3.1 The different models

The first attempt at an empirical fire behaviour model in Europe comes from TRABAUD (1979), who presents an equation for the spread rate of fires in *Quercus coccifera* garigue.

However, few models have been developed up to now, due to the rarity of field experiments, the widespread use of ROTHERMEL's model in management applications, and the focus by several research teams on physically-based models.

The statistical analysis of fire behaviour in Europe comprehends two types of equations based on field data, respectively simple descriptions of fire propagation (e.g. SZCZYGIEL 1988; PEREZ and VALETTE 1995; CARREGA and NAPOLI 1998), and models whose functional relationships are supported by physical reasoning whenever possible.

Within-fire analysis of the spatial and temporal variation of fire behaviour in response to wind and fuel variation has been examined by FERNANDES et al. (2000) in shrubland and FERNANDES et al. (*in press*) in a *Pinus pinaster* stand.

This type of studies can give insights on the development of empirical models, provide detailed data to test existing models, and is useful to analyse specific phenomena, e.g. the transition from surface to crown fire.

The main motivation for empirical fire behaviour modelling in Europe is, as in other regions of the world, to acquire a straightforward capacity of predicting fire behaviour, with input variables easily measured by fire managers, and using equations which reflect real-world conditions and produce reliable estimates within the environmental range of experimentation.

The overwhelming majority of the experiments has been conducted from Autumn to Spring, which means the application of the resulting models should be restricted to predict fire behaviour in the low to moderate range, namely in the prescribed burning decision-making process.

Models for shrubland fire behaviour in gorse and heath communities of NW Spain are presented in VEGA et al. (1998, 2001), including a slope effect and covering a relatively wide range in fire behaviour.

A small data base from four shrubland types in Portugal has allowed the development of an interim fire spread model for no-slope conditions (FERNANDES 2001).

Finally, the most extensive experimentation was conducted in *Pinus pinaster* stands in northern Portugal, and has produced equations to predict the likelihood of sustained fire propagation and the characteristics of surface fires in fuel types dominated by litter, grass-ferns or a low shrub strata (FERNANDES 2002; FERNANDES et al. 2002).

The slope effect included in the headfire rate of spread model is similar to Australian models.

The fuel complex in these models is described by vegetation height or cover for the purpose of rate of spread estimation, or by fine fuel load, when the objective is the prediction of flame length / fireline intensity.

Current work includes the analysis of a joint data base with shrubland fires from Spain, Portugal, Australia and New Zealand, which has already allowed the detection of a live fuel moisture content influence on rate of spread; such a report is exceedingly scarce in the literature.

1.3.2 Considerations about research priorities

The current state of the art of empirical fire behaviour modelling suggests some strategies and priorities for the future research activities.

1.3.2.1 To reinforce the connection

To reinforce the connection between empirical and physical approaches to fire behaviour prediction arises as the first urgent need.

The partial findings obtained by each method could orientate the research effort in the complementary procedure.

We need to have in mind that our aim is to have models which can be applied to real situations and be useful to the fire-decision makers.

The interaction between both methodological approaches could accelerate fire propagation modelling, testing and validation processes

1.3.2.2 To conduct experimental fires

To conduct experimental fires under a wide range of conditions.

Up to date most of the field experiments have been carried out in spring, winter and autumn, in mild weather conditions.

This constraints the applicability of the empirical models to fire season.

It is necessary to expand the range of the meteorological variables to reflect typical summer meteorological scenarios.

At the same time, the range of certain variables like live fuel moisture needs to be also enlarged.

It is necessary to explore different combinations of environmental variables (fuel, topography and weather) to avoid co-linearity between variables, a common problem in the empirical approach.

1.3.2.3 To determine the effect of slope terrain

To determine the effect of slope terrain in fire propagation and its interaction with wind, to obtain the maximum fire propagation direction and the rate of spread for any given direction.

The influence of slope on fire propagation has been taken account by a few empirical models, but most of field research has been conducted on flat terrain.

Moreover, the interaction between wind and slope, a relevant factor in fire propagation, is still poorly understood.

It is necessary and effort to determine the combined effect of both variables on fire behaviour.

1.3.2.4 To identify new fuel descriptors

To identify new fuel descriptors with a relevant influence in fire behaviour and reflecting natural fuels heterogeneity.

Surprisingly, fuel variables explain a low percentage of variability in fire rate of spread in the current empirical models.

Furthermore, sometimes, dummy variables has to be used to reflect the influence of unknown characteristics of fuel types.

Fuel inventory and physical fuel particles properties assessment is an expensive and time-consuming task.

Consequently there is a challenge to find new fuel variables describing fuel particle array influence and the natural heterogeneity effects on fire behaviour variability.

1.3.2.5 To develop empirical models

To develop empirical models for fire behaviour prediction under different ignition techniques used in prescribed fire.

The available empirical models have been conceived to predict fire propagation in a quasi-steady state with fuels burning freely under natural conditions.

This limits its applicability to prescribed burning operations where the ignition techniques are a factor of a relevant influence on fire behaviour.

In fact, ignition pattern tries to avoid that fire develops a stationary state in equilibrium with environmental conditions.

Models taking account of the effect of ignition techniques can be very useful to refine fire prescription to achieve different management objectives.

1.3.2.6 To implement empirical model

To develop empirical models to predict fire behaviour in manipulated fuels.

Fuel treatments are commonly used in wild land areas for a great variety of purposes (fuel breaks, silviculture activities, wildlife habitat improvement, fuel accumulation reduction, etc.).

These actions result in a mosaic of fuel complexes with different characteristics.

These situations are not considered in the existing empirical models. It is necessary to develop new models, which take account of these fuel conditions, and to enable to simulate the potential effect of those fuel treatments on fire hazard.

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2 PHYSICAL MODELLING OF WILDLAND FIRE BEHAVIOUR: A SHORT REVIEW

2.1 INTRODUCTION

Forest fire spread models are usually classified into two types (PITTS 1991):

- Stochastic models consisting to predict the more probable fire behaviour from average conditions and accumulating acknowledges obtained from laboratory and outdoor experimental fires,
- Deterministic models (Semi-empirical and physical) in which the fire behaviour is deduced from the resolution of the physical conservation laws (mass, energy, momentum...) governing the evolution of the system formed by the flame and its environment,

The main purpose of these models is to predict the local rate of spread of a fire front, when parameters characterising the condition of spread (vegetation, meteorology, terrain) are given.

It is reminded that stochastic models are only based on the observation of field fires (experimental fires and wildfires) from which the fire rate of spread (ROS) is related to relevant parameters in a purely statistical way (fuel type, fuel loading, fuel moisture, wind, ...).

These empirical relations depend strongly from the very specific conditions from which the statistical study was performed. Without systematic parametric studies, it is very difficult to extract a general behaviour for the fire.

