Eruptive Fire Behaviour in Past Fatal Accidents

D. X. Viegas, L. P. Pita, L. Ribeiro and P. Palheiro

Introduction

Many fatal accidents are associated to sudden fire acceleration of the fire front in steep slopes or canyons. This phenomenon that is known in the literature as a blow-up has deserved the attention of the authors during the past years. An extensive experimental program was carried out in field and laboratory tests for a wide range of fuels and geometrical configurations. In Viegas (2005) an original mathematical model to explain the occurrence of fire blow-up was presented. In this paper the designation of fire eruption is proposed given its similarity with that other natural phenomenon. In that study it is proved that eruptive fire behaviour is essentially associated to the feedback between the fire front and the ambient flow. The convective flow induced by the fire enhances the combustion reaction and as a consequence the flow in the vicinity of the fire front is increased as well; the rate of spread increases with time even if the overall conditions remain the same. It is proved that the occurrence of a fire eruption requires only the existence of a sufficiently long or steep slope covered by continuous vegetation, without the requirement of any other special effect like the occurrence of a sudden wind gust, the passage of a front the existence of a thermal belt or other similar explanations that are given to these occurrences in the literature.

The accidents of Mann Gulch of 1949 (Rothermel, 1993), Storm King of 1994 (Butler *et al.* 1998), Thirtymile of 2001 (Furnish *et al.,* 2001), and Freixo of 2003 (Viegas, 2004) are used to illustrate and to validate the applicability of the mathematical model for eruptive fire behaviour. Other accidents like the Loop Fire of 1966, the Rattlesnake Fire of 1953 and the Cramer Fire of 2003 are reanalysed using the interpretations given by the present model.

The consequences of the present model to fire safety are explained. Some preliminary recommendations on fuel management in canyons or in steep slopes are given.

Eruptive Fire Behaviour

The rapid acceleration of a fire in steep slopes or in canyons resembles an eruption and is designated here as eruptive fire behaviour. In the North American literature this process is designated as fire blow-up. The authors carried out an extensive study on fire spread in canyons (Viegas and Pita, 2004) that demonstrated that this eruptive effect is due to terrain or topography features alone without the need of other special atmospheric or fuel bed characteristics.

A mathematical model was developed by Viegas (2005) to predict the eruptive fire behaviour. This model takes into account the feedback between the fire and the surrounding flow and estimates the acceleration induced by this feedback effect. The mathematical model is closed using empirical data from laboratory and field experiments making it a semi-empirical model. The model was applied to field experiments and to some real cases.

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In: Butler, B.W and Alexander, M.E. Eds. 2005. Eighth International Wildland Firefighter Safety Summit: Human Factors - 10 Years Later; April 26-28, 2005 Missoula, MT. The International Association of Wildland Fire, Hot Springs, SD.

The basic equations of the model are given below. For more details please refer to Viegas (2005).

$$R' = \frac{R}{R_o} \qquad [1]$$

$$R' = 1 + a_1 U^{b_1} \qquad [2]$$

$$dU = a_2 R'^{b_2}\, dt \qquad [3]$$

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

The parameters involved in the model are six and they can be determined independently. These parameters are listed below:

R_o – is the basic rate of spread (ROS) that is used as a reference to define the non-dimensional rate of spread $R'=R/R_o$. The basic rate of spread is the ROS of a linear fire front in the same fuel bed without wind and without slope.

a_1 – is a coefficient that appears in equation [2] relating the rate of spread to the instantaneous wind velocity in the vicinity of the fire front.

b_2 – is an exponent that appears in equation [2].

a_2 – is a coefficient that appears in equation [3] relating the wind flow change induced during the time interval *dt* by a fire front spreading at a rate of spread *R*'.

b_1 – is an exponent that appears in equation [3].

t_o – is a residence time of the combustion reaction in the fuel bed.

In Viegas (2005a) estimated values of these parameters that were used in the test cases are given. In Viegas (2005b) a discussion on the role of these parameters is proposed.

In this paper the mathematical model shall be applied to some past accidents to check its applicability to the prediction of the eruptive fire behaviour that was observed and reported in each of them.

In order to integrate equation [4] it is necessary to specify the initial rate of spread R_1. Knowing R_o the corresponding value of R'_1 can then be evaluated as well. These parameters were estimated for each case from data given in the respective reports.

