EFFECTS OF MOISTURE ON COMBUSTION CHARACTERISTICS OF LIVE CALIFORNIA CHAPARRAL AND UTAH FOLIAGE

by

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GRADUATE COMMITTEE APPROVAL

of a thesis submitted by

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ABSTRACT

EFFECTS OF MOISTURE ON COMBUSTION CHARACTERISTICS OF LIVE CALIFORNIA CHAPARRAL AND UTAH FOLIAGE

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Current fire-spread models are based largely on empirical correlations based on fires burning through dead pine needles. There is a need to increase the accuracy of modeling wildfires in live vegetation. This project investigates the quantitative and qualitative ignition characteristics of eight live fuels, four from southern California (manzanita, scrub oak, ceanothus, and chamise) and four from Utah (canyon maple, gambel oak, big sagebrush, and Utah juniper). Individual leaves were observed as they were exposed to hot gases from a flat flame burner.

The broadleaf species from both California and Utah had noticeable surface changes during the ignition process. All fresh samples showed a color change on the leaf surface from a light dusty color to a dark wet color. This is likely due to the melting of the waxy protective layer. Samples of scrub oak, manzanita, ceanothus, canyon maple,

and gambel oak at moderate moisture contents (50 to 75%) exhibited bubbling under the leaf surface. Liquid droplets were observed on the surface of Manzanita samples at moisture contents near 75%, while bursting was observed on the surface at moisture contents near 100%. This bursting is due to evaporation of the moisture inside the leaf causing internal pressures to exceed the surface strength of the leaf.

Ignition was defined as the time when the first visible gaseous flame was observed near the leaf surface. Measurements of the time to ignition and the temperature at ignition were performed for all broadleaf species. A large degree of scatter was observed in the quantitative ignition data, due largely to variations in leaf thickness and moisture content. Time to ignition was found to correlate with sample thickness and the mass of moisture in the sample. Ignition temperature was constant for varying moisture mass but appeared to increase with thickness. The burning time, defined as the duration of a visible flame near the leaf, was found to correlate roughly with leaf mass. Several types of correlations were made to describe ignition temperature and ignition time as a function of leaf thickness and mass of moisture.

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I would like to thank Josh Engstrom and Jordan Butler for designing and building the experimental apparatus prior to my joining the project and for their preliminary work on this project. I would also like to thank Greg Spittle who worked long summer hours with me living our childhood dreams of burning leaves. I appreciate the support of Michael Clark, he was always willing to discuss the project and add his ideas. Thanks also to more recent contributors, Megan Woodhouse and Brent Pickett, with experiments and analysis.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

NOMENCLATURE

A	surface area (m^2)
Bi	Biot number
C_p	heat capacity (kJ/kg/°C)
C_1	constant in equation 1 (sec^{-1})
C_2	constant in equation 1 (1/°C)
C_3	constant in equation 1
D_{eff}	effective diffusivity (m^2/s
H	enthalpy (J/kg)
MC	moisture content (oven-dry basis)
T	average sample temperature (°C)
T_{gas}	gas temperature (°C)
T_i	initial leaf temperature (°C)
T_{ig}	ignition temperature (°C)
U_∞	gas velocity (m/s)
a	coefficient used in Equations 2, 8
b	coefficient used in Equation 2, 8
c	coefficient used in Equation 8
h	convection heat transfer coefficient (kW/m^2/°C)
k	thermal conductivity (W/m/°C)
m	mass (kg)

m_f	final mass, after drying (gm)
m_{H2O}	mass of moisture (gm)
m_0	original mass (gm)
q''	heat flux (kW/m^2)
t	time (sec)
t_{flame}	burnout time (sec)
t_{ig}	ignition time (sec)
u	velocity (m/s)
ΔH_{vap}	heat of vaporization for water (kJ/kg)
Δx	sample thickness (mm)
ε	emissivity or porosity
ρ	density (kg/m^3)

Subscripts

g	gas phase
s	solid phase

1. Introduction

Centuries ago, low intensity fires naturally burned forests, maintaining healthy tree densities and minimizing the amount of undergrowth. In the 20th century, the Forest Service has taken the philosophy of fighting all fires. As a result of fighting forest fires in recent decades, forests have become more dense and full of dead groundcover, especially in the western United States. This provides an unnaturally abundant supply of fuel for future fires. The large supplies of fuel and recent droughts have created conditions that make forests more prone to destructive, high-intensity wildfires. In recent dry seasons, fires have burned thousands of acres in California, Montana, Washington, Utah, Idaho, and other areas in the western United States.

To minimize the high intensity fires and restore the open tree stands of the past, the Forest Service is now trying to thin forests. One method of thinning forests is to perform prescribed burns. This is an intentional fire started when conditions (wind, fuel moisture content, air temperature, relative humidity, and slope) are ideal for a low intensity fire to burn undergrowth and smaller trees. At some conditions, the prescribed fire will not spread, and at other conditions, the fire will spread out of control. Wildfire models are used to determine the best conditions to perform controlled prescribed burns. The ability to predict the magnitude and spread of a fire will help increase safety and efficiency in performing prescribed burns and also in fighting fires. Fire managers would like to have a computer code that will accurately model the spread and intensity of a fire, based on the local fuel moisture content, wind speed and direction, and slope.

Several models describe the spread of forest fires. Weber[1] breaks down the existing models into essentially three classes: statistical, empirical, and physical.

Statistical models have no physical mechanisms; they are simply a statistical description of test fires. These models can be useful when modeling fires under similar conditions to the test fires, but are less accurate when modeling outside of the test conditions. Statistical models typically calculate a fire danger index value by considering the air temperature, relative humidity, wind velocity, and degree of curing.

Empirical models are based on the principle of conservation of energy, but do not differentiate between the different modes of heat transfer. Important parameters in this model are the fuel surface area-to-volume ratio, fuel bed density/solid fuel density, wind velocity and direction, and slope. Rothermel[2] performed experiments over a wide range of fuel parameters and environmental conditions to make this type of model widely applicable. Rothermel's work is the foundation of BEHAVE,[3] a fire behavior prediction package used by fire managers. However it is empirical and therefore does not scientifically describe fire spread, and is inaccurate in conditions outside of the test conditions.

Physical models differentiate among the modes of heat transfer and use fundamental science to describe how the fire will spread. These models describe the modes of heat transfer from the flame, embers, and hot combustion gases to the unburned fuel. An energy balance is performed on the fuel, resulting in a differential equation for the enthalpy of the fuel. This type of model requires extensive knowledge of the fuel properties and the fire environment. Many physical models have been constructed and modified to accurately model wildfires.

Existing empirical models are based on extensive correlations developed by Byram,[4] Fosberg and Deeming,[5] Albini,[6] Rothermel,[7] Van Wagner,[8] and Albini.[9] These correlations are incorporated in the current models used by fire managers: BEHAVE[3] and FARSITE.[10] More recent models have focused on the interaction between the atmosphere and the fire.[11, 12] Current models take into account fuel moisture content, fuel type and quantity, wind, and slope of the terrain. These models are largely based on experimental data from dead fuels, and hence are generally accurate when modeling fires at similar conditions to the experimental data. However, the models deviate when trying to model fires in live vegetation.

2. Literature Review

Numerous studies have been performed on the ignition characteristics of different fuels and the strategies to model the pyrolysis and ignition of these fuels. In particular, a number of studies have focused on ignition and burning of wood materials, but little work has been performed on the pyrolysis and ignition of live foliage. The following literature review summarizes the progress made in characterizing the ignition of (a) wood (Section 2.1) and (b) foliage (Section 2.2).