2.2 SEMI-EMPIRICAL MODELS

Semi-empirical models are based on a global energy balance (FRANSEN 1971) and on the assumption that the energy transferred to the unburned fuel is proportional to the energy released by the combustion of the fuel, several terms of the model being fitted to laboratory fire experimental results (ROTHERMEL 1972).

The simplicity of this approach has allowed to develop operational tools such as **BEHAVE**, **FARSITE**...

2.3 PHYSICAL MODELS

On the other hand, **physical models** take into account one or several process of energy transfer from the burning zone to the unburned fuel.

They describe how a part of the energy released by the fire preheats the unburned fuel, providing its own propagation.

The fire front is generally supposed to be an infinite straight line perpendicular to the direction of spread.

These models rest on a simplified representation of each of the phenomena which are taken into account.

Generally the flame is assimilated as a radiating panel at a fixed temperature (flame temperature) transferring its energy toward the vegetation by radiation.

This leads to writing one equation of energy balance for the unburned fuel in a frame attached to the flame (steady-state regime of propagation) and in one space dimension (the direction of fire spread x).

For this, these models consider a homogeneous and uniform fuel bed made of one type of particle of plant material.

The unburned fuel is separated from the burning zone by a surface where the fuel ignites.

On this surface, named ignition interface, the fuel particles have been raised to the ignition temperature, which is a given property of the fuel.

The differences between physical models are essentially due to the choice of the control volume used to establish the energy balance equation and due to the processes of energy transfer they take into account.

Most of these models calculate the energy balance in one dimension (x) and for this consider either a control volume over the whole fuel bed depth (e.g. HOTTEL *et al.* 1965) or a small control volume located at the top of the fuel bed (e.g. HOTTEL *et al.* 1965).

As for him, ALBINI (1981,1985,1986) calculates the energy balance in two space dimensions (x, z) and for this, he uses a small control volume around a point of co-ordinates (x,z) located inside the fuel bed.

In the most sophisticated models of this type, the energy transfers taken into account for preheating the unburned fuel are the radiation from embers (often calculated as radiation from the ignition interface), the radiation from the flame, the radiation from the unburned particles themselves (ALBINI 1985, 1986), and one or several terms of a convective type rendering the thermal exchange between the fuel particles and the gas (PAGNI and PETERSON 1973).

Some authors add a term of energy loss to the ambient medium, which can be of radiative or convective nature (or both).

Hence, physical models often permit a simple calculus of the fire rate of spread, however only when some properties of the embers, of the flame, of the hot gases at the vicinity of the ignition interface (...) are given as input parameters of these models.

These properties of the sources of energy directly depend on the fire itself, thus they are not parameters which only characterise the combustible medium and the environmental conditions.

It's a **weak point of this modelling approach**, which will be now called a **phenomenological approach**.

In order to better understand the difference with other approaches reviewed in the following, it is worth noting that in the previous models, the energy balance does not contain any term of energy source due to the combustion of the plant material.

This kind of term is implicitly contained into the properties of the flame, the embers or the hot gases, used to calculate the energy transfers.

There are models which are difficult to classify, but, in their principle, are similar to the models previously described.

They consist in using one equation of energy balance, generally applied to a surface (terrain surface), which is of a generic mathematical form and may include convective, diffusive and/or radiative processes.

In addition, the balance equation contains a term of energy source, which often depends on the temperature.

It describes the consumption of fuel but without any reference to a chemical reaction (global heat release).

The balance equation sometimes is one-dimensional and time dependent (CEKIRGE 1978), often two-dimensional and time dependent (x, y on a plane or ξ, η on a generalised surface representing a terrain).

The energy balance equation may be coupled with a model of atmospheric air flow (LYMBEROPOULOS *et al.* 1998).

Using these models, if the empirical coefficients that calibrate each term representing each physical process in the balance equation, are known, one can calculate the fire rate of spread and a temperature field, sometimes with the help of hard numerical methods.

Up to this point, none of the reviewed models took into account the basic phenomena which explain the behaviour of a forest fire (pyrolysis, oxygen transport, gaseous phase combustion, embers combustion).

Starting from a description of these basic phenomena comes down to no longer assuming that the properties of the flame, the embers and the hot gases are known.

In others words, the only input parameters of the model must be the initial characteristics of the medium and these properties are calculated by the model itself.

This kind of approach, which will be called a **detailed physical and multiphase approach**, is presented in the following.

2.4 DETAILED PHYSICAL AND MULTIPHASE APPROACH

Four groups of work based on a detailed physical approach of forest fire behaviour modelling have been found in the literature.

In 1997, GRISHIN reports in a book the main results of the researches carried out in Russia (and ex-USSR) on the modelling of forest fire behaviour (see also GRISHIN *et al* 2002).

Among these works, a general mathematical model of forest fire behaviour has been described at a first time in 1992.

The numerical solutions of this detailed model are not presented.

However, numerous approximate models based on this approach have been produced before this date and are described in the same book. LINN (1997) presents a PhD dissertation entitled "a transport model for prediction of wildfire behaviour", which is a first step of a wider project aiming to develop the abilities of "self-determined" models of fire propagation through forest fuels.

The practical interest of the physical approach to study wildfire behaviour was demonstrated in a paper (Hanson *et al* 2000) comparing numerical predictions obtained for historical fires using various physical formulations with those obtained with classical empirical (or semi-empirical) approach.

Finally, LARINI *et al.* (1998) (and in a more teaching form LARINI, 1998), PORTERIE *et al* (2000), MORVAN *et al* (2000,2001,2002,2003) provide the bases for the formulation of a complete model for forest fire propagation, particularly by describing how the usual equations of continuum media mechanics can be transformed following a rigorous method into equations well-suited to a multiphase medium, here a vegetation sustaining a fire.

We summarise here after the last two approaches, because only these authors completely describe how the multiphase equations for forest fire modelling are obtained.

Then, we briefly mention the main differences with the works of GRISHIN and LINN.

When a combustible medium is observed at a sufficiently small scale, a gaseous phase that surrounds solid particles of combustible vegetation can be seen.

These particles can be leaves, small twigs, needles, grasses, ...

The combustible medium is considered as a multiphase medium composed of a gaseous phase and several solid phases.

Each solid phase consists of the same fuel particles, which have the same shape, the same size, the same physical-chemical properties, thus the same behaviour with respect to a fire.

In particular, each family of particle is characterized by its Surface Area / Volume (SA/V) ratio and in order to achieve a spatial description of the medium, the fraction of space volume occupied by each family or each solid phase, at each point and each time, must be known.

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In particular, each family of particle is characterised by its surface-to-volume ratio and in order to achieve a spatial description of the medium, the fraction of space volume occupied by each family or each solid phase, at each point and each time, must be known.

In the approach of SÉRO-GUILLAUME et al, the vegetal phase is considered as a fractal medium, which can be described mathematically.

Moreover the different parts of plants are considered as a porous medium, in order to take into account the internal structure of vegetation.

Therefore this model is more complex than the preceding one, and the difference of view point leads to substantial change in the mathematical formulation.

