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# FIRE SPREAD ACROSS FUEL TYPES

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# Fire spread across fuel types

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## Introduction

When bushfires occur emergency services have to plan their response. They need to know the likely direction and rate of spread of fires, and their intensity. This enables them to respond to questions such as:

> Are people likely to be in danger? If so, should they be evacuated from their present locations?
> Should roads be closed to the public?
> What firefighting resources should be deployed? Where and when?

To answer these questions, emergency services make considerable use of computer models to predict the behaviour of bushfires. These operational models are capable of providing a range of likely fire scenarios in a timely manner so that appropriate responses can be planned and implemented. This is their great strength, but it also gives rise to one of their limitations. The limitations arise because operational models are essentially empirical, and as a result they can be confounded when presented with unique or extreme fire scenarios. In other words, they lack a certain generality. Generality is inherent in models that reflect the 'regularities of nature'. These are realised by developing mathematical models that are based on well-established and ubiquitous principles of science. This approach will enable us to better:

> Predict the interaction of the atmosphere and vegetation on the rate of propagation of bushfires. This will enable us to model the behaviour of fires over a wide range of terrains and atmospheric conditions.
>
> Obtain a deeper understanding of the physico-chemical processes that underpin the propagation of bushfires and management strategies such as the location and size of fire breaks, thinning of forests, prescribed burning and so on.
>
> Appreciate the physical and chemical nature of fuel types so that one can predict their impact on the rate of spread of fires.
>
> Simulate unusual fire scenarios to help train fire fighters and keep them out of danger.
>
> Determine the circumstances under which operational models may require to be refined.

The development of a next generation physics-based model of bushfires is a multi-faceted task, and it contrasts starkly with empirical based models that rely heavily on correlating the rate of spread of fires with the wind speed, the moisture content of the vegetation, ambient temperature and humidity and so on. Sullivan highlights some of the difficulties that arise when specifying the nature and condition of the fuel - how precisely would the moisture content of a fuel be measured, and how would we interpret the measurements of wind speed? The next generation of bushfire models will evolve in the spirit of consilience, used here in the E. O. Wilsonian sense. That is, the next generation of bushfire models will draw increasingly on a synthesis of deep knowledge from a wide range of disciplines, including science. The advantage of this approach is that it provides a coherent intellectual framework within which to work. For example, measurements of wind speed in a forest canopy must be made in a strategic manner that informs modellers in a way that enables them to predict with some confidence the rate of spread of fires. There must be a defensible reason for the choice of the measurement. Thorpe has dubbed this approach as being 'omni-scientific', implying that inputs from a wide range of disciplines are required to accurately interpret the physical world. Whilst 'omni-science' is by definition all-embracing it attempts to transcend technical specialisms. It is in this spirit that the next generation of bush fire models will be developed.

This approach demands that modellers are *au fait* with contemporary trends in a wide range of disciplines, and they require the intellectual insights to be able to identify areas of research that are likely to be productive. In this project, one issue that will be explored in some detail arises from the need to account for physical phenomena that range in scale from a fraction of a millimetre to a kilometre or more. Furthermore, computing resources are always limited, and for the foreseeable future we can resolve the outputs of our models on a length scale of about 1 metre. This implies some form of averaging, and this is usually accompanied by a reduction in information. The immediate thrust of this project is to devise accurate models of propagation of bushfires by employing the principles of physics and computational science.

**The Project**

The principal aim of the project is to develop an accurate physics-based mathematical model that is computationally efficient. This will be achieved by implementing the following program of research.

<u>Step 1</u>

The first step will be to have a Wildland-Urban Fire Dynamics Simulator (WFDS) model (for grassland and forest fire) compatible with the latest version of its sister version Fire Dynamics Simulator (FDS) model of building fires. FDS continues to evolve at a fast pace (FDS version 6 has just been released and we have been working with a pre-release version for almost a year). Dr Ruddy Mell commenced the extension of FDS to WFDS mainly from FDS' version 4. We have conducted grassland and tree fire simulations using FDS4 compatible WFDS.