2.1 Ignition Characteristics of Wood Fuels

2.1.1 Ignition Temperature

Studies on ignition temperature of wood started early in the 20th century. Table 1 is a summary of the different studies performed on wood samples over the past century. The studies are broken down into piloted ignition and auto-ignition, and the corresponding ignition temperatures (T_{ig}) were recorded. The studies were performed on different types of wood samples and sizes. Essentially two methods were used to heat wood samples to ignition to study ignition temperature. These methods are (1) inserting the sample into a furnace at an elevated temperature or (2) radiatively heating the sample in open air.[13] The different methods are indicated in Table 1 by using **bold** for type 1 experiments and underline for type 2 experiments. Babrauskas[13] did not specify the ignition method for the values in regular text.

Table 1. Summary of Ignition Temperature for Various Woods (taken from Babrauskas 2001[13])

Year	Investigator	Specimen Size	T_{ig} (°C)		Comments
			Piloted	Auto-ignition	
1887	Hill[14]	0.5-15 g		**220-300**	Measured air temperature near sample
1910	Bixel, Moore[15]	35mm?		200-250	Measured oven temperature; scant details
1922	Banfield, Peck[16]	50 x 50 x 200 mm		302-308	Measured surface temperature
1934	Brown[17]	1-5 g		**220-250**	Measured oven temperature; tiny samples; unsound ignition criterion
1936	VanKleeck[18]	Chips		**235**	Measured oven temperature; unsound ignition criterion
1947	NIST	Shavings		**228-264**	Softwood shavings in test tube; criterion – glowing or flaming
1949	Graf[19]	7-13 g		**232-245**	Measured oven temperature; tiny samples; unsound ignition criterion
1949	Angell[20]	13 x 19 x 51 mm		204	Measured gas temperature close to specimen
1950	Fons[21]	2-9 mm cylinders		343	Measured oven temperature; solved inverse problem
1958	Narayanamurti[22]	?	228		Measured oven temperature
1959	Thomas et al.[23] (Data of Prince, 1915)	32 x 32 x 102 mm	210		Measured oven temperature; solved inverse problem
1959	Akita[24]	20 x 20 x 1.8 mm	450	489	Measured oven temperature; solved inverse problem
			< 350		Measured oven temperature only
1960	Simms[25]	8 mm		525	Calculated from correlation, error found in calculation by Koohyar
1960	Moran[26]	50 x 50 x 6.4 mm		255	At flux = 25kW m^{-2}; measured surface temperature
1961	Patten[27]	3 g shavings	**260**	**260**	Measured oven temperature (Setchkin test)
1961	Buschman[28]	57 x 57 x 8 mm	369		Calculated from correlation; fluxes 14.3 to 37.2 kW m^{-2}
1964	Shoub, Bender[29]	920 x 920 mm		254	Measured surface temperature; flux = 4.3 kW m^{-2}
1964	Tinney[30]	≥ 6 mm		350	Measured oven temperature
1967	Simms, Law[31]	76 x 76 x 19 mm	380		Calculated from correlation
1967	Muir[32]	80x160 mm	364-384		Measured surface temperature; flux range from 15-25 kW m^{-2}
1967	Koohyar[33]	100x100x12-19mm	361	402	Measured surface temperature; flux range from 18-35 kW m^{-2}
1969	Melinek[34]	100 x 100 x 13 mm	353	382	Calculated from correlation
1969	Jach[35]	Few grams		**260-290**	Measured oven temperature
1970	Smith[36]	75 x 75 x 19 mm	350	413-714	Temperature measured by optical pyrometry; autoignition values dubious

1983	Atreya[37]	64 x 19 mm	<u>370</u>		Temperatures measured, but below surface; flux = 18 kW m^{-2}
			<u>350</u>		Temperatures measured, but below surface; flux ≥ 30 kW m^{-2}
1986	Atreya et al.[38]	75 x 75 x 19 mm	<u>330-405</u>		Temp meas., but below surface
1988	Abu-Zaid[39]	150 x 75 x 37 mm	<u>420</u>		Forced-air flow; temp. measured but below surface; flux = 18.5 kW m^{-2}
			<u>350</u>		Forced-air flow; temp. measured but below surface; flux > 25 kW m^{-2}
				<u>530</u>	Flux = 40 kW m^{-2}
1991	Janssens[40]	100x100x17 mm	<u>300-364</u>		Surface temp. measured; fluxes 25 to 35 kW m^{-2}
1992	Li, Drysdale[41]	64x64x18 mm	<u>411-497</u>		Temp. measured but below surface; flux < 20 kW m^{-2}
			<u>353-397</u>		Temp. measured but below surface; flux > 20 kW m^{-2}
1993	Masarik[42]	2.5 g	**220-240**		Tested wood fiberboard; measured oven temperature (Setchkin test)
1996	Fangrat[43, 44]	100x100 mm	<u>296-330</u>		Surface temp. measured; fluxes ≥ 25 kW m^{-2}
1997	Moghtaderi[45]	100x100x19 mm	<u>332</u>		Temp. measured but below surface; at 20 kW m^{-2}
			<u>297</u>		Temp. measured but below surface; at 60 kW m^{-2}
2001	Boonmee[46]	40x40x40 mm		650	Measured w/infrared camera; at 40 kW m^{-2}
				400	Measured w/infrared camera; at 75 kW m^{-2}
*Values in bold are furnace experiments, while underlined values represent radiatively-heated experiments					

Ignition temperature values for piloted ignition vary from 210-497°C and for auto-ignition 200-530°C. Three studies from Table 1 (Simms 1960[25], Smith 1970[36], and Boonmee 2001[46]) are excluded in this range. Simms calculated T_{ig} from a correlation, which was later found to have an error (discovered by Koohyar). Smith measured the sample temperature using optical pyrometry, which may be dependent on if and how much the sample is already undergoing glowing ignition; these values appear to be too high (413-714 °C). Boonmee measured T_{ig} using an infrared camera and the reported value corresponds to the temperature of a glowing wood particle rather than the temperature prior to ignition. Babrauskas[47] gives the following reasons to account for the wide variation in the reported values:

- variations in the ignition definition of researchers
- piloted vs. auto-ignition conditions
- design of the test apparatus and its operating conditions
- specimen conditions (e.g., size,, moisture, orientation)
- species of wood

Further analysis by Babrauskas showed that the operating conditions, especially the heat flux, have considerable effect on the ignition temperature. Table 2 shows the conclusions made by Babrauskas pertaining to effects of heat flux on ignition temperature. At a minimum heat flux, wood samples ignited at about 250 °C for both piloted and auto-ignition. At a higher heat flux, there are different ignition mechanisms that occurred at different temperatures. For the low heat flux and piloted ignition, the ignition was either a glowing ignition, or a glowing followed by flaming ignition. The observed T_{ig} for this condition rapidly increased with increasing heat flux, and peaked between 350-400 °C. For medium heat flux, Janssens performed experiments on softwoods and hardwoods and determined the piloted T_{ig} to be 300-310 °C and 350-365° C respectively.

Table 2. Summary of T_{ig} Results (from Babrauskas[47])

	Flux		
	Minimum	**Low**	**Medium**
Ignition type	glowing	glowing or glowing/flaming	flaming
T_{ig} (°C), piloted	250	350-400 peak, lower for fluxes close to minimum	300-310 hardwoods 350-365 softwoods
T_{ig} (°C), auto-ignition	250	no data	400??

Li and Drysdale[41] and Moghtaderi et al.[45] performed studies to understand the effect of heat flux on the T_{ig} of wood. Figure 1 shows the piloted T_{ig} decreasing with increasing heat flux for four different wood species reported by Li and Drysdale.[41] Moghtaderi et al.[45] reported a similar relationship between T_{ig} and heat flux for Radiata pine samples. In addition to the heat flux relationship, Moghtaderi et al. also studied the effect of moisture content on T_{ig}; results are shown in Figure 2.