Assuming that the medium is known, what are the mechanisms that will govern the propagation of a fire through this medium ?

Observing the medium at a very small scale, which allows distinguishing one fuel particle from surrounding gas, the behaviour of this particle is described in the case of an approaching fire.

The particle receives energy from this fire by convection and radiation.

Its temperature is then raised from the ambient temperature to the boiling water temperature, at which it loses its water.

As soon as the particle is dried, its temperature can raise again.

The plant material is decomposed step by step releasing pyrolysis gases.

The reactive part of these gases is combined with the oxygen of the air (gaseous phase chemical reactions).

The gas temperature then increases, causing its expansion and, due to buoyancy forces, the gas moves.

These movements play a very important role in the necessary transport of oxygen and also in the energy transfers.

At the end of the pyrolysis, the particle is mainly composed of chars.

Oxygen may reach the surface of the particle and react with the remaining chars.

It's the combustion of chars, which causes the regression of the particle surface.

Now the problem is to know how to describe the evolution of such a medium at the scale of a particle.

The medium is known when at each point of the gas, the velocity, the temperature, the mass fraction of chemical species and the pressure are known, and when at each point of the motionless particle, the temperature, the mass fraction of chemical species and the density are known.

At this scale, in order to calculate the state of the medium at each point of the gas, the balance equations of reactive fluid mechanics are available (mass, momentum, energy and chemical species) and at each point of the particle, a system of balance equations (mass, chemical species, energy) is available, which describes the behaviour of a solid conductive medium that can lose its water and be decomposed into pyrolysis products.

In addition, at the interface between the solid particle and the gas, some conditions must be verified (local interface conditions).

Solving all these equations at this scale can be done only in very simple geometric configurations, but cannot be done in real configurations with numerous particles distributed in a gas.

In this last case, and at this scale, it is impossible to obtain solutions of the strongly coupled balance equations at each point of the gas, each point of each particle, which in addition must verify all local interface conditions.

Thus, it's necessary to change the scale of observation, in fact, to increase this scale.

From a mathematical point of view, operating this change of scale is equivalent to average the equations established at a point of the gas or at a point of the particle over some volume around these points.

It's a usual operation for modelling multi phase multi constituents materials and several methods of averaging are available.

In both approach, balance equations for the gaseous phase and the balance equations for each solid phase have been integrated over the whole volume occupied by the gas and over the whole volume occupied by each solid phase, using a spatial weighting function (ANDERSON and JACKSON 1969).

After some mathematical transformations, a system of equations is obtained for each phase (gaseous phase and solid phases).

These equations establish the relations in time and space between the weighted average of the different variables (temperature, velocity, density,...).

It is worth noting that the averaging operation leads to the appearance of new terms in the balance equations, which are due to the interactions between the different phases (here between the gaseous phase and each solid phase).

Thus, systems of partial derivative equations are obtained that are strongly coupled through these terms of interaction.

For instance, these terms of interaction are due to the mass transfers related to the drying and pyrolysing process of the particles, to the drag forces, to the heat transfers by convection and by radiation.

A system of multiphase, reactive and radiative equations, rigorously deduced from the instantaneous point equations (generalised NAVIER-STOKES equations for the gas and point balance equations for the solid), is now available.

Before solving these equations, it is necessary to close them. The closure operation differs for both approaches.

In LARINI's approach, some assumptions are made and sub-models that describe the basic phenomena at the multiphase scale are provided.

Among these phenomena, there are of course chemical reactions and in addition, different interactions between phases, which appeared after the transformation of point equations into multiphase (i.e. averaged) equations.

In the other approach, closure is obtained by thermodynamics argument.

Let us pinpoint that the used thermodynamic is an extended one allowing the averaging on very large representative element volume R.E.V. (the concept of REV is equivalent to the notion of fluid particle).

For this, some assumptions must be made and furthermore, it is necessary to establish sub-models that describe the basic phenomena at the multiphase scale.

Among these phenomena, there are of course the chemical reactions and in addition, the different interactions between phases, which appeared after the transformation of point equations into multiphase (i.e. averaged) equations.

These systems of partial derivative equations have been yet solved in one and two space dimensions (plane symmetry and axi-symmetry) (MORVAN *et al.* 1998, PORTERIE *et al.* 1998, 2000).

These approach have been used with success to study various fire propagating through a dead fuel bed (PORTERIE *et al.* 1998, 2000) (MORVAN *et al.* 2000, 2001), a living Mediterranean shrub (MORVAN *et al.* 2002), a complex shrub/canopy Mediterranean forest, a fuel break (MORVAN *et al.* 2003) (**EFAISTOS & FIRESTAR UE programs**).

Some physical properties such as the ratio between the respective contribution of the two modes of heat transfer (radiation and convection) between the flame, the burned hot gases and the vegetation has been quantified for the two regimes of propagation of a surface fire (Plume dominated fires and Wind driven fires).

Calculating numerical solutions of these equations is hard and time consuming.

This is the reason why simplified models have been also deduced from the complete sets of equations (GIROUD 1997, DUPUY and LARINI 1999).

MARGERIT *et al.* [1997], [2002], has proposed a new approach using asymptotic analysis in order to derive or relate the detailed physical approach to 2D propagation models.

They obtained a model very similar to the so called physical model, see above.

Propagation of fire is modelled by a reaction diffusion system of partial differential equations.

This model has been coded and numerical experiments of propagation have been provided at laboratory and terrain scales.

This effort is still continuing and recent results, see SÉRO-GUILLAUME *et al.* [2002], SÉRO-GUILLAUME [2003], show the clear relation between different approach of modelling (**INFLAME & SPREAD UE program**).

2.5 APPROXIMATE MODELS

Thus, two kinds of **approximate models** are available: those of the phenomenological approach presented at the beginning of this review, and those which are directly deduced from the complete physical and multiphase approach described above.

LINN (1997) aims at simulating large scale forest fires.

For this, he introduced a sophisticated turbulence model, including the dissipation of turbulent energy due to the solid particles.

However, because of the large scale of space, he had to make strong assumptions on some of the basic mechanisms (especially the combustion process in the gaseous phase is not really described).

The approach remains very similar to the previous one (LARINI *et al.*).

In the different models proposed by GRISHIN (1997), there is only one solid phase made of different components (dry material, water, chars, ashes).

In addition, for most of these models, the solid phase is assumed to be in thermal equilibrium with the gas (one-temperature models).

Hence, this approach differs from the previous ones.

Physical and Semi-empirical approach are complementary approaches, they can be mixed to describe wildfire behaviour at large scale.

Recent studies have shown the interest to compute the local atmospheric flow using a physical approach coupled with a heat released curve representing the fire.

In this case the ROS of the curve fire is evaluated from a modified ROTHERMEL model taking into account the local conditions of propagation (state of the vegetation, wind velocity, slope...) (CLARK *et al.* 1996, HANSON *et al.* 2000).

