P5.3 IGNITION BEHAVIOR OF LIVE CALIFORNIA CHAPARRAL LEAVES

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1. ABSTRACT

Current forest fire models are largely empirical correlations based on data from beds of dead vegetation. Improvement in model capabilities is sought by developing models of the combustion of live fuels. A facility was developed to determine the combustion behavior of small samples of live fuels, consisting of a flat-flame burner on a moveable platform and a horizontal balance. Qualitative and quantitative combustion data are presented for representative samples of California chaparral (manzanita, scrub oak, hoaryleaf ceanothus, and chamise). Ignition temperature data for each sample type followed a bell shape curve, whereas time to ignition data varied based on the sample non-uniformity.

Keywords: Wildland Fires, Ignition

2. INTRODUCTION

Current forest fire models in the United States are based on the extensive empirical correlations developed by Rothermel (1972), Van Wagner (1973), Albini (1976), Byram (1958), Fosberg and Deeming (1971) and others. The operational models currently used by fire managers are FARSITE (Finney, 1998) and BEHAVE (Andrews, 1986), which use the empirical correlations to account for effects of fuel quantity and type, wind, and slope. These models have proven to be accurate for prediction of surface fire spread rates in forests and rangelands under many conditions from which the empirical correlations were developed. Fire spread rates and intensity in live vegetation are also predicted by these models, but with less accuracy.

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Combustion data for live vegetation must be obtained in order to improve current forest fire models, especially when trying to predict when fires move from the ground to the tree crowns and for predicting flare-ups.

The combustion behaviors of 20 live and dead fuels were investigated by Susott (1982) using thermal gravimetric analysis (TGA). Very little difference was observed in the pyrolysis behavior of leaves of different species, although differences were observed between classes of vegetation, such as between leaves and bark. The differences in pyrolysis behavior observed in the TGA between the different shredded live fuel samples do not explain observed variations in combustion behavior such as flame height and brands. Brands are burning pieces of fuel that are separated from the rest of a burning fuel body and lofted away. These burning pieces of fuel have the potential to start fires in new locations, also called spotting (Tarifa et al. 1965, Woycheese 2000).

The lack of variation in the pyrolysis behavior of the live vegetation samples studied by Susott seems to indicate that combustion behavior of live vegetation is limited by the effects of heat and mass transfer. Therefore, in order to understand the differences in live fuel combustion behavior, an apparatus was developed to study the combustion behavior of whole leaf samples. This paper describes the characterization of this apparatus and the first data on combustion behaviors of live vegetation.

3. EXPERIMENTAL APPARATUS

The experimental apparatus was designed to closely resemble the conditions of a forest fire flame front. Two modes of heat transfer are involved in fire spread, namely radiation and convection. Heat energy from radiation initially preheats the fuel while heat from convection brings the fuel to the ignition temperature. Temperatures in wildland fires are thought to be about 1200 K, with heating rates of approximately 100 K/s (Butler, 2002).

To simulate this condition the fuel sample was attached to a stationary horizontal rod connected to a cantilever-type mass balance. A flat-flame burner (FFB) was positioned on a moveable platform to simulate the flame front. A 6000W, 25.4 cm-square quartz radiative heating panel was also positioned on the moveable platform to simulate radiative heating ahead of the flame front. However, the radiative panel was not used in the experiments described here. The platform was pulled by a 0.5 hp motor at a constant velocity toward the fuel sample. The post-flame gases from the flat-flame burner simulated heat transfer by convection. The experimental apparatus is shown in Figure 1.