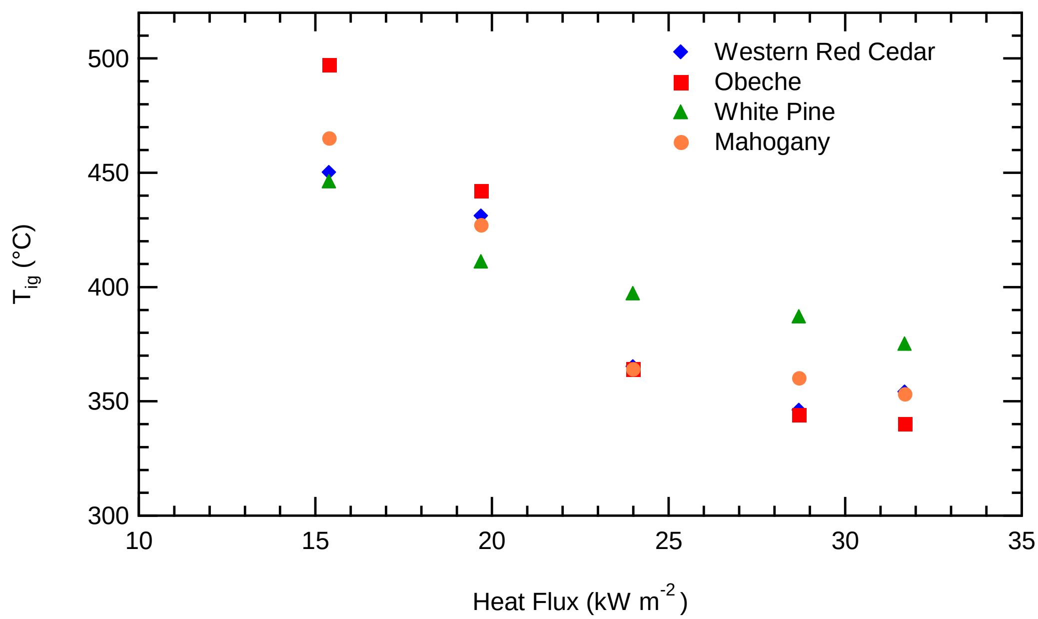


Figure 1. Effect of heat flux on piloted T_{ig} for various wood species. (from Li and Drysdale[41])

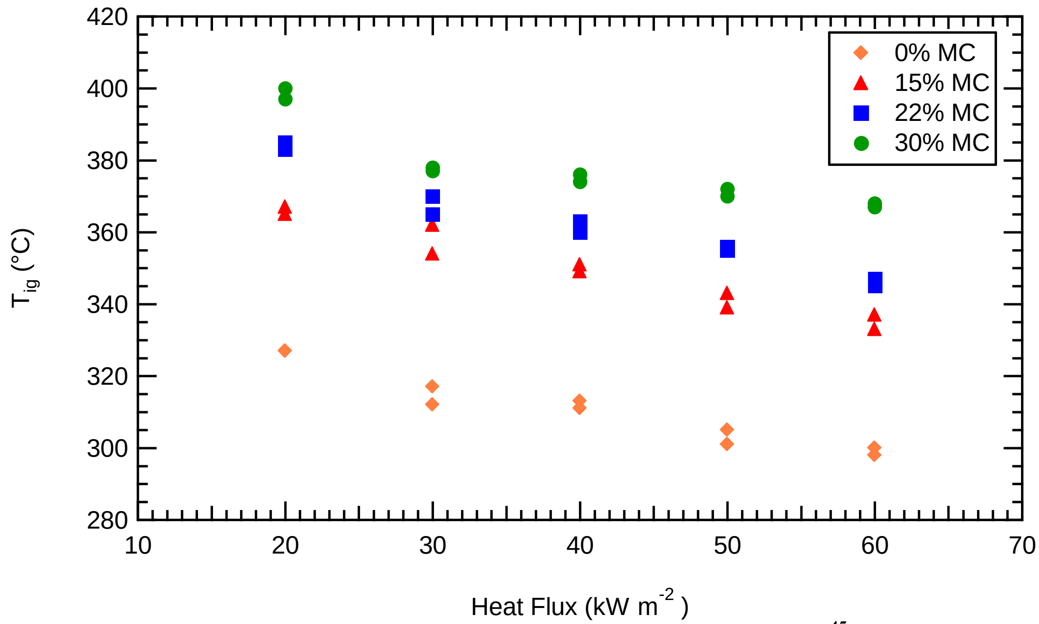


Figure 2. Measured T_{ig} for dry and conditioned samples of Radiata pine.[45]

Moghtaderi and coworkers reported an increase in T_{ig} with increasing moisture content for Radiata pine wood samples. However, these wood samples were initially dried and then conditioned to have the varying moisture content levels shown in Figure 2. Moisture content (MC) is defined on an oven-dry basis (i.e., mass of moisture/ mass of dry solid). Drying the wood and then treating it to absorb moisture may change how the wood responds to heat and eventual ignition, compared to fresh live wood found in forests.

The results from Li and Drysdale[41] and Moghtaderi et al.[45] contradict the conclusions made by Babrauskas in Table 2. This may be a result of the different methods of measuring the temperature. For example, if the temperature is measured beneath the surface, it may not be the same as the surface temperature. Because of the conflicting reports for the effect of heat flux on T_{ig}, the actual effect is unclear.

2.1.2 Ignition Time

Effects of specimen size, moisture content, and initial temperature on ignition time (t_{ig}) for wood were explored by Fons[21] and Lu and coworkers.[48] Fons observed that t_{ig} increases with increasing ponderosa pine specimen diameter and increasing moisture content. He suggested that the delay due to moisture was more than could be accounted for by the change in specific heat. The increased t_{ig} was said to be due to the water vapor changing the concentration of the flammable gases, causing a delay in reaching the flammability limit. Thickness dependence was also recently demonstrated by Lu et al.[48] for sawdust particles heated in a furnace up to approximately 1200K. Lu and workers observed that different shapes of sawdust particles heated up at different rates. The near spherical particles took longer to heat up than the cylindrical particles. Additionally, Lu and coworkers measured internal and surface temperatures. A temporary plateau in the temperature was observed (due to moisture evaporation) for the interior measurements but not surface temperature measurements.

2.2 Ignition Characteristics of Forest Foliage

Wildland fires generally spread through foliage faster than through bark or branches, therefore it is valuable to understand how leaves, needles, and grasses ignite. Table 3 is similar to Table 1, but is a summary of the ignition work that has been performed on foliage rather than wood. Table 3 also indicates the different types of foliage, and if t_{ig} was reported. The studies shown in this table were compiled by Babrauskas.[47]

Table 3. Summary of Ignition Temperatures of Different Foliage (based on review by Babrauskas[47])

Year	Investigator	Substance	Spec. Size	T_{ig} (°C)		t_{ig} reported?	Comments
				Piloted	Auto-ignition		
1932	Wright[49]	Pine duff			*725*	?	Hot surface pressed against vegetation
1934	Fairbank, Bainer[50]	Dry Oats			*448*		Using hot exhaust manifold T_{ig} is the temperature required of the manifold
		Pine needles			*760*		
		Dry grass			*663*		
1951	Bowes[51]	Dry Grass			249		MC = 6%
1970	Harrison[52]	Dry pine needles			*350*	~4min	
		Dry grass			*400*	~4min	
1971	Montgomery, Cheo[53]	34 different samples			X	Yes	Correlation for t_{ig} vs. thickness
1974	Stockstad[54]	Ponderosa Pine Needles		280	365		
		High MC		350	390		MC = 33%
		Cheatgrass		380	450		
1974	Kaminski[55]	Rotten wood			270-300		
		Cheat grass			330		Glowing ignition
		Cheat grass		270			
		Sawdust		260			
1976	Trabaud[56]	Variety of vegetation			X	Yes	Radiant Heat Flux; 25 kW m^{-2}
1980	Johnson et al.[57]	Corn "beeswings"			302		Ignition was defined at a certain rate of temperature rise
		Fir Sawdust			313		
		Locust Sawdust			291		
		Tobacco			272		
		Willow Oak Leaves			282		
1986	Yamashita[58]	Variety of leaves			375-400		
		branches			350-375		
1993	Xanthopoulos, Wakimoto[59]	Pondersosa Pine Lodgepole Pine Douglas Fir	15 cm	X		Yes	Varied moisture content and T_{gas}
1996	Gill, Moore[60]	50 different Australian species	Leaf	X		Yes	Probability of ignition as a function of MC
1997	White et al.[61]	8 different coniferous species	Branch	X		Yes	Cone Calorimeter; 25 kW m^{-2}
1999	Di Blasi[62]	Straw	Beds		250		Increase in T_{ig} with higher heat