The values of these parameters that were used in each case that is reported in this paper are given in Table 1.

Table 1
Values of the model parameters used in the computations

Reference	R_o	a_1	b_1	a_2	b_2	t_o	R'_1
	cm/s	(1)	-	(2)	-	s	-
Freixo de Espada-a-Cinta	1.0	1.1	20.2	6×10^{-4}	1.16	1000	15
Mann Gulch	0.6	1.4	1.7	5×10^{-4}	1.3	500	1.4
South Canyon	0.17	1.1	2.02	4.5×10^{-4}	1.16	1000	4
Thirty Mile	0.56	1.1	2.02	5×10^{-4}	1.16	1000	1.2
Rattlesnake	7.5	1.4	1.3	5×10^{-4}	1.1	600	1.2
Cramer	6.7	1.4	1.25	5×10^{-4}	1.1	800	2

(1) The physical units of a_1 can be derived from equation [2]. The indicated values are in the SI system.

(2) The physical units of a_2 can be derived from equation [3]. The indicated values are in the SI system.

Case Studies

Freixo de Espada-a-Cinta

This accident occurred in Portugal near Freixo de Espada-a-Cinta on the 5th of August of 2003 and was reported in Viegas (2004). A couple of forest owners was killed by a fire blow up some twenty minutes after the main fire was given as extinguished but for a small extension of flames in the bottom of a large canyon. An overview of this area is shown in figure 1 (a). By coincidence there was a meteorological station on the top of the ridge that was in the path of the fire plume. The recovered data showed very clearly the fire eruption. For example the air temperature (ten minute averages) went up from 35ºC to 56ºC and the wind velocity went from 15 km/h up to 65 km/h with gusts of 96 km/h (see figure 1.b). The model predicted the rate of spread and the wind velocity increase with reasonable accuracy as it is shown in figure 1 (b). The parameters of the model that were used in this case are given in Table 1.

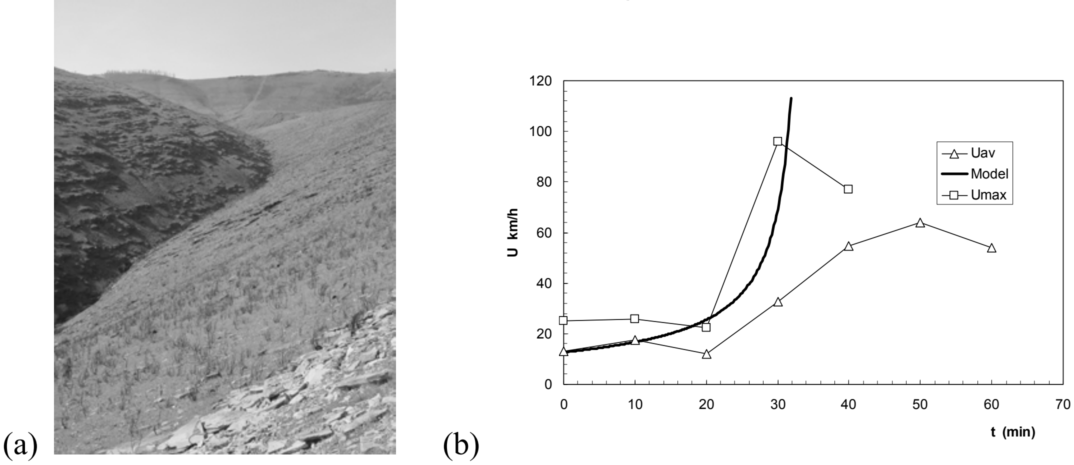


Figure 1 – (a) General view of the canyon in the area of the Freixo de Espada-a-Cinta accident and (b) the predicted and observed wind velocity at the top of the ridge.

