# Laboratory Fire Behavior Measurements of Chaparral Crown Fire

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## ABSTRACT

In 2013, there was an estimated 9,900 wildland fires that claimed more than 577,000 acres of land. That same year, about 542 prescribed fires were used to treat 48,554 acres by several agencies in California. Being able to understand fires using laboratory models can better prepare individuals to combat or use fires. Our research focused on chaparral crown fires. Chaparral is a shrub community that blankets 5% of California land. As a result, it becomes key fuel sources for wildfires. By using chaparral to model crown fires, our goal is to develop a model that can be deployed for evacuation planning or firefighting in the event of these fires. Laboratory experiments were conducted at the USDA Forest Service Pacific Southwest Research Station. We utilized a wind tunnel equipped with cameras for visualization, arrays of thermocouples, and an in-house developed MATLAB script to analyze experiments. By controlling wind tunnel velocity, fuel moisture content and fuel geometry, we have quantified the fires by their flame heights, flame velocities and fuel consumption rates. Experiments were conducted inside the wind tunnel, with a raised platform for modeling crown fires. Results showed that wind velocity significantly enhances fire intensity and creates a far more destructive flame relative to one without wind. Also, depending on other variables, torching, incomplete burns, or spotting were observed in our experiments. Finally, results were used to validate a Computational Fluid Dynamics program that simulates fires.

**Keywords:** Wildfire; Chaparral; Fire Dynamic Simulator; Computational Fluid Dynamic Model; Wind Tunnel; Crown Fire; Chamise; Experimental Modeling

## FACULTY MENTOR

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Doctor Princevac is interested in fundamental and applied fluid mechanic research – in particular, the application of fundamental turbulence concepts to studies in environmental flows. During his graduate studies and a short post-doctoral period afterward, he gained a strong background in laboratory and field experimental work. This helped him identify some physical phenomena and build simple physical laboratory models that can successfully explain complex field observations or a part thereof. He also has experience in developing idealized theoretical models to explain fluid dynamic processes.

## AUTHOR

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Chirawat Sanpakit is a second year Honors student majoring in Mechanical Engineering. As an HSI recipient, he conducts research in Dr. Marko Princevac's Laboratory for Environmental Flow Modeling. Working closely under Christian Bartolome (Ph.D.), undergraduate students, and the team from the USDA Pacific Southwest Research Station, he systematically explored mechanisms of Chaparral Wildfire in order to develop plans to combat or utilize them. He will serve as the 2015-2016 ASME Vice President and he hopes to pursue his Ph.D. in Aerospace Engineering or Mechanical Engineering.

## INTRODUCTION

Wildland fires pose both serious economic and safety problems. Having the ability to predict the potential behavior and effects of wildland fires is an essential task in fire management (Scott et al., 2005). Wildfires are complex phenomena and most models used in the U.S. operationally (see review by Engstrom et al., 2010) are based on the empirical correlations developed by Byram (1959), Fosberg and Deeming (1971), Rothermel (1972), Van Wagner (1973) and Albini (1976). Many of the models, such as FARSITE (Finney, 1998) and BEHAVE (Andrews, 1986), are suitable for use by fire managers. Despite their usefulness, the models are limited to surface fuels in rangelands and forests. Moreover, prediction of spread rates and fire intensity for live vegetation are not very accurate (Engstrom et al., 2010). Thus, to improve these models, numerous studies are being conducted on wildland fires. However, very little research has been done on chaparral crown fires with live vegetation. To address this disparity, an experimental design was developed to study crown fires.

## CONCEPTUAL FRAMEWORK

Our research focused specifically on the surface-crown interaction of wildland fires. Crown fire is a type of wildland fire that spreads faster than surface fires and occurs in elevated foliage (Rothermel, 1983). To improve current models of wildfires and their transition to tree crowns, fire experiments were conducted in a wind tunnel. Each experiment focused on understanding the behavior of chaparral crown fires, particularly the ignition, mechanism of flame propagation, spreading, flame front velocities, and fuel consumption rates. A Computational Fluid Dynamics (CFD) model was also deployed to predict and observe fire behavior. The Fire Dynamics Simulator (FDS) (McGrattan et al., 2013) was selected as the CFD model since it is readily available and has been modified for use in wildland fuel beds (Mell et al., 2009). Although computationally slower when compared to empirical models, CFD modeling is generally more accurate.