							flux
2000	Shu et al.[63]	Leaves			210-254		MC = 50%
		Twigs			228-244		MC = 50%
2001	Dimitrakopoulos & Papaioannou[64]	24 different species	Leaf	X		Yes	Report t_{ig} as a function of MC
2001	Burrows[65]						
2002	Rallis, Mangaya[66]	Fine, dry veld grass			250-350		Grass placed on a hotplate, hotplate temperature reported
2004	Engstrom et al.[67]	Manzanita	Leaf		346	Yes	MC < 10%
		Scrub oak	Leaf		311	Yes	MC < 10%
		Ceanothus	Leaf		319	Yes	MC < 10%
X - indicates the type of ignition but no T_{ig} reported							
*Values in **bold** are furnace experiments, <u>underlined</u> values represent radiatively-heated experiments, and *italics* represent ignition from a hot surface.							

Three different methods were used to ignite the foliage reported in Table 3: by (1) inserting the sample into an oven where it was heated convectively, (2) radiatively heating the sample in open air, or (3) pressing a hot surface into the vegetation and observing the temperature of the hot surface required for ignition. These different methods are indicated in Table 3 by **bold** for type 1, <u>underline</u> for type 2, and *italics* for type 3. Also indicated in Table 3 are some studies that included t_{ig} data.

To begin analyzing the auto-ignition temperature of the foliage, it is necessary to evaluate the validity of the data. The samples that were ignited using the type 3 method of pressing a hot surface to the vegetation will be neglected, since the reported T_{ig} is the hot surface temperature, not the foliage temperature at ignition, and is therefore too high. Using the remaining data for the auto-ignition of foliage, the average T_{ig} was 313.7 °C with a minimum of 210 °C and a maximum of 450 °C. T_{ig} varies for each of the studies, and may depend on the species (surface area to volume ratio, thickness), the method of ignition (apparatus), and the moisture content.

The five piloted ignition temperatures reported ranged from 260-380 °C, with an average T_{ig} of 308 °C, slightly lower than the auto-ignition temperature. From these data, one could conclude that the average ignition temperature for foliage is approximately 310 °C. This value is significantly higher than the accepted value of wood (250 °C) from Table 1 but lower than or comparable to the data shown in Figure 1 and Figure 2.

2.2.1 Time to Ignition

In addition to measurements of T_{ig} of foliage, studies have been performed on the effect of moisture content and thickness on ignition time (t_{ig}). The effect of moisture content on t_{ig} was examined by Xanthopoulos and Wakimoto[59], Dimitrakopoulos and Papaioannou[64], Shu et al.[63], and Gill and Moore[60]. Xanthopoulos and Wakimoto experimented with conifer tree branches having moisture contents similar to those found in nature. The results were used to develop a correlation for t_{ig} as a function of convection gas temperature and moisture content. Correlations were made for three different species: Ponderosa Pine, Lodgepole Pine, and Douglas-Fir. Equation 1 is the correlation of t_{ig} for these three tree species:

$$t_{ig} = C_1 \cdot \exp\left(- C_2 \cdot T_{gas} + C_3 \cdot MC\right) \qquad (1)$$

where C_1, C_2, and C_3 are constants specific to species, T_{gas} is the gas temperature (°C), and MC is the sample moisture content (%) on an oven-dry weight basis.[47] The general conclusion is that t_{ig} (in seconds) should increase exponentially with (a) increasing moisture content, and (b) decreasing gas temperature. Different coefficients were found for each species. A variation of up to 500% was observed when the time to ignition was plotted as a function of temperature and moisture content for the various species (see Figure 3). This variation suggests that ignition characteristics are species dependent. However, this species dependency may be due solely to shape and thickness factors rather than chemical structure.

Dimitrakopoulos and Papaioannou[64] tested the relationship of t_{ig} versus moisture content for 24 different species, and reported the following linear relationship:

$$t_{ig} = a + b\,MC \qquad (2)$$

where *a* and *b* are constants dependent on the species.

Additionally, the ignition characteristics may depend on the physical dimensions of the sample. Thin samples should heat up faster, and thus ignite earlier than thick samples. Montgomery and Cheo[53] performed experiments in a muffle furnace on 32 standardized leaf pieces and two filter paper controls. Leaf thickness varied from 0.05-0.58 mm, and t_{ig} varied from 0.89-2.71 seconds (see Figure 4). Montgomery and Cheo fit a regression line to the data with the equation:

$$t_{ig} = 1.02 + 3.40 \cdot \Delta x \qquad (3)$$

where Δx is the sample thickness. The regression line fits the data fairly well with an R^2 value of 0.73. Their data show that thickness has a significant effect on t_{ig}. Figure 4 shows the original data from Montgomery and Cheo with the fit and 95% confidence interval. The linear fit is indicative of thermally-thin behavior,[47] meaning there is little thermal gradient through the sample.

As seen in Table 3, there have been a number of studies on the ignition characteristics of foliage, but little work has been done on the ignition characteristics of live fuels. The majority of the materials tested in Table 3 are dry or dead fuels that will ignite differently than live, moist fuels. Emphasis has been placed on dry fuels, since they are often the most prone for ignition. However, once a fire has started, live, moist fuels can play a major role in the propagation or extinction of the fire. Weise et al.[68] have performed experiments with live chaparral to determine if fire will spread under different conditions of wind, slope, fuel density, and fuel moisture content. These experiments were performed on a large fuel bed of approximately 2 m^2.