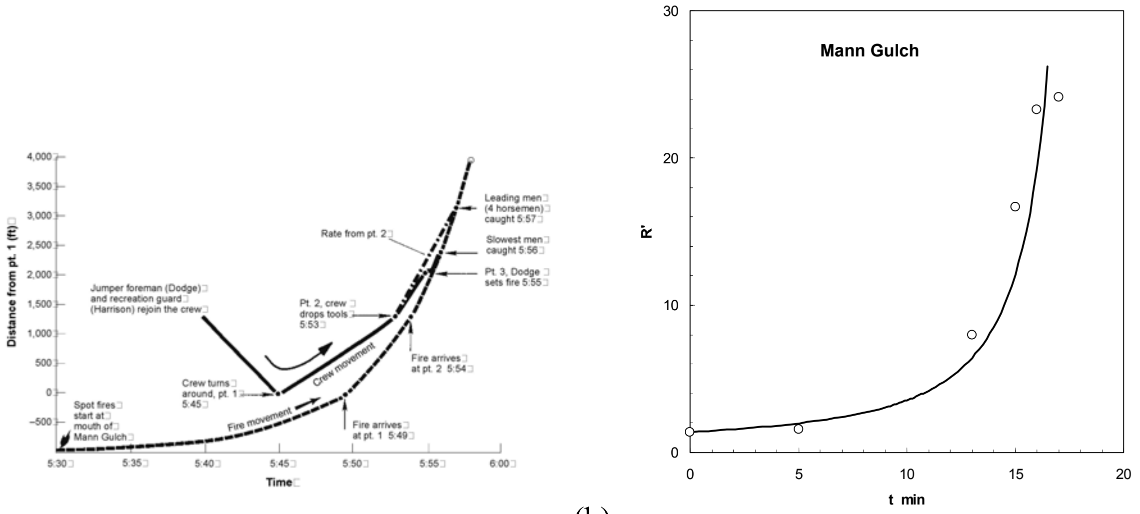
Mann Gulch Fire

This accident occurred in 1949 and it is reported in Rothermel (1993) and in Mc Lean (1992). Thirteen smoke-jumpers died in a race between fire and men that could not be won. The time evolution of the fire and of the fire men is shown in figure 2 (a) reproduced from Rothermel (1993).

ROS values were computed from figure 2 (a) and using R_o= 0.6 cm/s (typical of dried grass fuels) that values of R' as a function of time elapsed since the start of the fire eruption are shown in figure 2 (b). Using the model parameters that are given in Table 1 the fire evolution was computed and the results are shown as a solid curve in the same figure.

South Canyon Fire

This accident occurred in 1994 and it is reported in Butler et al. (1998) and in Mc Lean (1999). Fourteen persons died in this accident. The rate of spread values that were computed from data given in the report are shown in figure 3. These are compared with the corresponding output given by the model is shown in the same figure. We remark the fact that the ROS during the blow up reached values of the order on one thousand times the basic rate of spread of the fire in the same vegetation.



(a) (b)

Figure 2 – (a) Evolution of the main fire front and the crew position in the Mann Gulch accident (from Rothermel, 1993); (b) Observed and computed non-dimensional rate of spread for this case.

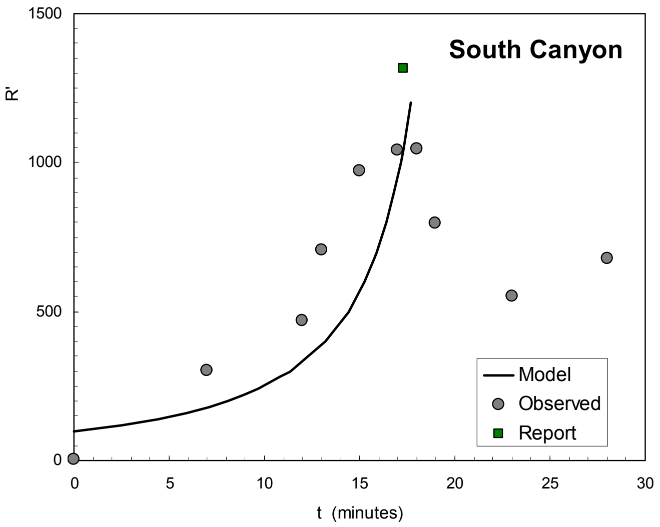


Figure 3 – Observed and computed non-dimensional rate of spread for the South Canyon accident. The round symbols correspond to values computed by the authors from data in the report. The square symbol corresponds to a ROS value that is actually given in the report.

Thirty Mile Fire

This accident occurred in the USA in 2001 and is reported in Furnish *et al.* (2001). The rate of spread values at given times during the history of this fire were taken from the report and practically the same parameters as in the previous cases were used in the computation with the model due to lack of more detailed information. The results are shown in figure 4.