## METHODOLOGY

All experiments were conducted inside of a wind tunnel (Figure 1) at the USDA Forest Service, Pacific Southwest Research Station (PSWRS). Once activated, a large fan spins at 40 Hz, simulating wind moving at 1m/s on the flames. Each test utilized load cells, MATLAB, thermocouples, scales, wet-bulb hygrometer, and video analysis for data gathering. To model surface fuel and crown fuel, 500 grams of excelsior (shredded wood) and 2000 grams of chamise, a common chaparral shrub were used, respectively. The chamise was harvested locally from the North Mountain Experimental Area to minimize moisture loss. Wind velocity, height of the crown fuel, presence of surface fuel, and fuel moisture content were changed between experimental runs. The gathered data was used to analyze the resulting flame heights, flame front propagation velocities, and fuel consumption rates.

***Figure 1:*** *Live burn being conducted on chamise (Upper platform) by ignition of excelsior (lower platform) inside of the wind tunnel.*

### Experimental Classifications

The experiments were classified into six specific classes based on the presence of the excelsior surface fuel bed, the height to the base of the crown fuel bed, and wind velocity. Table 1 presents what variables were involved and what parameters were kept constant for each class (A-F).

***Table 1:*** *Organization of different classes of experiments.*

| Classification | Surface Fuel Bed | Wind | Crown Height |
|---|---|---|---|
| A | Absent | No wind | 60 or 70 cm |
| B | Absent | 1 $ms^{-1}$ | 60 or 70 cm |
| C | Present | No wind | 60 cm |
| D | Present | No wind | 70 cm |
| E | Present | 1 $ms^{-1}$ | 60 cm |
| F | Present | 1 $ms^{-1}$ | 70 cm |

## Setup of the Experiments

A wire mesh basket was raised to the specified height to model the crown fuel. Five equally spaced thermocouples were placed in the crown fuel to measure the temperature and, indirectly, the crown fuel flame spread rate. The 2000 g of chamise were evenly distributed in the wire basket. The surface fuel bed was laced with ten, equally spaced, thermocouples that were also used to measure the temperature and surface flame spread. The 500 g of excelsior was evenly spread across this surface. Load cells were placed under the surface fuel bed to measure mass loss rate. Before the start of each trial, samples of chamise were collected to determine the fuel moisture content. Finally, each experiment was recorded using a video camera. The setup is depicted in Figure 2.


***Figure 2:*** *Setting up of live experiments. Excelsior is uniformly spread on surface.*

For experimental classes C-F, the surface fuel was ignited by a hand-held lighter along a line of ethyl alcohol, perpendicular to the wind. For experiments A and B, the crown was directly ignited.

## Fire Dynamic Simulator

The Fire Dynamics Simulator (FDS) is a CFD model that solves a numerically discretized form of the Navier-Stokes equation for low speed, thermally-driven flow and/or scalar transport in fire structures (McGrattan et al., 2013). The equation is solved on a user-specified 3-D mesh (grid) and the model becomes more accurate, though more computationally intensive, as the distance between grid points is decreased. The model was formulated to simulate fire in rectangular buildings so rectilinear grids are the simplest numerical grids applicable. Because FDS is a large eddy simulation (LES) model, uniform mesh spacing is preferred. Once the mesh is established, a rectangular object that defines the geometry is easily created. The model's governing equations of the conservation of mass, momentum and energy, are approximated using second-order finite differences on a collection of uniformly spaced three-dimensional grids (McGrattan et al., 2013).

## Combustion and Radiation Model in FDS

To be able to simplify and make the fire simulation tractable, the FDS model assumed that the number of fuels was limited to one, the number of reactions was just one or two at most, the incoming air stream was left open due to the possibility of the fire extinguishing from a lack of oxygen, and that the air was neither fuel or product and was treated as a single gas species. FDS uses a modified finite volume method to calculate radiative fluxes during simulations. This method is derived from the Radiative Transport Equation (RTE) for non-scattering grey gas (Hume, 2003). FDS assigns the temperature generated from a flame sheet to adjacent cells. This can greatly impact calculated radiation because of radiation's large dependence on temperature.

## Deployment and Output of FDS

The user builds an input file that details information such as grid size, geometry of the scenario being modeled, or boundary conditions. For visualization, the output is shown in Smokeview (Figure 3), a packaged add-on in FDS. Quantitative data display uses techniques such as 2D and 3D contouring. A realistic display is used to present the data in a form that would actually appear in real life (Fourney, 2013).