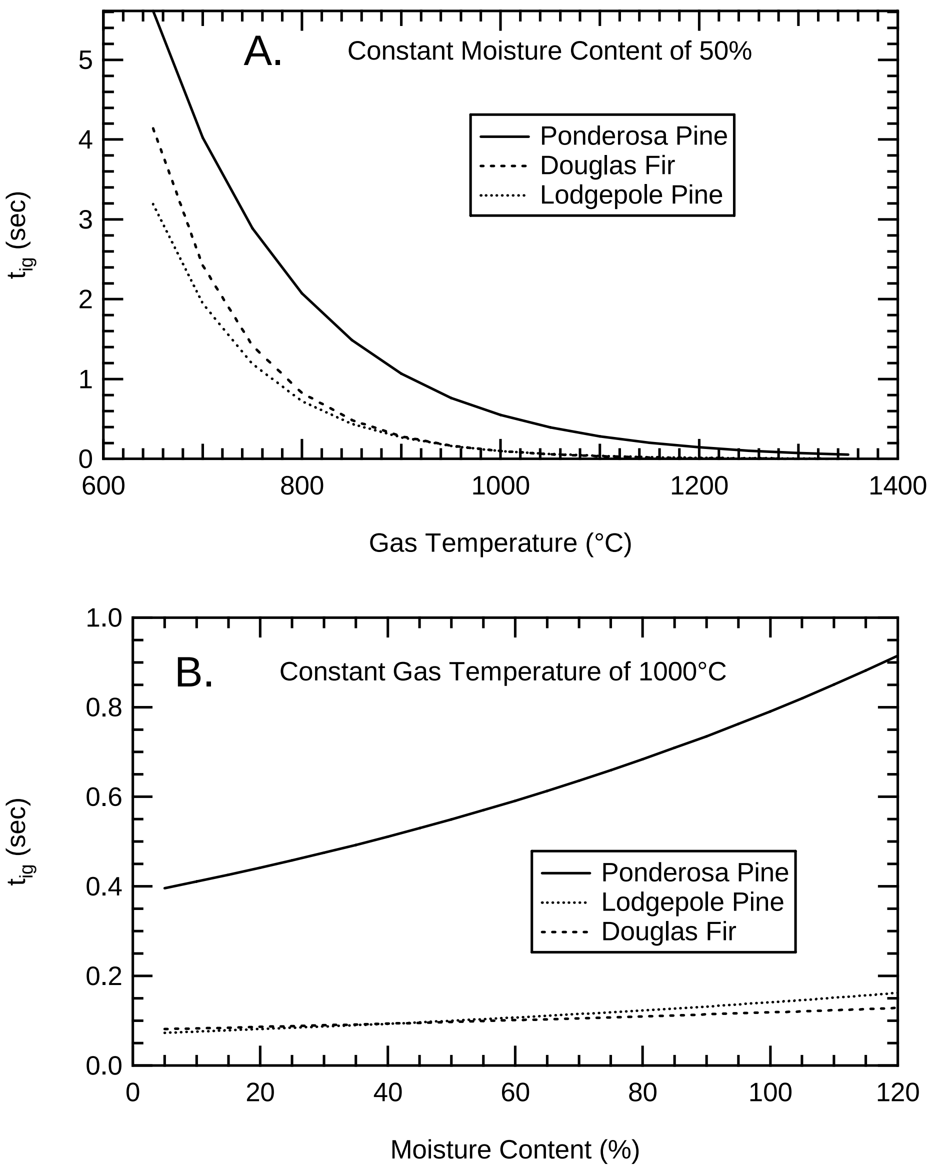


Figure 3. **Plot of correlation for t_{ig} as a function of (a) T_{gas} with constant moisture content (50%), and (b) moisture content, with constant T_{gas} = 1000 °C for different conifer species (see Equation 1).**

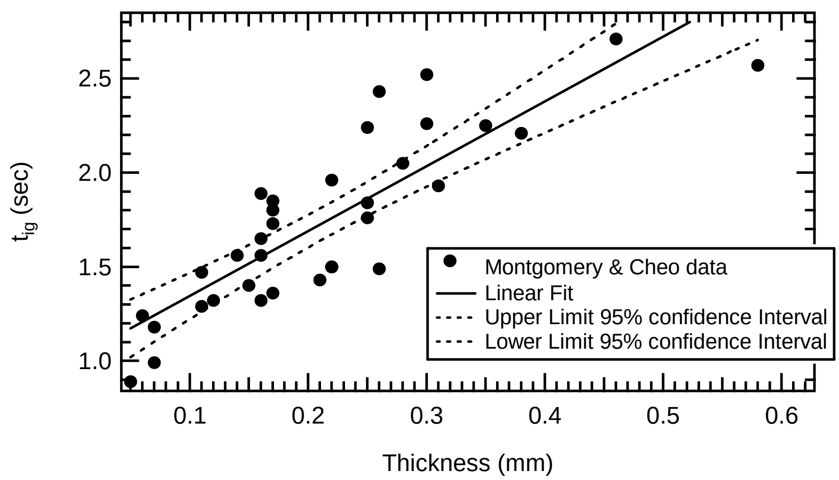


Figure 4. Measured values of t_{ig} for varying species with a linear fit and 95% confidence interval. Data from Montgomery and Cheo.[53]

2.2.2 Modeling the Effects of Moisture Content

There are additional publications that address modeling the effects of moisture content on the ignition and combustion of forest fuels.[45, 69-71] Mardini et al.[69] developed a model to study the burning of live fuels, namely chamise twigs with needles. They report that light hydrocarbons (i.e. methane, ethane, ethene, and acetylene) are released from chamise at temperatures as low as 50 °C. This model assumes that the fuel temperature will not go above 100 °C while there is still water present. Later experiments performed by Mardini et al.[71] show the fuel temperature plateaued at 100 °C, supporting the above assumption for modeling "green" sticks of wood. Based on results from Susott,[72] it is assumed that there is a pilot species present, one which will ignite in the gas phase at lower temperatures than glowing ignition occurs. Mardini and coworkers suggest the pilot species may be acetylene or diethyl ether, which have spontaneous ignition temperatures of 305 °C and 185 °C, respectively. In contrast, glowing ignition is assumed to begin at 450 °C. Their model indicates that flaming ignition will often occur before glowing ignition. Mardini and Lavine[71] showed that moisture content has a significant effect on t_{ig}, and that seasonal effects can be more significant than a simple change in moisture content.

Catchpole et al.[70] postulated that the increase in ignition temperature with moisture content was due to the dilution of hydrocarbon species by the evaporating moisture. This explanation is in agreement with the theory of Mardini and coworkers[69] that a pilot species must be within its flammability concentration limit and temperature before it will ignite. If the sample heats up rapidly or is a large sample, then moisture will continually be evaporating from its deeper layers while the sample surface is giving off ignitable gas. This dilution by the moisture may cause the sample to increase to higher temperatures before ignition occurs, and will certainly delay the ignition. Although Catchpole and coworkers recognized this effect, a constant ignition temperature was still used in their proposed model because the effect was yet to be quantified. There is a need for more information on how the ignition temperature changes with moisture content.

Research has been performed on different species and parts of fuels to determine the effect of chemical content on ignition characteristics.[72, 73] Brown et al.[73] measured the chemical content of the pyrolytic vapors from trees, hoping to add to the chemistry and kinetics of current wildfire models. In their study, they found that samples of leaves, needles, and bark had similar characteristics, and as a whole behaved differently than hardwoods and softwoods. The leaves, needles, and bark had a higher fraction of extractives (hydrocarbons i.e., terpenes, fats, waxes, oils, etc.[72]), which may have contributed to their higher flammability.

Susott[72] performed thermal analyses on 20 fuel species to determine their different burn characteristics. The fuels were separated into four groups of vegetation (foliage, wood, stems, bark), and ground up to pass through a 20 mesh screen (particle diameter less than 0.03 inches). Bomb calorimetry experiments and evolved gas analysis (EGA) were performed on these ground samples to determine the heats of combustion for the different species and vegetation types. The results indicated that all samples (different species and vegetation) had about the same heat of combustion on a dry basis, with a mean of 21.4 MJ/kg and a standard deviation of ±1.4 MJ/kg. The changes in heats of combustion could not explain the changes in flame or ignition characteristics of the different samples. For example, pine needle fuel beds may burn vigorously, in contrast to the slow glowing combustion of some woods. However, the EGA results indicated that fuels release variable amounts of volatiles at different temperatures. The results from the EGA and bomb calorimetry were used to separate the samples into three groups of similar characteristics: (1) wood, (2) foliage, and (3) bark or lignin[74]. Large variations were observed between these three groups, but very little variation was observed between different species. This conclusion contradicts what is observed in wildfires, i.e., that species burn differently. The observed differences in combustion characteristics may therefore be due to the effects of heat and mass transfer.

2.3 Literature Summary

Moist, live fuels are believed to burn differently than dry, dead fuels. It is uncertain why fresh fuels burn differently, possibly due to moisture content and/or size and shape differences. Experimental work must be performed on live foliage to develop an understanding of the combustion of live fuels. Experimental data can lead to correlations based on fundamental heat and mass transfer theories. Correlations are needed for implementation into existing wildfire models to improve accuracy when modeling wildfires burning through live vegetation.

3. Objectives and Approach

The objectives of this study were (a) to measure the fundamental combustion characteristics of live fuels from the western United States, and (b) to develop correlations to predict ignition characteristics. This work investigated the effects of heat and mass transfer on sample heat-up, ignition, and burning. Thickness, shape, moisture content, and species type were investigated to determine their effect on ignition temperature, time to ignition, burn times, and mass release. The results of this experimental work were used to develop a preliminary correlation for live fuels.