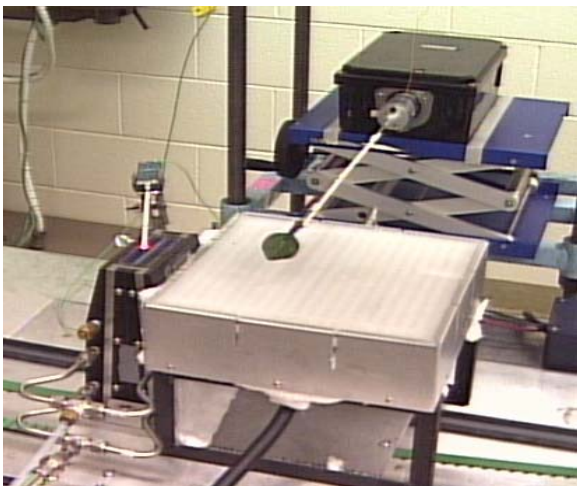

Figure 1. Experimental apparatus, showing the flat-flame burner (lower left), radiative heating panel (center), and cantilever mass balance (top right).

Methane, hydrogen, nitrogen, and air were fed into the FFB to make a stable flame to provide the heat source for the experiment. The fuel and air were passed through a honeycomb mesh, mixed, and ignited to form small diffusion flames that burned approximately 1-mm above the FFB surface. The gases were fed such that post-flame conditions consisted of approximately 10 mol% oxygen. Figure 2 demonstrates the profile of a 127 μm diameter type K thermocouple 5 cm above the FFB. The temperature at this location above the FFB was determined by igniting the FFB 10 times and allowing the thermocouple to come into equilibrium. For the ten repeat experiments, the average temperature was 987 °C and the standard deviation was 11.9 °C. Temperature was not adjusted to account for radiative heat loss.

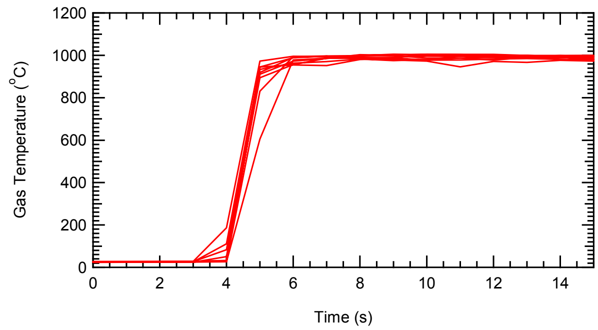

Figure 2. Time-dependent gas temperature measurements with the thermocouple held 2" above the flat-flame burner surface.

The optimal location for sample placement was determined using an IR camera (FLIR Thermacam SC 500‡), operating in the wavelength range between 7.5 and 13 μm. The IR camera showed the thermal characteristics of the post flame gases from the FFB (CO_2 and H_2O) rather than the flaming combustion (i.e., soot) of the burning manzanita leaf. The temperature profile of the post-flame gases above the FFB is shown in Figure 3. The edges of the horizontal manzanita leaf appear brighter than the surrounding flame due to the low emissivity of the combustion gases.

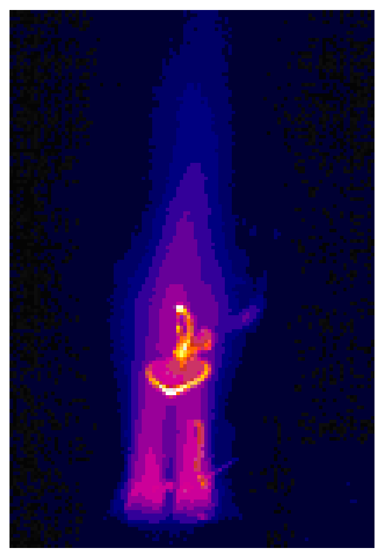

Figure 3. Infrared image of a horizontally-oriented manzanita leaf in the post-flame gases of the FFB.

A sharp interface can be seen in Figure 3 between the hot post-flame gases from the FFB and the surrounding air at room temperature. The

‡ Trade names are presented for information purposes and do not constitute endorsement by the U. S. Department of Agriculture

sharp temperature interface of the FFB post flame gases explains the sharp rise in the thermocouple temperature profiles of Figure 2. The thermocouple temperature does not rise until the FFB is directly under the thermocouple. In a similar manner, samples of vegetation are not pre-heated by the FFB until the FFB is directly under the sample. A sample height of 5 cm was chosen in these experiments so that the sample was well within the hot zone of the post-flame gases.