2.6 FUTURE PROSPECTS

In terms of **future prospects**, we want to underline that every modelling approach must be accompanied by experiments.

The reverse is true, except if one chooses to follow a statistical or purely empirical approach of the phenomena.

The required **experiments** have different objectives.

First, it's necessary to **characterise the fuel**, on one hand the particles which compose the medium (morphological and physical-chemical properties), and on the other hand, the combustible medium, in other words the spatial arrangement of the particles.

One attempt has been done, CALOGINE et al. [2001], [2002] to establish models that describe the vegetation in details from parameters that should be easy to obtain on the field, this work should be pursued and improved, see report of WP 02.

Second, of course, experiments must permit the **validation** of fire behaviour models, by carrying out both laboratory and field fires.

Conversely, this kind of experiment can show phenomena which cannot be easily explained and thus make questions to the modellers arise.

This kind of experiment is yet widespread at the international level (studies of wind effect, slope effect, fuel type effect... on fire behaviour).

But, faced with the increasing requirement of varied validation data, these experiments should be encouraged.

Finally, in particular in the frame of the complete physical and multiphase approach, the closure of forest fire behaviour models requires physical **sub-models** which can be directly established only with the help of specific laboratory experiments.

In this case, the experiment must sufficiently isolate the studied physical mechanism.

Up to now, this kind of experimental work has been scarce in the forest fire modelling domain, and it's necessary to develop them.

All these experiments must be accompanied by an improvement of the **metrology**, in both laboratory and field conditions.

For instance, gas temperature measurements using thermocouple sensors have shown limits, and other physical variables are still difficult to measure (field of gas velocity, solid phase temperature, gas and particles radiation ...). it seems that optical methods should be a relevant solution to numerous arising problems.

Today, the computer resources, which are available for solving the partial derivative equations derived from the detailed physical and multiphase approach, permit the correct calculation of the physical phenomena only at the local fire scale (~100-200 m) and during a relatively short time (~10 minutes), and in addition, with still high duration of calculation.

The objective is to solve these equations in larger spatial domains, in three space dimensions, and more generally, **to change the scale of prediction**.

For this, the most obvious way is to use "super-computers" (e.g. massively parallel computers) with more and more efficient numerical methods (algorithms).

Another idea is to use **larger numerical meshes** without transgressing too much the physics of the model. this has been initiated by LINN who used PDF (Probability Density Function) for describing the source terms of equations.

This kind of work must continue, but new research ways, which would be more specific of the forest fire problem, should be investigated.

In order to change of scale of prediction, **developing approximate (simplified) models** can be also envisaged.

We remind that these models can be either phenomenological models or models directly deduced from the complete physical and multiphase approach.

Their interest is that they have a physical base and that they are easier to solve and less time consuming than complete models.

Of course, in order to achieve such models, it is necessary to often make strong hypothesis.

Thus, in order to evaluate the relevance of this hypothesis in a given studied situation, the detailed approach may be used.

2.7 CONCLUSION

In the face of the thematic diversity and the extent of the work to carry out, it is essential to group together and co-ordinate the research means, and in particular, to not forget that modelling and experimental works are closely related.

The work to carry out implies **long term researches**

For basic reasons that cannot be developed here, one can expect that researches conducted in the field of forest fire behaviour modelling bring up very relevant scientific questions and leads to producing results of a more general significance.

However, it will be necessary to reply to some of **the questions of the users of research results** as soon as possible.

For this, it seems that users and researchers should define together which applied problems must be investigated in priority and which researches are expected to provide the best solutions.

Indeed, some of these studies will directly answer to the questions of users, and on the other hand, some of them will consist in an essential step to progress toward a complete solution of the problem.

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3 WILDLAND FIRE MODELLING: A SHORT REVIEW ON SMOKE DISPERSION

3.1 INTRODUCTION

Biomass burning is a locally, regionally, and globally important biospheric phenomenon, and an important source of various environmentally significant gases and solid particulate which can produce severe degradation of air quality on a local and/or regional scale.

Its combustion products include carbon dioxide (CO₂), carbon monoxide (CO), methane (CH₄), non-methane hydrocarbons (NMHC), nitric oxide (NO), nitrous oxide (N₂O) and atmospheric particulate.

CO, CH₄, NMHC, and NO are chemically active gases that strongly influence the local/regional concentrations of the major atmospheric oxidants ozone (O₃) and the hydroxyl radical (OH).

Recent measurements suggest that biomass burning may be a significant global source of methyl bromide (LEVINE *et al.*, 1995).

Bromide leads to the chemical destruction of O₃ in the stratosphere and is about 40 times more efficient in that process than is chlorine on a molecule-for-molecule basis.

Production of aerosols is also very important, giving rise to local pollution, and affecting the radiation budget of the Earth and, hence, impacting global climate.

There is a growing awareness that smoke from wildland and prescribed fires can expose individuals and populations to hazardous air pollutants.

The fires that burned in the rain forest of Amazonia, Indonesia and Philippines in 1997 and the resulting air pollution affected the health of tens of millions of inhabitants.

The World Health Organisation (WHO) is aiming to provide health guidelines for forest fire episodic events in order to protect public health from adverse effects (SCHWELA, 1998).

In the USA the 1990 Amendments to the Clean Air Act (CAA) specify that individual States must consider smoke from wildland fires in their State Implementation Planes.

Anyone using prescribed fire must consider smoke management.

Smoke management requirements and procedures vary because of the different amounts of fuel burned, fuel type, topography, meteorology, and presence of smoke sensitive areas (http://fire.r9.fws.gov/ifcc/research/air_quality.htm).

Land managers must have a clear understanding of the regulations and processes that must be complied with to manage smoke.

They have the responsibility to do the best job possible to control and mitigate the impacts of smoke that result from their actions or treatment.

The effects of smoke on health, air quality and regional haze are very important to all land managers.

They must recognise the need to manage smoke from wildland fires using the Best Available Control Measures.

Every manager must determine the level of smoke management necessary to provide the least impact on the public, both in terms of health and visibility.

The effects of smoke on fire fighters also must be considered when managing wildland fires.

3.2 MODELS

Smoke dispersion models are becoming increasingly valuable tools in smoke management, especially for screening and planning.

The desired result of all models is the ability to estimate particle and gas concentrations that affect human health and alter visibility.

Smoke production, transport, and dispersion depend on several related features.

The combustion process that involves the chemistry, the phases, and the efficiency of combustion is of fundamental importance for estimating emissions from forest fires.

Some strategies for smoke management rely on manipulation of the amount of fuel consumed in each combustion phase because types of emissions and factors regulating their production mainly depend on the combustion phases.

In spite of the combustion process, fire emission products vary greatly with the type of fuel, the fireline intensity, the fuel moisture, wind, and temperature of the fire.

In order to estimate the emission rate of a pollutant, the following variables are needed: available fuel, the combustion rate, and the emission factor.