The WFDS model adopts two approaches to modelling vegetative fuels, namely:

(i) the fuel element model for vegetation that occupies a specified volume such as trees and
(ii) the boundary element model for surface fuels such as grasslands.

*Boundary fuel model*

Dr Mell has developed the boundary fuel method (for surface fuel) to full functionality in the most recent version ofW FDS6 and conducted basic tests against the Australian grassland experiments C064 and F19. However, more testing needs to be done.

*Fuel element model*

Preliminary tests imply that the current release of FDS6 requires further refinement. As Dr Mell's current priority is WFDS_LS (a non-physics based level set approach), Australian researchers can concentrate on this part. The aim of this phase is to have a version of WFDS' forest fuel subroutines that are compatible with subroutines of FDS version 6, besides being compatible with a boundary fuel model.

<u>Step 2</u>

In this we will create a set of cases for validation and verification of the WFDS model. For both grassfires and forest fires, at least one set of Australian fires and one set of North American fire scenarios will be selected. For each cases input and output parameters will be identified. It will also identify which input parameters need to be measured using bench-scale experiments (such as cone calorimeter, thermo-gravimetric analysis (TGA), differential disc calorimetry (DSC), hot-disk analyser etc). For each case, FDS input data files will be created which will be updated as the model evolves.

*Forest fire- laboratory scale:*

CESARE has state-of-the-art experimental facilities (3 MW and 15 MW calorimeters) to conduct extensive fire experiments to support the development of WFDS. Experiments will be conducted measuring heat release rate, mass loss rate and radiation flux associated with burning species on Australian flora. These will be included as an Australian benchmark case. Burning vegetation of different sizes and with different ignition conditions would be valuable. Therefore, igniting trees (or other raised vegetation) of different sizes, moisture levels and bulk densities with igniters of different heat release rates (representing different surface fire intensities) will be conducted.

*Forest fire- field scale:*

At least three validation and verification cases will be developed as follows:

a. There is a number of case studies reported in the literature to test the simplistic fire model (FARSITE).

b. Data are available on heat flux and video observations (from Fire Sciences Laboratory, Rocky Mountain Research Station, USDA Forest Service, Missoula, Montana) obtained from seven experimental crown fires.

c. Between 1995 and 2001 the International Crown Fire Modelling Experiment (ICFME) project conducted a set of highly instrumented crown fires near Fort Providences, Northwest Territories, Canada.

Step 3

In this step, we would like to develop and improve specific subroutines of WFDS.

*Reducing Grid Sensitivity*
It has been observed that obtaining grid independent results for a fire in an open space, especially when the fire is not prescribed, is highly problematical. Furthermore, if grid independence were to be achieved it would have to be when the grid size is on the order of 0.1m or larger, otherwise running the program for practical reasons is not feasible. It is important that the grid sensitivity in this type of fire be reduced as a first step. LES uses the size of the grid cells as a filter to separate large and small eddies which may be linked to grid sensitivity. The research team is currently exploring the effect of 'implicit' and 'explicit' filtering techniques of the LES sub-model in both WFDS and FDS as part of a project funded by the former Bushfire CRC. In the 'implicit' method, the filter size is directly related to the grid size. Therefore, with changes to the grid size the output of the model change. On the other hand 'explicit' techniques tend to pre-set the filter size. It is expected that the 'explicit' filtering technique will reduce the grid sensitivity of WFDS/FDS. Although this technique has some inconsistency with LES principles, it is more important to reduce grid sensitivity for the purpose of model validation leading to further improvement. The 'explicit' filtering is already showing some promising results.

Since the commencement of the former Bushfire CRC-funded study, WFDS/FDS has implemented four sets of 'implicit' filtering techniques, and the effects on reducing grid sensitivity are being explored. Recent work by one member of the research team shows that the stretched-vortex method (developed at the California Institute of Technology) can be superior in reliability, most notably, in predicting atmospheric boundary layers. The atmospheric boundary layer, that is, the lowest kilometre or so of the atmosphere characterised by vigorous turbulent motions, interacts directly with bushfires. In this study, a vortex-stretching method will also be implemented in WFDS and this sub-model will be evaluated. As we know, accurate implementation of LES is challenging and the research team includes the required intellectual resources to meet this challenge.