Leaf surface temperature data were obtained at 60Hz using 127 μm diameter type K thermocouples (Omega). The thermocouple was embedded in a pinhole in the leaf edge near the ignition point for the manzanita (*Arctostaphylos parryana*), scrub oak (*Quercus berberidifolia*), and hoaryleaf ceanothus (*Ceanothus crassifolius*), samples. Thermocouple data were not taken for the chamise (*Adenostoma fasciculatum*) samples. The thermocouple signal was fed into a PCI 4551 (NI) data acquisition (DAQ) card, yielding temperature data at 60 Hz. Video data were obtained at 30 frames per second (fps) using a PCI 1411 (NI) DAQ card and a Hi-8 camcorder (Minolta 8-918). Video, mass loss, and temperature data were collected using a program written in LabVIEW 6.0 (National Instruments). All of the mass, video, and temperature data were time stamped for quick and accurate comparison.

4. SPECIFIC OBJECTIVES

The objective of this project was to determine both qualitative and quantitative differences in combustion behavior of freshly cut leaf samples from the California chaparral, namely: manzanita; oak; ceanothus, and chamise (see Figure 4). The qualitative behavior was observed using the video camera. Differences in combustion behavior were noted with different sample types and by changing the sample type, shape, and orientation above the flame. Temperature and video data were gathered and compared to quantitatively determine the ignition temperature and time to ignition for the broad leaf samples (manzanita, oak, and ceanothus). It was not possible to obtain temperature data for the chamise samples.

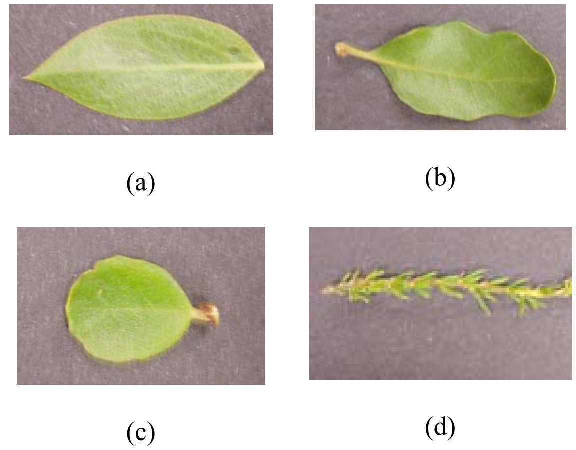

Figure 4. Representative photos of California chaparral samples: (a) manzanita; (b) oak; (c) ceanothus; (d) chamise.

5. RESULTS AND DISCUSSION

5.1 *Qualitative Experiments*

Combustion experiments on all four leaf samples were performed in the FFB to determine ignition location as well as shape and orientation effects. Data were recorded with the video camera. The chamise samples were separated from the broad leaf samples when studying effects of shape and orientation.

The effect of the sample shape was investigated and it was found that the leaves ignited in a similar pattern for the broadleaf species when cut in similar shapes. Round shaped samples ignited along the perimeter of the sample then propagated towards the center. The square-shaped samples ignited first at the corners then propagated along the perimeter before burning towards the middle (Engstrom et al., 2003).

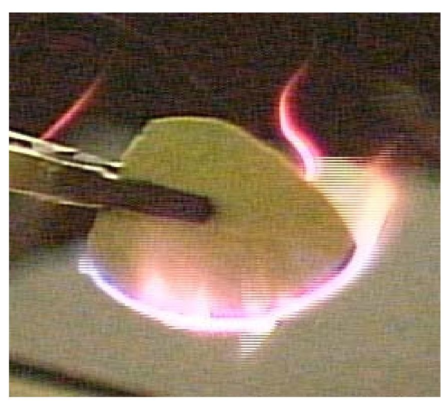

Figure 5. Combustion photo of a vertically-oriented manzanita sample.