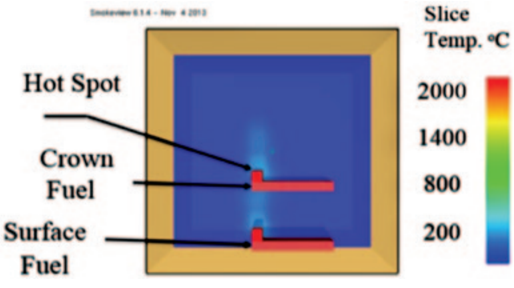


***Figure 3:*** *2D viewpoint of a simulation outputted in Smokeview. Hot Spot is introduced in a way such that the buoyant flow of hot air is induced. This effect represents a firebrand in the live experimental setups.*

## RESULTS

The crown fire experiments were repeated at least 9 times per class in order to ensure the repeatability and accuracy of results. For each experiment, we determined the flame front velocity, flame height, and heat production.

### Flame Front Velocity

Flame propagation velocity was obtained from the analysis of thermocouple data after several experimental trials (Figure 4). The peak temperatures of each thermocouple were determined to indicate the flame arrival, and the thermocouple distance was then divided by time between temperature peaks to obtain the desired velocity. Note that 4 out of the 8 crowns in class C, as well as 2 of the 8 crowns in class D, failed to ignite despite the surface flames. Similarly, no experiments in class A were able to burn to completion.

### Flame Heights

All heights shown in Figure 5 are averages of still images that were captured from video analysis of experiments. However, crown flame height exceeded the frame of the video and could not be calculated in class C-F. Flame height and length are used interchangeably in literature, but for the purpose of this research, the vertical distance to the flame tip was referred to as the flame height (Alexander and Cruz, 2012).

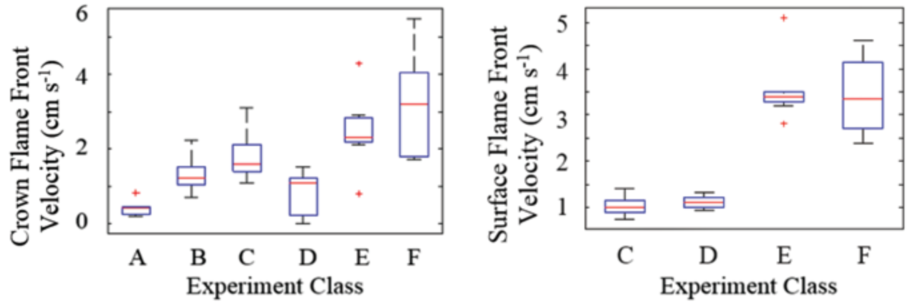


***Figure 4:*** *Calculated Flame Front Velocities. (a) Velocities for Crown fuel. (b) Velocities for Surface fuel.*

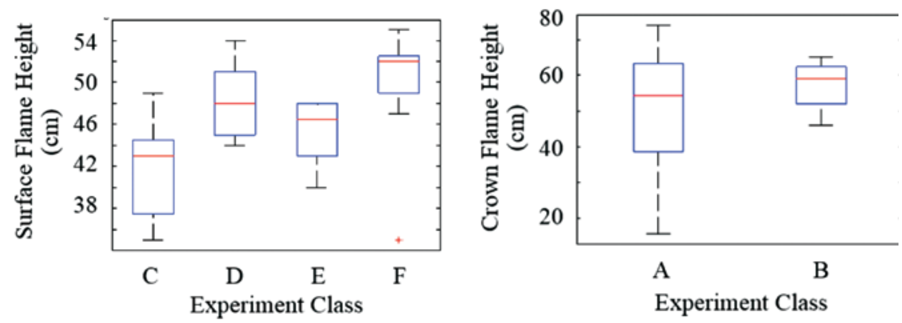


***Figure 5:*** *Flame heights of live experiments. (a) Height of Surface fuel flames from video analysis of live experiments. (b) Flame heights for the crown fuel bed. Class C-F experiments exceeded frame of video and thus could not be calculated.*