*Accounting for roughness of the terrain*

The behaviour of bushfires is constrained, if not enslaved, by details of the terrain over which they occur. These details encompass the nature of the vegetative litter on the forest floor, trees and branches measured on the scale of metres, through to hills and mountains that are measured on the scale of kilometres. These details obstruct wind and affect the supply of fuel, moisture and heat. Hence, it is essential that a credible physics-based simulation be developed. In this project, such a model will be developed that captures the aggregate effects of these details in the form of suitable boundary conditions. Currently, this knowledge is nascent.

In this part of the project, the team will systematically investigate the effect of various roughness scales on the flow (wind) above it. This fundamental study will involve the direct numerical simulation of turbulent flow over roughened surfaces. Simulations such as these resolve all spatial and temporal scales of the flow without approximations and they are computationally extremely costly, but they may be taken as a faithful representation of reality. The first set of simulations will investigate the effect of varying a single scale of roughness, and the second set of simulations will investigate the effect of combining two or more scales of roughness. The team will then perform a detailed analysis of the simulation data to develop suitable boundary conditions for bushfire simulations.

*Improvement of the pyrolysis sub-model*

The accuracy of models of bushfires is limited, in part, by imprecise knowledge of the pyrolysis of solid fuels. This is exacerbated by difficulties in implementing variations of thermo-physical properties and kinetic parameters in relation to temperature, heating rate and radiation flux. Members of the research team have suggested a set of methodologies to improve the modelling of solid fuel gasification and burning. This proposition informs the strategy of a second strand of the proposed research, namely the requirement to obtain more reliable information on thermal properties that affect the pyrolysis of Australian fuels and significant modification of WFDS' pyrolysis routine.

*Development and Improvement of firebrand submodel*

It is essential that data on the physical and combustion characteristics of firebrands produced by Australian vegetation be collected. To this end, a firebrand generator will be constructed. Experiments on the generation of firebrands will be carried out within an intellectual framework that facilitates the experimental results being used in the three-dimensional mathematical models. This includes development of a firebrand sub-model for WFDS in conjunction with Dr Mell.

*Reducing computational demand*

Adaptive Mesh Refinement (AMR) is thought to be a possible solution for the limitation imposed by computer resources. Figure 1 illustrates how mesh can be refined adaptively in regions of high gradients of properties and velocities. There are two types of AMR: structured AMR and unstructured AMR. Examples of current physics-based codes for unstructured AMR are FLUENT and FireFOAM. Although WFDS (and its building fire version FDS) is a comprehensive physics-based 3-D firespread model, it is yet to have AMR capability.

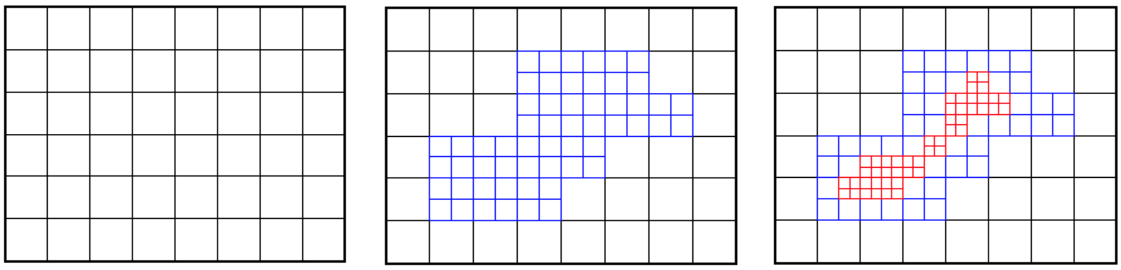

Figure 1: Point-wise structured refinement of a computational mesh. The mesh is finest in regions in which gradients of properties such as temperature, velocity and concentrations are the steepest.