There was a significant effect of leaf orientation on combustion behavior; broad leaves held horizontally exhibited quite different combustion behavior than broad leaves held vertically. When the leaves were oriented vertically above the flat-flame burner, the leaves ignited at the edge closest to the flame and propagated to the top edge of the leaf regardless of shape differences (Figure 5).

In the horizontal configuration of the manzanita leaves, bubbles were observed on the leaf surface prior to ignition, indicating either moisture evaporation or degradation of the waxy layer on the surface of the leaves. At higher moisture content, the bubbles burst on the surface leaving crater like holes on the leaf before burning (Figure 6). Bursting was only observed when moisture content was near 100%. The bursting occurred slightly before ignition.

Figure 6. Bursting of bubbles on the surface of manzanita leaf.

Horizontally-held manzanita leaves ignited almost uniformly around the leaf perimeter before burning in towards the center of the leaf (Figure 7).

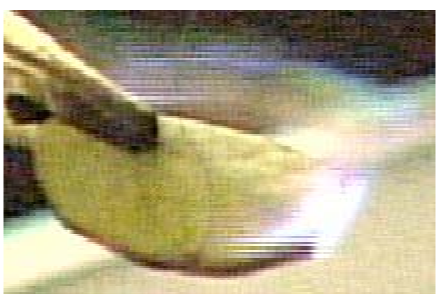

Figure 7. Combustion photo of a round-shaped manzanita sample burning horizontally above the FFB.

Oak leaves in the horizontal orientation exhibited different characteristics than manzanita. Many of the oak leaves had sharp points (i.e., spines) around the outer edge. The oak leaves would ignite at these points, sometimes accompanied by small explosions of the points that led to the ejection of small brands (see Figure 8). The ignition at the points was followed by ignition along the perimeter then burning towards the center of the leaf.

Figure 8. Combustion photo of an oak sample above the FFB with brands exploding off after ignition.

These qualitative experiments on the broad leaf samples identified the approximate ignition location, which was where the thermocouples were placed in subsequent quantitative experiments (described below) to measure ignition temperatures and ignition delay times.

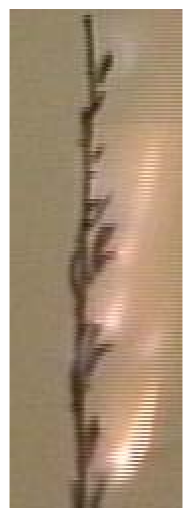

Figure 9. Combustion photo of chamise burning in the vertical orientation.

As shown in Figure 4, chamise consists of both the small green needles and the stem, both of which contribute to combustion. When the chamise was burned by the FFB, the needles on the stem would ignite first at the tips, as shown in Figure 9. The first needles to ignite in the vertical position were the ones closest to the FFB. Once the bottom needles ignited, the flames would propagate to the top needles. It was observed that after flaming combustion had neared completion for the needles, the stem would begin flaming combustion. When the chamise was burned in the horizontal position above the FFB, the needles ignited first along the entire sample, followed by the ignition of the stem. Flame propagation from the bottom needles to the top needles was not observed in the horizontal configuration, which was different from the vertical configuration.

As the chamise burned, occasionally a brand would be lofted off the main stem and float away from the FFB (Figure 10). The image in Figure 10 was taken with the IR camera, and the image of the brand was circled. Brands have the potential of landing in a spot beyond the main fire and starting a new fire. Of the four fuels studied, chamise and oak were the only ones that were observed to generate brands.

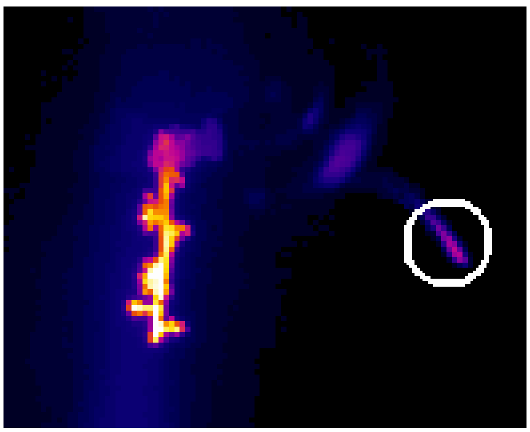

Figure 10. IR image of burning chamise (bright yellow) with a burning brand (circled).