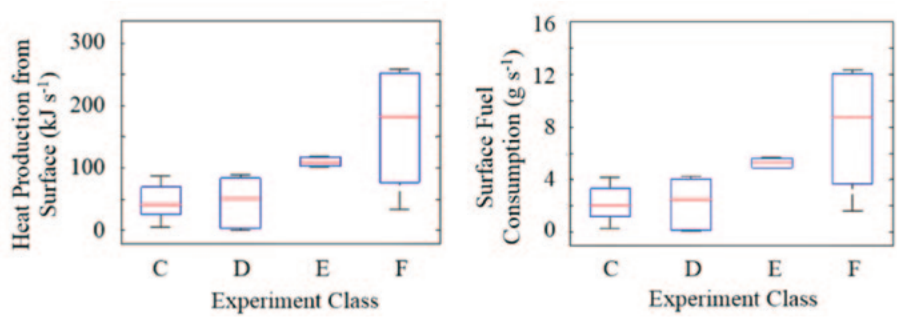


***Figure 6:*** *Vegetation burn off rate. (a) Calculated heat production rate of Surface fuel. (b) Mass consumption rate of Surface fuel from load cell data.*

### Fuel Consumption

The burning rate of the surface fuel was investigated (Figure 6) and can be effectively expressed as $q = H\,dm/dt$, where $q$ is the energy released, $dm/dt$ is the mass loss rate per unit time (fuel consumption rate), and $H$ is the heat value of the material being burned.

## Results of Fire Dynamic Simulator

Five classes of simulations were run for 8-40 seconds of simulation time. Surface fuel bed depth and height between fuel beds were kept constant at .2 and .7 meters, respectively. Table 2 shows the classes of FDS simulations and their respective parameters. Table 3 shows values of the simulation parameters as well as resulting burnout times.

***Table 2:*** *Classes of FDS simulation and their parameters.*

| Class | Surface Fuel | Crown Fuel | Hotspot on Surface | Hotspot on Crown |
|---|---|---|---|---|
| 1 | Absent | Present | Present | Present |
| 2 | Present | Present | Present | Absent |
| 3 | Present | Present | Present | Present |
| 4 | Present | Absent | Present | Absent |
| 5 | Present | Present | Present | Absent |

***Table 3:*** *Parameters of various simulations within each class and burnout time results.*

| Simulation # | Class | Bulk Density (kg/m$^3$) | Hot Spot (deg. C) | Burnout Time (sec) |
|---|---|---|---|---|
| 1,2,3,4 | 1 | 20,15,10,5 | 5000 | 8,7.99,6.95,4.85 |
| 1,2,3,4 | 2 | 20,15,10,5 | 5000 | 7.99,7.5,5.7,4.46 |
| 1,2,3,4 | 3 | 20,15,10,5 | 5000 | 7.6,6.32,5.51,4 |
| 1,2,3,4 | 4 | 20,15,10,5 | 5000 | 7.98,7.78,6.46,5.08 |
| 1,2,3,4 | 5 | 15 | 5000,6000,7000,8000 | 8.65,7.14,6.46,5.24 |

## DISCUSSION

Experiments were conducted over several classes. Each class depicted a change in either crown height, presence of surface fuel, wind, fuel moisture content, or any combination of these parameters. Ignition temperature is the critical fuel temperature at which flaming combustion initiates (Saito, 2001; Williams, 1982). Thermocouple data showed that hot gases from the surface fuel provided convective heating and raised the chamise's temperatures to 564K, above the reported ignition temperature of 523K for chamise (Babrauskas, 2003).

The largest contributing factor to the flame's propagation speed, consumption rate, and height was the addition of wind. The fuel consumption rate, crown speed, and height all increased, as shown in figure 4, 5 and 6, due to the addition of wind. The wind caused the flame to bend over, which allowed the fuel to be preheated more efficiently. This led to an increase in the measured parameters when compared to no wind conditions.

## CLASSIFICATION A-F

The class A setup produced an extremely slow moving flame that was never able to completely consume the crown. The class B setup (Figure 7) included wind which caused the flame tilt. The flame front velocity increased approximately 3 times from .42 cm s$^{-1}$ to 1.30 cm s$^{-1}$ when compared to class A and in 78% of the cases, the crown was completely consumed. Heat production of class B was estimated to be 235.5 kJ s$^{-1}$. Class C experiments (Figure 8) studied the interactions between surface fuel and crown fuel at 60 cm crown height without the addition of wind. A more columnar flame was observed and results showed that the surface flame did in fact help with the propagation of crown flames. Here, there were 78% of cases with a successful crown ignition due to surface flames and 44% of the cases had full crown consumption.