From the state of the art review it was possibly to verify that a considerable number of works are already developed in order to estimate forest fire emissions, namely: FOFEM (REINHARD *et al.*, 1997), CONSUME (OTTMAR *et al.*, 1993), EPM (SANDBERG and PETERSON, 1985), ERPLAN (PETERSON and OTTMAR, 1991) and FETM (SCHAFF *et al.*, 1996).

The calculation of emission production is not sufficient to estimate the effects of smoke on air quality.

Air pollution questions require estimates of the concentration of a pollutant some distance from sources of known emission characteristics, involving different phenomena.

PHURO *et al.* (1976) outline these phenomena, which affect transport and smoke dispersion.

In practice the estimation procedure can be divided in three parts, which are not necessarily independent of each other:

The rise of effluent, before it moves with the ambient air, is estimated.

The transport speed and direction of the pollutants is estimated from the known distribution of wind and direction.

The dispersion of the pollutant is calculated.

The height that the centre of the smoke plume attains is called plume rise.

During the convective lift phase of combustion, heat release by the fire causes convective lift of emissions from the fire in a definitive column.

As this heat diminishes the plume loses its columnar shape to a point where lift of emissions is almost result of vertical atmospheric mixing alone.

Plume rise, therefore, is a function of heat release rate, atmospheric stability, and transport wind speed.

PHURO *et al.* (1976), based in the work of BRIGGS, present some equations to use to calculate final plume rise. SESTAK and RIEBAU (1987) in their description of the SASEM development also describe plume rise formulas, based in BRIGGS work.

Heat release rates and emission rates for each gas species and particle size that are calculated from the source strength component go into the plume rise calculations.

To accurately model plume rise, ambient conditions of the atmosphere (temperature, wind, and humidity) and its mixing height must be known.

In what concerns the transport speed and direction of pollutants it is fundamental to know the wind field.

The majority of the revised works assumes a uniform wind field, considering a single value of wind speed and direction as input.

However, this is not a correct approach, mainly in areas of complex topography, where a large number of wildfires occur.

Some of the works, namely TSARS (SESTAK *et al.*, 1991), CALPUFF (SCIRE *et al.*, 1999), TAPAS (FOX *et al.*, 1987), NFSPUFF (HARRISON, 1996), and DISPERFIRE (MIRANDA, 1998) models, already integrate the determination of the wind field through interpolation of surface wind measurements by adjusting for conservation of mass.

The interpolation becomes more accurate as the number of input observation sites increase.

Recently some projects were developed making use of and integrating meteorological mesoscale models (MIRANDA, 1998; SPEER and Leslie, 1998; DANARD and GALBRAITH, 1990).

Mesoscale circulation can be very important because they directly affect the dispersion of smoke by causing abrupt changes in local atmospheric stability and can influence the direction in which smoke will be transported.

Once the smoke plume has reached its maximum rise height and becomes completely dominated by the local wind field, dispersion is normally calculated by the modified GAUSSIAN equation of TURNER (CHANDLER *et al.*, 1991).

Plume trajectory and dispersion is usually simulated assuming a straight-line trajectory or, for plume trajectories that vary in time and space, employing a standard LAGRANGIAN method.

Whether straight-line or LAGRANGIAN a GAUSSIAN distribution of particles and gases along the trajectory is assumed.

BEYFOGLE and FERGUSON (describe and evaluate some of the smoke dispersion models for biomass burning.

<http://fire.r9.fws.gov/ifcc/research/smokemodels.htm>)

According to the type of application, smoke dispersion models can be classified as:

- 1. Research models, which are capable of modelling many chemical compounds, concentrations, and a large radius of receptor sites and their concentrations.
- 2. Regulatory/Planning models that could be used for permit approval and would be capable of showing dispersion over large geographic areas. Offer the possibility to run various weather scenarios well in advance of the actual fire. However, because any model has been yet officially validated for biomass burning, regulatory use would be inappropriate at this time.
- 3. Screening models for field users concerned with smaller prescribed burns that would aid to visualise what fuel and weather conditions are best suited. Could be used as a planning tool prior to fire and at the time of the fire with the real-time weather data.

Several models have been adapted or specifically designed to accommodate the peculiarities of biomass burning: SASEM (SESTAK and RIEBAU, 1988), HYSPLIT (DRAXLER and HESS, 1998), TSARS (SESTAK *et al.*, 1991), CALPUFF (SCIRE *et al.*, 1999), AIRFIRE (MIRANDA, 1998), DISPERFIRE (MIRANDA, 1998), VALBOX (SESTAK *et al.*, unpublished), TAPAS (FOX *et al.*, 1987), VSMOKE-GIS (HARMS, unpublished) and NFSPUFF (HARRISON, 1996).

Despite the large number of smoke dispersion models, there are also some management systems that take into account, in a very simple way, the efficiency of the atmospheric dispersion of smoke through the use of dispersion indexes.

FFMIS (BRENNER *et al.*, 1999) is an example of this type of tools.

It is mainly a fire management system that spatially simulates the current and forecast state of the surface weather, atmospheric stability, fire danger, fire weather index and fire behaviour potential.

The Atmospheric Dispersion Index (ADI) is calculated using surface and upper air weather stations.

Annex A presents a general description of the referred models.

From the state-of-the-art review it was possible to verify that many of the developed packaged computer programs can provide information concerning smoke dispersion useful for managing or interpreting fire effects.

However, and unfortunately, modelling smoke emission, transport, and dispersion from forest fires is not a trivial task.

Although the existence of some systems already covering the main questions to be taken into account, it stills remains (excepting for the AIRFIRE system) a lack of integration concerning fire progression.

3.3 FIRE ASSESSMENT AND EXPERTS SYSTEMS

Currently, fire assessment systems are starting to be planned in order to integrate all the needed variables in a common and user-friendly tool.

The Wildland Fire Assessment System, although still under development, constitutes one integrated system planned to incorporate high resolution fuel maps; fire growth, and smoke production models; smoke dispersion and regional haze assessment (BURGAN et al., 1997).

Specialised computer programs, called "expert systems", may be available in the next few years.

Expert systems are being developed or planned that can assist in the development of fire prescriptions to meet specific resource objectives, and to achieve specific fire effects, like effects in the air.

Melanie MILLER (presents a detailed description of computer software to manage and interpret fire effects. [http://fire.r9.fws.gov/ifcc/monitor/Guide/computer software.htm](http://fire.r9.fws.gov/ifcc/monitor/Guide/computersoftware.htm))

Computer technology and applications are developing so quickly that any list of software is incomplete as soon as it is published.

Despite forest fires effects on the air quality, health and visibility, air quality and/or fire studies, with the exception of USA ones, do not take into account this source of pollutants.

This is clear from the state-of-the-art, where only four of the about twenty-one revised works proceed from outside USA, namely from Portugal, Canada and Australia.