Furthermore, various schemes for parallelising the computational code will be explored and implemented to improve efficiency leading to reduced demand for computing resources.

**Activities**

<u>Recruitment</u>

*Postdoctoral Fellow*

A global search for a postdoctoral fellow was undertaken. This was carried out in two stages. During the first informal stage expressions of interest were called for on a computational fluid dynamics users group web site. This was followed by a formal selection process and a total of 45 candidates applied, and this was reduced to a shortlist of four.

Following interviews, Duncan Sutherland has been offered the position and he will commence in early September. Duncan holds a first class honours degree in applied mathematics from the University of Sydney. He has carried out research on energy dissipating structures in fluid flows, an area of relevance to modelling bushfires in which turbulent energy is both produced and dissipated. His interests also extend to parallel computing and high Reynolds number flows. Duncan has also given a presentation on the aerodynamics of cyclists, and he speculates on the effect of their hairstyles on their performance.

*PhD student*

A postgraduate student has been recruited by VU to the project – again this was achieved through a competitive process. The successful candidate, Rahul Wadhwani, has a degree in chemical engineering with a specialisation in hydrocarbon engineering from the Indian Institute of Technology, Roorkee. As an undergraduate he carried out computational fluid dynamics studies on the design of chemical reactors. Rahul's PhD studies will concentrate on developing pyrolysis models . This PhD project will firstly focus on obtaining more reliable information on thermal properties that affect the pyrolysis (gasification) of Australian fuels and significant modification of WFDS' pyrolysis routine to incorporate the various suggestions. The resulting data will form an essential component of our strategy to develop a platform on which to build the next generation of bushfire models. Further, data on the physical and combustion characteristics of firebrands produced by Australian vegetation will be collected. All these data will be used as input parameters to the WFDS model. Additional experiments will be conducted for sub-models validation. The two sub-models will be refined to achieve validation.

*The design and construction of a prototype firebrand/ember generator*

During bushfires, embers and firebrands can be dispersed hundreds of metres downwind of burning vegetation and potentially promote numerous vegetative and structural fires. An essential element of the project on the rate of fire spread across vegetation involves quantification of the interaction of embers and firebrands with vegetation. Hence, a component of the research comprises the gathering of data on the physical and combustion characteristics of firebrands produced by Australian vegetation. In this study, a firebrand generator will be constructed based on the experience developed by NIST, but it will be somewhat more refined. Experiments on the transport of firebrands will be carried out within an intellectual framework that facilitates the experimental results being used in the physics-based model and leading to improved firebrands transport model. It is planned to generate a controlled and repeatable size and mass distribution of glowing firebrands.

The CESARE dragon will consist of two parts, namely the main body and a continuous feeding mechanism. With the exception of the flexible hose, all components of the firebrand generator will be constructed of galvanized steel or stainless steel (0.8 mm thick).

<u>The development of a detailed roadmap of the project</u>

A detailed roadmap of the project has been produced to help guide its strategy.

**Integrated project team members**

*Researchers*

Dr Daniel Chung, University of Melbourne
Associate Professor Khalid Moinuddin, Victoria University
Professor Andrew Ooi, University of Melbourne
Professor Graham Thorpe, Victoria University

*End-users*

Dr Simon Heemstra, Manager Community Planning, NSW Rural Fire Service
Andrew Stark, Chief Officer, ACT Rural Fire Service
Lawrence McCoy, Senior Fire Behaviour Analyst, NSW Rural Fire Service
Ralph Smith, Branch Manager, DFES, WA
Chris Wyborn, Senior Technical Officer, Fire Protection Association of Australia
Mike Wouters, Senior Fire Ecologist, DENS, South Australia
Paul Fletcher, Assistant Chief Fire Officer, SAMFS
Andrew Sturgess, Fire behaviour analyst, Queensland Fire and Emergency Services
Rochelle Richards, Forestry Tasmania