Since the chamise needles were small and the stem was thin, it was not possible to place a thermocouple with a bead as large as 127 μm through a pinhole in this sample. Therefore, only these qualitative observations were made with chamise.

5.2 *Quantitative Experiments*

Quantitative data (i.e., ignition temperature and time to ignition) were gathered for manzanita, oak, and ceanothus, and are discussed by Engstrom et al. (2003). The focus of this work is additional experiments performed on fresh manzanita and oak samples. Engstrom and coworkers also performed measurements on paper samples that were cut to a uniform size and shape to demonstrate the repeatability of the experiment. For this experiment, ignition temperature was defined as the temperature when a flame was first visible. The thermocouple was placed at the point where ignition would first occur. The video data and thermocouple data were recorded simultaneously and had a synchronous time stamp attached to each video frame and thermocouple reading. The ignition temperature was determined for each sample by matching (a) the time stamp of the video frame showing the first visible flame to (b) the temperature time stamp.

The average ignition temperatures for the samples ranged between 300 and 500 °C (see Table 1 and 2). Moisture content was observed to influence the ignition temperature in oak and manzanita samples (see Tables 1 and 2). The samples with high moisture content were observed to ignite at temperatures that were 80 to 140 °C higher than the low moisture samples. Ignition temperature data have not yet been collected for high moisture ceanothus samples. The influence of moisture content on the ignition temperature was more significant than expected. However, this effect is repeatable, and should be explored further.

Table 1. Oak ignition temperature and time to ignition statistics

Moisture Content	Average Ignition Temperature (°C)	Standard Deviation (σ in °C)	Average Time to Ignition (sec)	Standard Deviation (sec)
< 5%	311	74	---	---
7%	343	72	0.905	0.422
43%	485	121	1.83	0.73

Table 2. Manzanita ignition temperature and time to ignition statistics

Moisture Content	Average Ignition Temperature (°C)	Standard Deviation (σ in °C)	Average Time to Ignition (sec)	Standard Deviation (sec)
< 5%	346	61	---	---
19%	380	82	2.07	1.17
76%	463	71	8.35	1.5

Histograms of ignition temperature for the low moisture samples, along with the paper samples, are shown in Figure 11. The distribution in ignition temperature seems to follow a normal distribution, and seems to be narrower for the paper samples. Sample to sample variation in size, shape, moisture content, orientation, etc., gives rise to these variations.

The ignition time was based on the amount of time it took for the sample to ignite once the sample was above the flat-flame burner. The start time was defined as the time when the temperature reached 30°C. The ignition time was calculated by subtracting the time stamp of the first thermocouple reading at or above 30°C from the time stamp of the thermocouple reading at the point of ignition.

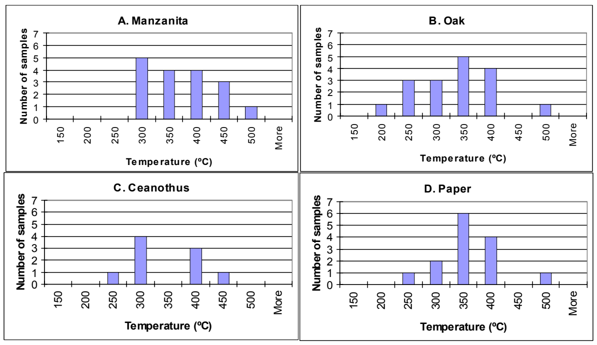

Figure 11. Ignition temperature histograms: (a) manzanita; (b) oak; (c) ceanothus; (d) paper

The effects on ignition temperature and time to ignition of varying moisture content for oak and manzanita can be seen in Tables 1 and 2, respectively. A significant change in the average ignition temperature was observed for both species. A more substantial change in ignition time was seen in the manzanita samples than the oak.