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4 FIRE BEHAVIOUR PREDICTION: EMPIRICAL AND SEMI-EMPIRICAL)

4.1 INTRODUCTION

Before stepping to the more specific subject of this review, it is perhaps worthwhile to mention the broad synthesis of ANDRÉ *et al.* (1992) [1], covering virtually all aspects of research on the physics of forest fires, namely, mattering for /1.1-2/, /1.4-5/, /2.1-6/ and /3.1-2/.

In this review, four main criteria are used to organise the state-of-the-art of research, based, respectively, on:

- the concept of fire development phase; the concept of *fire regime*¹;
- the main aspect of the fire behaviour that is predicted; and
- the more or less applied character of the research.

Although they are used essentially in parallel, there is some cross linking among these criteria.

4.2 FIRE DEVELOPMENT PHASE

Following ANDRÉ (1996), we can distinguish eight main potential development phases in the history of a general *forest fire*, named after:

- (1) *ignition*;
- (2) *build-up*;
- (3) full development of a specific *fire regime*;
- (4) (eventual) transition of *fire regime*;
- (5) decay;
- (6) extinguishing of the flame (for a flaming fire front); (
- (7) *smouldering combustion*, till its *extinction*; and
- (8) cooling of the combustion residues to ambient temperature.

The study of *ignition* (1st phase) is relevant for /1.3-5/.

As it is a rather self-contained research area, bearing few relation with fire spread studies, we do not review it here (see, for instance, ANDRÉ *et al.* 1992 [1]).

The exceptions apply to:

- the influence of *ignition* conditions on the *build-up* phase of the *fire history* (see below);
- the concept of temperature of *ignition*, which is used by most semi-empirical fire spread models; and,
- in a less extent, the concept of *ignition* time delay, which is seldom used (for instance, in the semi-empirical fire spread model of FONS 1946).

During the *build-up* phase (2nd phase), the fire progressively loses the memory, so to say, of the *ignition* conditions, before attaining a fully developed *steady* regime.

The duration of this phase is a matter of interest for initial *dispatch* operations /1.2/ and also for the performing of fire experiments.

From a theoretical point of view, three effects that are responsible for the time variation of the *rate of spread* of the fire during this phase, have been studied, although not very deeply:

- the establishing of the fire front depth (EMMONS 1964);
- the establishing of a *steady* temperature field in the part of the fuel bed (or *fuel complex*) still non-burned, ahead of the *fire line*, in a reference frame linked to the latter (FUJII *et al.* 1980); and the effect of the *fire line* curvature characteristic of a point-ignited fire (CEKIRGE 1978, WEBER 1989).

Relevant experimental studies on this subject are: MC ARTHUR (1966), JOHANSEN (1987) and MC ALPINE (1988).

After the *build-up* phase, the fire becomes fully developed (3rd phase), being characterised by a (quasi)-*steady* behaviour which is exclusively determined by the fuel bed and ambient conditions.

¹ Terms in italic are defined in the DELFI Vocabulary.

This is, by far, the most studied phase of forest fires. Indeed, throughout the remaining sections of this review, when not mentioned otherwise, it should be understood that the works cited deal with the behaviour of fire during this phase of its history.

It is also the richest phase of the *fire history* in what concerns the diversity of possible behaviours of the fire.

In the latter regard, the concept of *fire regime* introduced in Section 3, can be envisaged as a very convenient way of subdividing the study of the fire in this phase.

Some fires pass through a fourth phase which consists in a transition of regime caused by a significant change of the fuel bed or ambient conditions.

This phase is usually rather brief due to strong non-linear effects that come into play.

Its complexity explains the relatively few research done on it.

Below, two particularly important *fire regime* transitions are mentioned: *flare up* from a *smouldering fire*, and *blow-up* of a *large crown* or *bush fire* from a less intense *surface fire*.

When the conditions of the fuel bed (p.e. high *fuel moisture* or very low *fuelbed porosity*) or the ambient (p. e. strong opposing wind) turn it difficult for the fire to spread, the fire may enter into an unstable decay phase (5th phase), in which the *rate of spread* shows a very high sensitivity to the fuel bed or ambient pertinent parameter.

Although the fire is non-*steady* in this phase of its history, for brief periods of time, it behaves in a way that is similar to a *steady fire regime* that belongs to a class of, so called, marginal *fire regimes*, the research of which is reviewed in Section 3.

The decay phase may ultimately lead to the flame *extinction* (6th phase).

The study of the fire in this phase is specially interesting associated with the use of *fire suppression* means (see /1.2/ and /1.7/, and also ANDRÉ *et al.* 1992 [1]).

Usually, the flame *extinction* phase is followed by a seventh phase, characterised by a *smouldering combustion* regime in the fire front, which

- proceeds at the surface of the solid fuel bed particles (usually, during this phase, already practically reduced to char), and
- requires much less oxygen (air) and
- has a much lower burning rate, and, so, a much higher *residence time*, than flaming combustion (cfr. CHANDLER *et al.* 1983).

The study of this phase of the fire is relevant for (see /1.2/, /1.5/, /2.3/, /3.1/): the soil heating (p.e. DIMITRAKOUPoulos and MARTIN 1990); the *smoke* generation (p.e. KANURY 1976, RASBASH and DRYSDALE 1982); and the rekindling of flame (*flare up*) due to sudden changes of the fuel bed or ambient conditions (p.e. FONS 1950, Chandler *et al.* 1983).

The final cooling of the combustion residues (8th phase) has not attracted much research attention (see, however, /3.1/).

4.3 FIRE REGIME

The concept of *fire regime* is thoroughly defined and explored in ANDRÉ (1996) [2].

As it is said above, this concept allows a finer discrimination of the fire behaviour during its fully developed phase, although it can also be used, for short periods of time, during other, non-*steady* phases of the *fire history*, such as the *build-up* and the decaying phases.

Below, four main criteria of subdivision of the *fire regimes*, not entirely independent, are used to review the research.

These criteria are based, respectively:

- on: the combustion regime in the fire front, which can be glowing or *smouldering*, with *laminar* or *turbulent* diffusion flames, or even, although seldom, with a premix flame (cfr. ROTHERMEL 1991, on tree torching);
- the type of forest fuels that carry the front, which can give place to *ground fires*, *surface fires* and *crown fires* that are either free or dependent on *surface fires* spreading underneath;
- the sensitivity of the fire *response* to a change in a given input parameter of the fuel bed or of the ambient;
- the order of magnitude of the values of certain properties of the *fire line*, such as, the *rate of spread* (slow and fast *fire regimes*) or the *fire line intensity* (low, medium and high intensity *fire regimes*).

The class of, so called, marginal *fire regimes* [3] deserves a special reference, for its interest in the study of both the transition between the *ignition* and *build-up* phases, and the decaying phase of the *fire history*.