The following tasks were accomplished in this thesis project:

Task A. Experiments were performed to examine the ignition behavior of California chaparral samples (manzanita, scrub oak, hoaryleaf ceanothus, chamise) and local Utah samples (sagebrush, gambel oak, canyon maple, juniper). The experimental apparatus was previously designed and constructed by Engstrom and coworkers.[67] Data collected from the experiment were sample thickness and shape, average fuel moisture content, temperature, visual images of the experiment, and mass all as a function of time. The analysis determined t_{ig}, T_{ig}, and burnout time (t_{flame}).

Task B. The effects of thickness, diameter (size/shape), and moisture content on the ignition characteristics of the species listed in Task A were determined. A correlation was developed to predict T_{ig} and t_{ig} based on the most significant variables.

Task C. A new mass balance was incorporated into the experiment that increased the sample readability from 10 mg to 0.1 mg. The balance was connected to the computer and interfaced with LabVIEW software to record the instantaneous mass readings and to time-stamp the data. This new balance was capable of capturing the details of the changing sample mass through heat-up and ignition. Mass release data were preliminary, and are only briefly discussed in this thesis

Task D. A simple lumped-capacitance model was developed for predicting t_{ig} and T_{ig} and compared to the data collected for California chaparral. Additional models developed by Lu et al.[48] and Di Blasi et al.[62] were also modified and compared to the data.

4. Description of Experiments

4.1 Experimental Apparatus

The experiment was previously designed by Engstrom and coworkers[67] to heat single leaf or twig samples by convection and/or radiation at initial heating rates of approximately 100 K/s and gas temperatures of 1260 K. Figure 5 shows a flat-flame-burner (FFB), an Omega 6000 W 25x25 cm square quartz radiative heating panel, and a Mettler-Toledo cantilever mass balance. The FFB and heating panel (positioned on a moveable platform) are capable of simulating a fire front approaching a sample that is held on the mass balance. A 0.5 hp Leeson motor pulls the platform at a constant velocity. The motor stops when the FFB is positioned under the sample. The radiative heating panel simulates radiative pre-heating of fuels that occurs during a forest fire. Limited experiments were performed using the radiative heating panel.

The hot gases from the FFB transfer heat by convection. Methane, hydrogen, nitrogen, and air were fed into the FFB to provide a stable flame, providing a post-flame gas temperature and oxygen concentration that resembled a forest fire environment. The flow rates of the gases were adjusted to alter the stoichiometry to produce the desired post-flame conditions. The approximate post-flame conditions used in this project were a gas temperature of 1260 K and 10 mol% O_2. The FFB (see Figure 6) consisted of two mixing chambers, one for oxidizer (air and N_2) and one for fuel (CH_4 and H_2). The fuel flowed through capillary tubes from the fuel chamber, through the air chamber, through a honeycomb mesh, to the burner surface. In this way, the fuel and oxidizer only mixed at the tips of the capillary tubes, creating laminar diffusion flamelets 2 mm from the burner surface.

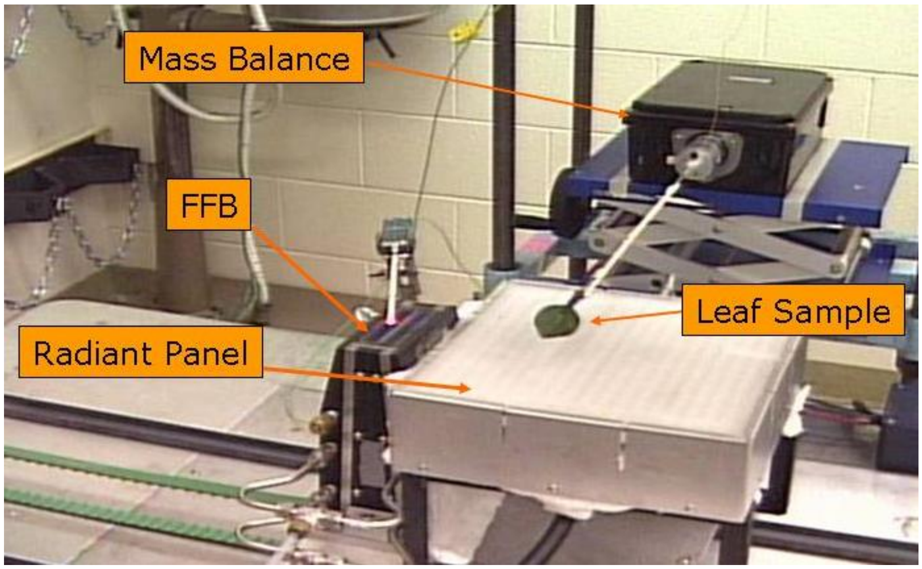


Figure 5. **Experimental apparatus, showing the flat-flame burner, radiative heating panel, and cantilever mass balance.**

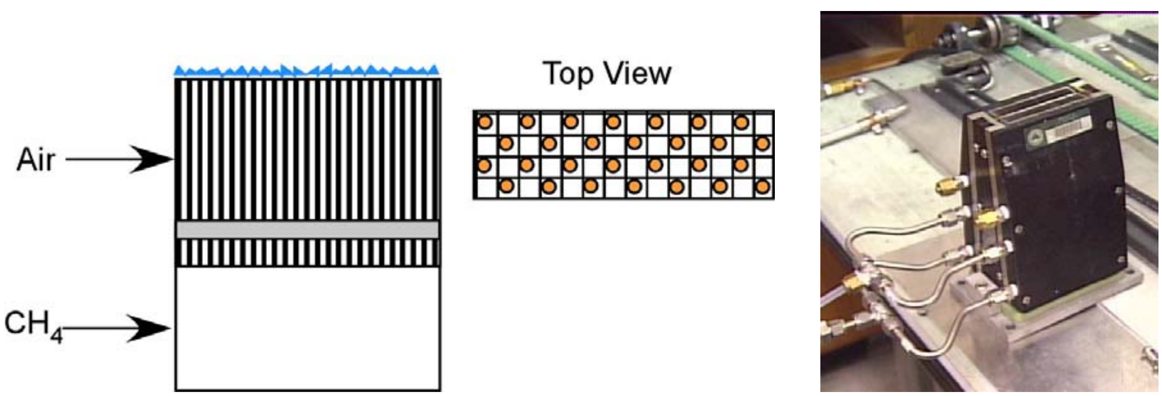


Figure 6. **Schematic of FFB from a sliced view and top view and image of the flat flame burner**

Ten experiments were performed by Engstrom et al.[67] to determine the repeatability of the post-flame conditions (see Figure 7). The average gas temperature after the initial heating region was 987 °C. The thermocouple measurements were corrected for radiation losses according to standard techniques. These corrections amounted to only 17 °C. The corrected gas temperature was therefore 1004°C, with a standard deviation of 11.9 °C.

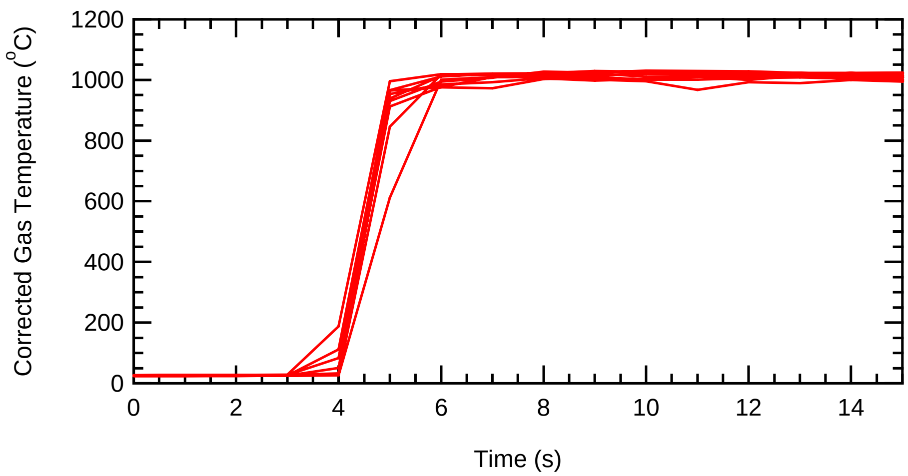


Figure 7. Time-dependent gas temperature measurements with the thermocouple held 5 cm above the flat-flame burner surface. Thermocouple measurements are corrected for radiation losses.