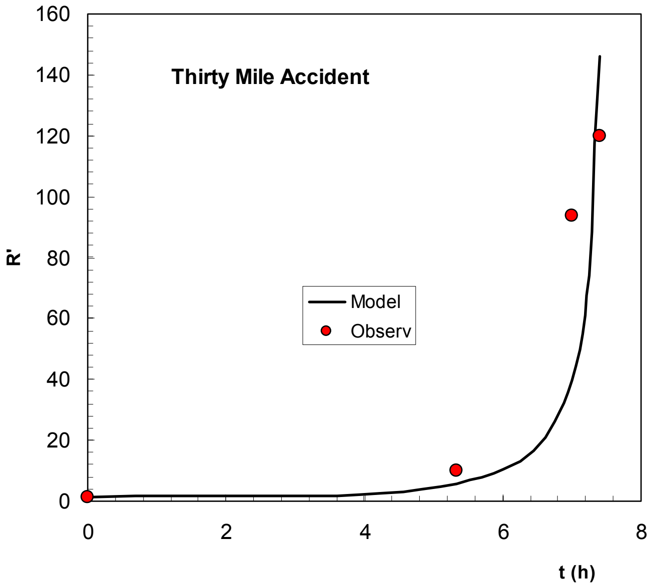


Figure 4 – Comparison between observed and predicted values of the rate of spread during the Thirty Mile accident. Notice that the unit of time in this figure is ‘hour’ instead of ‘minute’ as in the other cases.

Rattlesnake Fire

This accident occurred in the USA in 1953 and is reported in Cliff *et al.* (1953). The rate of spread values for the head fire were computed from the fire perimeters that are shown in figure 5 (a) taken from that report. Comparison with the present model predictions are shown in figure 5 (b).

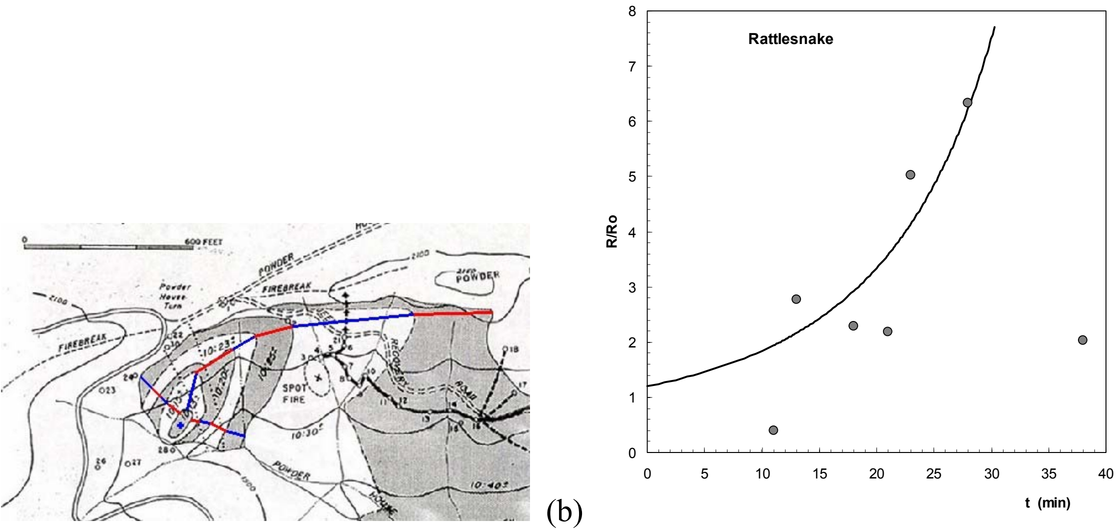
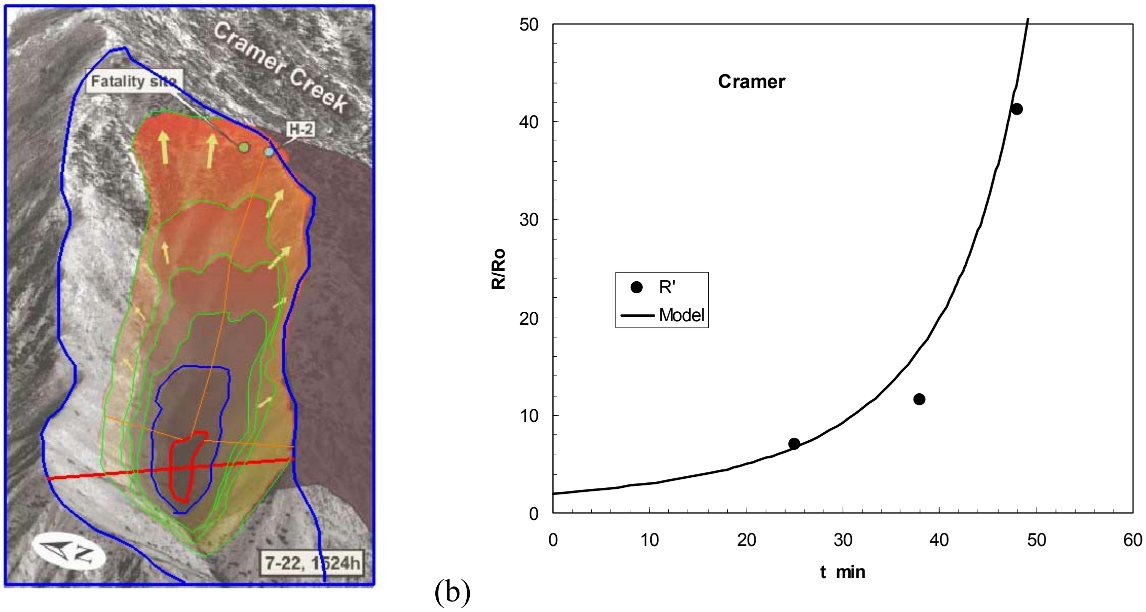