The histograms for the low moisture data on time to ignition are shown in Figure 12. The ignition times show more scatter, since heatup times are more a function of size, shape, and moisture content than ignition temperature. The relatively uniform paper samples showed the narrowest distribution, demonstrating the repeatability of the experiment.

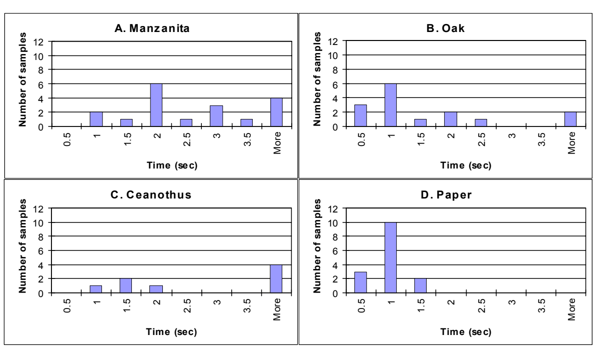

Figure 12. Histograms of measured time to ignition: (a) manzanita; (b) oak; (c) ceanothus; (d) paper.

The manzanita data were studied in more detail to show the effects of leaf thickness on the surface temperature history. Figure 13 shows how leaf thickness leads to slower heating, due to heat transfer effects. Similar data analysis of other experiments is planned, which should lead to better heat transfer correlations for these types of leaves as a function of thickness and moisture content.

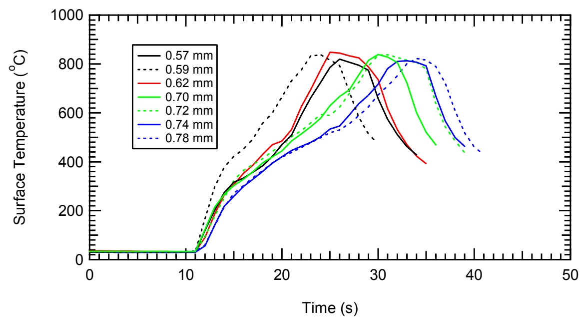

Figure 13. Temperature profiles for horizontally-oriented manzanita of varying thickness.

These data show that moisture content seems to greatly influence ignition temperature. Chemical composition (i.e., samples of different species) was also shown to affect ignition temperature (compare samples of similar moisture content in Tables 1 and 2). The time to ignition for samples of similar moisture content but different species seems to vary significantly, indicating that leaf heatup is influenced by moisture content, size, shape, thickness, and possibly chemical composition.

6. CONCLUSIONS

An experiment was developed to study the combustion behavior of live fuels, focusing on size, shape and moisture content factors of leaves. Qualitative experiments with the broad leaf samples have shown that combustion behavior varies with shape and orientation. Vertically-oriented samples ignited first at the bottom edge, while horizontal samples ignited first in the gas phase slightly above the leading edge of the leaf, followed by surface ignition at the leaf edge. Small bubbles were observed in the central part of horizontally-oriented broad leaf samples prior to ignition. When moisture content in manzanita exceeded 100% these bubbles burst before ignition, causing small craters in the leaf surface. Flame propagation through the chamise needles was observed in the vertical orientation, but not the horizontal orientation. Small brands of chamise were observed to detach and be carried away by gas currents during the late stages of burning. Small brands of oak samples were observed to detach in an explosive manner from the points on the leaves near the time of ignition.

Quantitative measurements of ignition temperature and time to ignition were made for the broad leaf samples, as well as for samples of paper. The ignition temperature did not appear to be a significant function of size and shape factors for each sample type but rather a function of moisture content and fuel type. However, the time to ignition was significantly affected by the type, size, shape, orientation, and the moisture content of the sample. The experiments performed on uniform paper samples showed much less variation in the time to ignition than did the broad leaf experiments.

These experiments show promise for understanding the details of the ignition and combustion processes for leaves in a wildland fire environment. The qualitative and quantitative data from this experiment should prove valuable in developing correlations to improve descriptions of combustion behavior in wildland fire models.

7. ACKNOWLEDGEMENTS

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