An interesting open question concerning forest *fire regimes* is the (eventual) existence of multiple *fire regimes* for the same conditions of the fuel bed and ambient, depending on the *history of fire* prior to the fully developed phase and, in particular, depending on its *ignition* conditions (EMMONS and SHEN 1971, STEWARD 1974, PALMER and NORTHCUTT 1975, THOMAS 1967,1971).

4.4 ASPECTS OF THE FIRE BEHAVIOUR PREDICTED

4.4.1 Main fire front

4.4.1.1 Ground fires

Ground fires, perhaps because they are the least intense of all the forest *fire regimes* (due to the *smouldering combustion* regime that characterises it, differently from the much more energetic flaming combustion regimes that characterise the *surface* and *crown fires*), have not attracted much research attention.

On this subject, besides the references given above about the *smouldering combustion* phase of the history of a more general fire (7th phase), see: Mc MAHON *et al.* (1980), WILLIAMS (1982) and WADE (1984).

4.4.1.2 Surface fires

This is the area of *forest fire* physics research in which more theoretical and experimental work has been done.

A useful reference covering practically all types of fire spread models mostly dealing with the main fire front behaviour of surface forest fires, is the recent review of ANDRÉ and VIEGAS (1999) [4], which is addressed to non-specialists.

A major division that ought to be done in the research in this area respects the distinction between the modelling of a small section of the *fire line* during small periods of time, and the modelling of the whole *fire line* for long time periods.

The former type of predictions are said to have a local character while the latter have a global character.

4.4.2 Behaviour of a small section of the *fire line* (local prediction)

Almost all studies included in this first group apply to a 2D (i.e., straight line and infinite), fully developed and flaming fire front, spreading through a statistically homogeneous fuel bed, on plane but inclined terrain, under an uniform wind field.

Moreover, all the properties of the fuel bed and the ambient are constant and, if they exist, the directions of maximum slope and of wind velocity are both perpendicular to the straight *fire line*.

Closest to the empirical bottom of the modelling scale, we have the fire behaviour models based on *wildfire* observations and field tests, typically with a scope of application rather restrict, such as: in Australia, the works reported in LUKE and MC ARTHUR (1978), GILL and NOBLE (1989) and CATCHPOLE (1998) [5]; in Canada, large parts of the work underlying the Canadian Forest Fire Behaviour Prediction System [18]; and, in the USA, the early work of Curry and FONS (1940).

Upper, in a second level of the modelling scale, there are the empirical models based on laboratory experiments.

However, in the first place, it should be stressed that most of the laboratory work has other goals, such as:

- studying the phenomena that control the fire spread in certain *fire regimes*;
- investigating the influence of given input parameters of the fuel bed and ambient (such as: the thickness and *moisture* of the fuel bed particles, the *fuel load* and the *fuel bed porosity*, the *windspeed* or the slope), either in an isolated fashion or in small groups, on given output parameters characterising the fire front behaviour (such as: the *rate of spread*, the depth and *residence time* of the fire front, and the flame length and inclination),
- sometimes leading to the proposal of particular empirical correlation; or validating any fire behaviour model of the semi-empirical (physical incomplete) or comprehensive (physical complete) type.

STEWARD (1974) [8], ANDRÉ *et al.* (1992) [1], VAZ (1997) [6] and CATCHPOLE and CATCHPOLE (1998) refer numerous studies of this kind.

NELSON and ADKINS (1988) and CARRIER *et al.* (1991) deal specifically with Dimensional Analysis and Similitude

Theory problems posed by these type of experiments.

One of the few, and, clearly, the most outstanding laboratory empirical fire spread model is the model of ROTHERMEL [7], which is the core of the well known software BEHAVE [19].

Going up the modelling scale, we find, at a third level, the physical-incomplete or semi-empirical fire spread models.

These models are back-up on a set of physical laws, the most important of which expresses the conservation of energy in a control volume located in the part of the fuel bed not yet burned, ahead of the *fire line*

The *rate of spread* of the fire, which is the main output of the models, appears as an integral parameter (albeit, eventually hidden) in this equation.

The equation explicitly includes two sets of terms associated, respectively, with heat sink and heat flux phenomena, but the positive heat flux terms, representing an income of energy to the control volume, depend on a third set of heat source phenomena occurring at the fire front.

In fact, even ROTHERMEL model is based on such a law, written in the simplest possible (space-time integral) form, but, contrary to the semi-empirical models, does not model in a physical way the heat flux terms.

However, the semi-empirical models can not be considered as physical-complete models because they do not model the heat source terms.

The following are review works specifically dealing with this class of fire spread models: STEWARD (1974) [8], CATCHPOLE and DE MESTRE (1986) [9], WEBER (1991) [10] and CATCHPOLE (1994) [11].

ANDRÉ *et al.* (1992) [1] contains also interesting material on this regard.

A first group of models of this type, treating the fire spread in a space-time continuous way, is: EMMONS (1964), THOMAS *et al.* (1964), HOTTEL *et al.* (1965), FANG (1966), VAN WAGNER (1967), ALBINI (1967), THOMAS (1967), FANG (1969), ANDERSON (1969), BERLAD (1970), SANDHU (1970), FRANDBEN (1971), THOMAS (1971), STEWARD (1971), HOTTEL *et al.* (1971), PAGNI and PETERSON (1973), TELISIN (1974), PAGNI (1975), CEKIRGE (1978), FUJII *et al.* (1980), ALBINI (1985,1986), DE MESTRE *et al.* (1989) and WEBER (1989).

There is a second group of models in which the fire spread is modelled in a discontinuous way, as a succession of jumps from particle to particle along the fuel bed.

Although these models seem more adapted to cope with very low *porosity* fuel beds, in any case, they can always be converted into formally continuous fire spread models.

Here is a list of works in this group: FONS (1946), VOGEL and WILLIAMS (1970), EMMONS and SHEN (1971), STEWARD and WAIBEL (1973) and WEBER (1990).

The software FIRELAB (GUARNIERI *et al.* 1998) [20], under development, implements some of the former models in an easy-to-use way.

Finally, in a fourth level of the modelling scale, there is still another group of fire spread models that can be already classified as physical complete models (see the DELFI review of LARINI).

It is a striking fact that the rate of production of new semi-empirical models practically comes to zero in the nineties, while the one of physical complete models begins to rise.

4.4.3 Behaviour of the whole *fire line* (global prediction)

Let us now step to the global scope of prediction of the fire behaviour, in which the whole *fire line* is followed for long periods of time, paying attention to the significant space and time changes of the fuel bed and ambient conditions along the *fire line*, during the time interval of prediction.

In this area, not accounting for the models of the physical complete type (see the DELFI review of LARINI), practically all the research can be cast into the theoretical framework of ANDRÉ and VIEGAS (1998b) [12], which is summarised in ANDRÉ and VIEGAS (1999) [4] (see also the critical proposal of VIEGAS *et al.* 1998).

However, there also exist some works with a deep statistical nature, using concepts and tools of Chaos Theory, such as: percolation models, cellular automata models and fractal geometry, that have been applied to study the behaviour of forest fires at a global level, with the purpose, for instance, of identifying critical behaviours (eventually associated with marginal *fire regimes*) or of determining the fractal dimension of the burned area.