(a) (b)

Figure 5 – (a) Fire perimeter evolution for the Rattlesnake accident (from Cliff et al., 1953), (b) Comparison between predicted and observed values of the non-dimensional rate of spread for this case.

Cramer Fire

This accident occurred in the USA in 2003 and is reported in Donoghue *et al.* (2003). This report includes a series of graphs that show the estimated evolution of the fire front during relevant periods of the fire history. One of these pictures is reproduced in figure 6 (a). Rate of spread values were computed from these graphs and the results are shown in figure 6 (b) in comparison with the present model predictions.



(a) (b)

Figure 6 – (a) Fire perimeter evolution for the Cramer accident (from Furnish et al., 2003), (b) Comparison between predicted and observed values of the non-dimensional rate of spread for this case.

Discussion and Conclusion

In past research many explanations are given for the occurrence of a blow-up. Quite often these involve the unlikely existence of low probable events like thermal belts, wind jet-streams near the surface, inversion layers, instability layers, mid-slope winds, passing of cold fronts and so on (cf. Chandler et al. 1983, Pyne, 1984 and Pyne et al., 1996). This interpretation can be misleading at it may induce the fire fighters to consider that the probability of occurrence is very low given the number of factors that are supposed to contribute for it to occur. The present model explains the existence of a fire blow up due to the existence of a steep slope or a canyon. The present results are preliminary but they show that it is possible to interpret the events that occurred in several fire related accidents. From this knowledge it is expected that less uncertainty will exist in the future thus leading to safer operations.

Acknowledgements

The authors wish to thank to the persons and institutions that helped in the realization of the present research. Support given by Comandante J. Mamede from the Fire Brigade of Freixo de Espada-à-Cinta during the investigation of Freixo accident is acknowledged. The availability of meteorological data for the same case by Quantific Company is also gratefully acknowledged. The present research is included in the program of Projects Winslope (Contract POCTI/34128/ EME/2000) and SPREAD (Contract EVG1-CT2001-00043) supported respectively by *Fundação para a Ciência e Tecnologia* and by the European Commission under the Program Environment. This support is also gratefully acknowledged.

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Domingos Xavier Viegas was Born in Goa (India) on 24 August 1950. He graduated in Mechanical Engineering from the *Instituto Superior Técnico* (Lisbon) in 1972 and obtained his PhD in Aerodynamics from the University of Coimbra in 1981. He has been full Professor of the Department of Mechanical Engineering, of the Faculty of Science and Technology of the University of Coimbra since 1992, where he has been head of the Fluid Mechanics Group since 1981.

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