A 127 μm type-K thermocouple bead was placed into a pinhole made in the sample to measure sample temperature. The thermocouple was placed at the location in the leaf where ignition was expected to occur first. Ignition occurred along the edge of the leaf, therefore thermocouple beads were placed as close to the edge as possible, usually within 3 millimeters of the leaf edge. Expected ignition location was determined by observing the ignition of the species using a Minolta 8-918 HI-8 camcorder. A program was written in National Instruments LabVIEW 5.1 and later updated in LabVIEW 7.1 to record the video images, mass, and temperature data on a computer. Originally, the data were recorded at approximately 6 Hz, but later upgrades permitted transfer rates of 18 Hz. All of the data were time-stamped for accurate comparison between the temperature, mass, and visual data.

Additional leaf temperature measurements were made with a FLIR thermal imaging (IR) camera (models SC500 & A20M) to validate the thermocouple readings. There were two challenges in measuring the temperature with the IR camera. The first was to determine the emissivity (ε) of the leaf. This was done by using the emissivity calculator in the FLIR Researcher Pro software and validating it with values in the literature. The emissivity calculator compares the IR temperature reading with a known temperature reading (from a thermocouple) and calculates the appropriate emissivity. The calculated emissivity is likely a function of both viewing angle and time. The second challenge was to obtain the temperature of the leaf at the thermocouple location as a function of time. This was a challenge because the samples would bend and twist as they burned. Figure 8 shows a representative image from the IR camera and Figure 9 shows a typical plot of the thermocouple readings compared to the maximum IR temperature near the location of the thermocouple. The thermocouple data correlate well with the IR temperature data using ε = 0.70-0.85, with the best fit being ε = 0.75. Most errors are on the order of ±10%, but some range up to 20%.

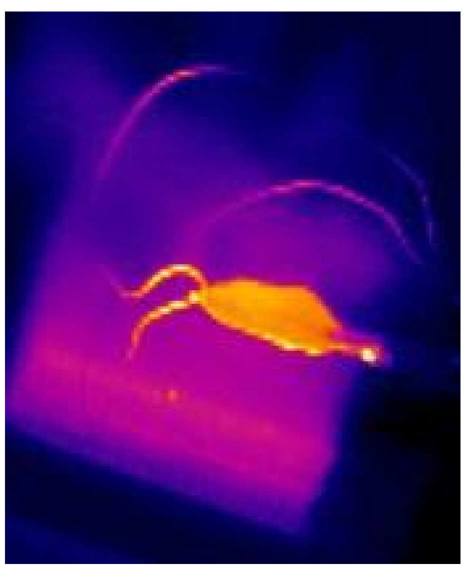


Figure 8. Representative IR image.

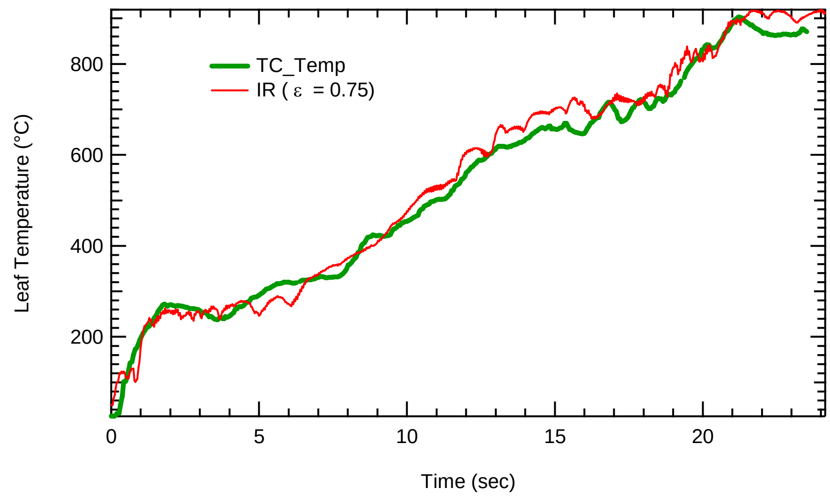


Figure 9. Comparison of type K thermocouple reading to IR temperature reading on a manzanita leaf.

Ignition was determined by inspecting the video images frame by frame for the first visual indication of a flame in the gas phase (see Figure 10). The timestamp for the first frame with ignition was compared to the thermocouple timestamp to determine T_{ig}. Ignition time was determined by taking the timestamp where ignition occurred and subtracting from it the timestamp of the first thermocouple temperature greater than 30 °C.

California chaparral samples were obtained from the USDA Forest Service Pacific Southwest Research Station, Forest Fire Laboratory, located in Riverside, California. The Forest Fire Laboratory collected live samples and shipped them overnight to BYU. Local Utah samples were collected from the surrounding areas. The samples were burned within one day of being received (within 2-3 days of being collected) to ensure that the samples were similar to live, natural forest fuels. To capture a broad range of moisture content, additional experiments were performed on the following days as the foliage dried.

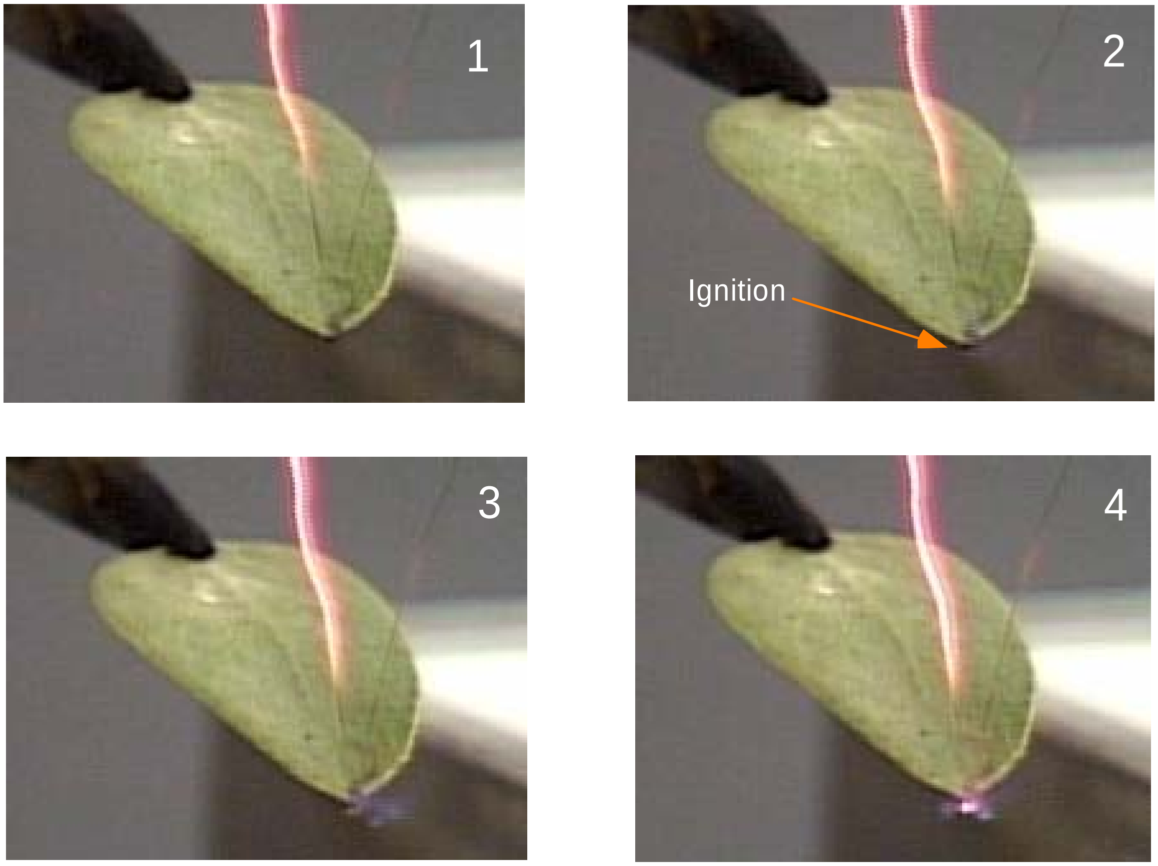


Figure 10. Time of ignition on the point of a representative manzanita sample.