These works, essentially distinct from the works of the main stream, are not reviewed here (see the early work of VON NIESSEN and BLUMEN 1988, and the recent review of DUARTE 1997).

4.4.4 Large crown fires and bushfires

Large crown fires and *bushfires* are much less studied than lower intensity *surface fires*.

See ANDRÉ *et al.* (1992) [1] for a more extensive review of this subject.

The initiation of a *fire regime* of this class is usually associated with a regime transition from lower intensity *surface fires*, named *blow-up*, which is studied in the following works: BYRAM (1954), SHAEFER (1957), MOLCHANOV (1957), VAN WAGNER (1964,1977 [13]), EMMONS (1966), BROWN and DAVIS (1973), DIETERICH (1976), BROTAK (1978), LUKE and MC ARTHUR (1978), WILLIAMS (1982), CARRIER *et al.* (1985), HAINES (1988) and SIMARD and EENIGENBURG (1990).

Tentative identifications of different *fire regimes* within this class are done by: BYRAM (1966), LEE (1972), PALMER and NORTH CUTT (1975) and ROTHERMEL (1991) [15].

Dimensional Analysis and Similitude Theory considerations relevant to the modelling of *large forest fires* can be found in BYRAM (1966) and WILLIAMS (1969).

Some authors studied the strong flows induced by this type of fires, such as, the main *fire plume* and different vortex flow structures, but as this subject pertains more to /2.4/, we do not review it here.

Regarding the fire spread models that have been proposed specifically to model *large forest fires*, we have:

- the empirical models of VAN WAGNER (1989) [13] and ROTHERMEL (1991) [15], which are incorporated, respectively, in the Canadian Forest Fire Behaviour Prediction System [18] and in the software package BEHAVE [19] (see Section 5);
- the semi-empirical model of ALBINI (ALBINI and STOCKS 1986) [16]; and, finally,
- some models of the physical complete type (see the DELFI review of LARINI).

An on-going important field experimental program on crown fires is reported in ALEXANDER *et al.* (1998) [14].

4.4.5 Spotting

Spotting, albeit being present in any type of flaming *forest fire*, even in the least intense ones (cfr. STEWARD 1974), only in medium-to-high intensity fires becomes a really important phenomenon in the context of /1.2/ and /2.5/, which ought to be predicted in addition to the behaviour of the main fire front (see Section 4.1).

However, this is a relatively self-contained research problem seldom addressed.

Following ANDRÉ *et al.* (1992) [1], we can distinguish three main subproblems in the study of *spotting*:

- the production of *firebrands* in the main fire front (or, more generally, in any *spotting* source, such as can be an isolated torching tree);
- the transport of the *firebrands* by the flow of hot gases and wind, from the *fire line* towards the still non-burned part of the fuel bed, beginning with the lifting of a *firebrand* in the fire *plume* and ending with its gravity fall across the wind flow; and
- the (eventual) *ignition* of a secondary fire *spot*, ahead of the main front.

The study of the transport problem, obviously, benefits from independent modelling both of the fire *plume* (see, p. e., LEE and EMMONS 1961, MORTON 1965, NIELSON and TAO 1965, SMITH 1967, BYRAM and NELSON 1974, WILLIAMS 1982), and of the wind flow over complex terrain /2.4/.

Similarly, the investigation of secondary fire *spots* can take profit of the research on the more general subject of *ignition* of *forest fires* (see Section 2).

Specifically addressing the *spotting* issue, we have: the *wildfire* observations reported by LUKE and MC ARTHUR (1978); the experimental studies of TARIFA *et al.* (1965) and STEPHEN and WRIGHT (1974); and the semi-empirical models of ALBINI (1979,1982) [17].

4.4.6 Fire whirls

Fire whirls are large scale coherent vortex flow structures –according to EMMONS (1964), these vortex can be assimilated to cylinders with (diameter x height) ranging from (10 cm x 30 cm), for a small fire whirl, to (100 m x 300 m), for a strong fire tornado ²–, carrying inside flames and *firebrands*, that sometimes detach from the fire front and wander around for a while till they dissipate.

As this seems to be a rather rare and fortuitous phenomenon in most forest fires, besides seldom posing *fire safety* problems ³, we do not review its research here (such a review can be found in ANDRÉ *et al.* 1992 [1]).

² Probably, forest fires can never become intense enough to generate such a fire tornado, which, on the other hand, has been observed in *large* industrial and *urban* fires.

³ Personal communication done to the author by Richard ROTHERMEL, at the 1st International Conference on Forest Fire Research (19-22 November 1990, Coimbra, Portugal).

4.5 APPLIED RESEARCH PRODUCTS

To simulate with a particular model the behaviour of a fire front in a natural dynamic scenery of fuel bed and ambient conditions, either on virtual, historical, real-time or prognostic grounds, one must solve two main problems: to get the input information required by the model, and to perform all the due mathematical computations.

In accordance, to ease these tasks to the operational user, an applied research effort has been done by the forest services of some countries (particularly the USA), by enterprises and by research groups, ultimately leading to the construction of more or less elaborated and user-friendly software packages.

Some of these software/systems are in the public domain, others are commercial products, and still others have an indefinite statute.

Many of these software systems, in addition to a module specifically dealing with the prediction of the fire behaviour, which incorporates some of the models reviewed above, contain other modules that help the user: in organising activities of *fire management* /1.1/, *fire suppression* /1.2/, *fire detection* /1.3/, *fire risk* /1.4/, or even other more or less specialised fire activities (/1.5/, /3.6/); in the fuel characterisation /2.1/ or in wind modelling /2.4/; or in the managing of *smoke* (/2.3/, /3.1/).

As all these functions pertain to other topics of DELFI Index, we concentrate here on systems possessing an important or original fire behaviour module.

The most important systems that give only local fire behaviour predictions are: the Canadian Forest Fire Behaviour Prediction System (CFBPS) [18]; and the software package BEHAVE [19].

Regarding the numerous Australian subsystems see [5].

Although aimed at laboratory simulations more than at operational applications, the software FIRELAB [20] should also be mentioned.

All the existing software systems that produce fire behaviour predictions with a global character and incorporate empirical or semi-empirical fire spread models can ultimately be framed within the theory [12] (see Section 4.1.2).

In fact, a rather general software kernel of implementation of this theory is presently under development [21].

Moreover, practically all systems use BEHAVE as Local Fire Spread Model.

Here is an illustrative list of such systems: FMIS™ [22], FIRESTATION™ [23], GEOFOGO [24] and CARDIN [25], using slightly different variants of the algorithm of DIJKSTRA to implement a Global Fireline Propagation Model based on the principle of the fastest path of propagation; and FARSITE [26], which implements HUYGENS' principle as the basis of a Global Fireline Propagation Model.

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