***Figure 7:*** *Class B Experiment. Flame velocity and fuel consumption rate rise significantly due to added wind.*

***Figure 8:*** *Class C Experiment. The propagation of crown flame is furthered by addition of surface fuel.*

***Figure 9:*** *Class E Experiment. Flame velocity and overall intensity is substantially higher due to addition of surface fuel and wind parameters.*

Crown heat production was found to be 412.0 kJ $s^{-1}$. Class D was similar to class C, except for the fact that the crown height was raised to 70 cm. This class exhibited torching at the mid-section, ignition near the middle of the crown bed, and backfires. Class D had a 75% crown ignition rate and 50% of the cases had full crown consumption. Moreover, the crown flame velocity was considerably less at 1.14 cm $s^{-1}$ for class D versus 1.82 cm $s^{-1}$ for class C. Here, the additional height seems to create difficulty for crown flame ignition to occur and also led to the slowdown of the crown flames themselves. Crown heat production was approximately the same as class C, producing 348.8 kJ $s^{-1}$. Class E experiments (Figure 9) were setup to investigate the interactions of surface and crown fuels at 60 cm crown height with the addition of wind. Both surface flame velocity and crown velocity increased significantly when compared to prior experiments, averaging at 2.47 cm $s^{-1}$ for the crown velocity. Also, 100% of the experiments showed crown ignition due to surface flames, furthering the idea that wind was a major contributing factor to the flame's overall properties. Class F experiments are identical to class E except for the crown height, which was 70 cm. Despite the difference in height, class E and F experiments were almost identical in terms of how the flames moved. The surface flame had no trouble igniting the crown, resulting in an 89% ignition rate. The crown was completely consumed 78% of the time and 89% of the time for class E and F, respectively. A considerably higher crown flame velocity was observed than class E, averaging at 3.16 cm $s^{-1}$. Finally, heat production between class E and F were fairly close to each other, averaging 575.5 kJ $s^{-1}$ for E versus 616.8 kJ $s^{-1}$ for F. Note that due to a lack of load cells, crown fuel consumption rate and heat production were not found in the same way as the surface fuel. Instead, a mass loss rate was determined by assuming the 2000 g of chamise burned evenly over the time it took the flames to entirely consume the fuel. Resulting heat production was later calculated and averaged. Class A was not available because 0 cases resulted in full crown fuel consumption. Data and video analysis supported observations and all results are summarized in Table 4.

*__Table 4:__ Summary of results from surface fire/crown fire transition experiments.*

| Class | Crown Ignition Rate (%) | Full Crown Consumption Rate (%) | Crown Flame Front Velocity (cm $s^{-1}$) | Heat Production (kJ $s^{-1}$) |
|---|---|---|---|---|
| A | No Surface Fuel | 0% | .42 | N/A |
| B | No Surface Fuel | 78% | 1.30 | 235.5 |
| C | 78% | 44% | 1.82 | 412.0 |
| D | 75% | 50% | 1.14 | 348.8 |
| E | 100% | 78% | 2.47 | 575.5 |
| F | 89% | 89% | 3.16 | 616.8 |

## Evaluation of Fire Dynamic Simulator

The results from Tables 2 and 3 show that in FDS modeling, the burn rate of solid fuels depended on flame temperature, bulk density, fuel thickness, and height between crown and surface fuel. A high hot spot temperature led to a faster burning rate, such as 8000K leading to a burnout rate of 5.24 seconds versus 5000K leading to a burnout rate of 8.65 seconds. Also, burning rate was inversely proportional to the bulk density of the solid fuel. A bulk density of 20 kg $m^{-3}$ yielded a burnout time of 8 seconds versus 5 kg $m^{-3}$ which yielded a burnout time of 4.85 seconds. The results in Table 3 also show that burnout times for simulations containing surface and crown fuel were shorter than simulations with only crown or only surface fuel. Finally, the burnout time of reacting solid fuel was automatically calculated by FDS as $t = (\rho\delta\Delta H)/q''$ where $\delta$ is the fuel layer thickness, $\Delta H$ is the heat of combustion, $\rho$ is material density, and $q''$ is the heat released.

## CONCLUSION

The laboratory experiments conducted on live chaparral crown fuel have shown that several variables can aid in the propagation of flames, which includes the addition of wind, decreased distance from surface flame, and presence of surface fuel. The CFD model deployed has also confirmed some of what was seen in the laboratory experiments, such as the shorter burnout times when both surface and crown fuel were present. The results gathered can be used to improve current models on wildland fires, which could lead to saving lives and property, especially in chaparral areas of California. Future work needs to be done on developing an experimental setup that can more successfully capture the crown flame heights as well as solving the problem of numerical instability that sometimes occurred in FDS. The other problem was the inability for FDS to recognize two fuels of different materials in the same simulation. Future development could yield a solution to this issue.

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