The moisture content of samples was analyzed by a CompuTrac moisture content analyzer. The analyzer recorded the initial weight, heated the sample to approximately 100 °C, and maintained that temperature until the mass no longer changed. The mass of moisture was calculated by subtracting the final mass from the original mass, according to the following equation:

$$MC = \frac{m_0 - m_f}{m_f} \times 100\% \qquad (4)$$

where *MC* is the moisture content (%), m_0 is the initial mass (gm) prior to drying, and m_f is the final mass (gm) after drying. This is defined in the forest products industry as an oven-dry weight basis,[47] meaning the mass of moisture divided by the mass of the dried sample (i.e., water content on a dry basis). Using this method, moisture content (MC) often exceeds 100%. Moisture content was measured three or more times during the period that experimental burns were performed (usually over a period of 1-2 hours) to determine the average moisture content of the collected samples. Each moisture content test was performed on samples of approximately 2 grams of foliage, which ranged from 5-40 leaves.

For most of the experiments performed in this investigation, an electronic digital caliper was used to measure the leaf thickness between veins and up to, but not crossing, the main vein that runs down the center of the leaf. By doing this, the thicker veins were avoided and the flesh portion of the leaf was measured.

T_{ig} and t_{ig} have been reported for wood as a function of incident heat flux, as was shown in Table 1 and Table 3. Hence, an estimate of the heat flux in this experiment is useful for comparative purposes. The heat flux estimation was made using the lumped-capacitance form of the energy equation for the leaf, neglecting both radiation and reactions:[75]

$$mC_p \frac{dT}{dt} = hA\left(T_{gas} - T\right) \tag{5}$$

where m is the mass of the leaf (kg), C_p is the leaf heat capacity (kJ/kg/°C), T is the average leaf temperature (°C), t is the time (s), h is the convective heat transfer coefficient (kW/m^2/°C), A is the leaf surface area (m^2), and T_{gas} is the gas temperature (°C). Equation 5 can be further reduced to

$$q'' = \rho \Delta x C_p \cdot \frac{dT}{dt} = h\left(T_{gas} - T\right) \tag{6}$$

where q'' is the total heat flux to the leaf (W/m^2), ρ is the leaf density, and Δx is the leaf thickness. Manzanita leaf densities were measured to be approximately 800 kg/m^3,[67] and the leaf heat capacity was estimated from values for wood:[76, 77]

$$C_p = 1.11 + 0.00486 \cdot T \quad (7)$$

where T is the sample temperature in °C. This relationship should be valid for temperatures below 150 to 200 °C, or until the region where significant moisture evaporation and/or pyrolysis must be considered.

The temperature derivative with respect to time was taken from a representative run similar to the temperature curve in Figure 11. Figure 11 shows how the calculated convective heat flux to the leaf varies with time for a dry sample of manzanita. A maximum and an average flux of 100 and 40 kW/m^2, respectively, were calculated from this analysis. The maximum convective heat flux varied from 80-150 kW/m^2 from run to run, depending on thickness of the leaf and the change in leaf temperature with time.

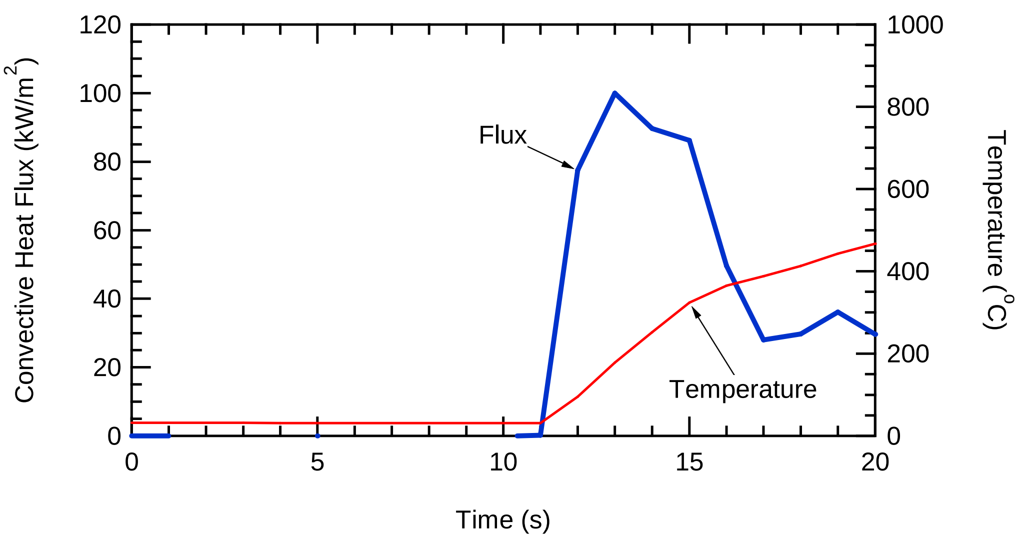


Figure 11. Estimated convective heat flux for 0.72mm thick dry manzanita sample in the horizontal position.

Table 4 is a summary of the measured fuel properties and the corresponding symbol.

Table 4. Summary of Measured Fuel Properties and Corresponding Symbols

Measured Fuel Property	Symbol
thickness	Δx
moisture content	MC
mass	m_0
approximate length	L
approximate width	W

4.2 Experimental Fuels – California Chaparral

California chaparral consists of mainly four species and accounts for the bulk of the natural foliage found in southern California where wildland fires occur. The four chaparral species investigated in this study are: (1) scrub oak (*Quercus berberidifolia*), (2) manzanita (*Arctostaphylos glandulosa*), (3) chamise (*Adenostoma fasciculatum Hook. & Am.*), and (4) hoaryleaf ceanothus (*Ceanothus crassifolius*). The California chaparral samples were collected from an experimental area 50 km east of Riverside, California by Joey Chong and coworkers at the Pacific Southwest Research Station located in Riverside, California. These samples were express mailed to BYU, where the experiments were performed within 2-3 days of being collected.

Proximate analysis was performed on chaparral samples according to ASTM[78] methods for coal and char material to determine the volatile matter and ash content. Samples were dried, ground, and sealed in plastic bags until used. Samples weighing approximately 1 gram were placed in platinum crucibles open to the air and were placed in a furnace. To determine ash content, the furnace temperature was ramped from 105 to 500 °C in one hour, then to 750 °C over the next hour. The samples remained in this environment for approximately 24 hours, or until mass remained constant. The remaining mass was the ash content.

The volatile matter was determined by placing approximately one gram of the ground sample in a ceramic crucible with a loose fitting lid. The crucible was placed in the furnace at 950 °C for exactly 7 minutes and then cooled down and weighed. The mass release minus the moisture content is the volatile matter. The ash content for the chaparral species studied varied from 2-5%, and the volatile matter content varied from 74.5-77% (see Table 5).

Table 5. Ash and Volatile Matter Content of California Chaparral on a Moisture-Free Basis

	Wt %, Moisture-free basis	
Species	Ash Content	Volatile Matter Content
Manzanita	2.2%	76.9%
Ceanothus	3.2%	75.8%
Chamise	2.8%	76.9%
Scrub Oak	5.1%	74.5%

4.2.1 California Scrub Oak

California scrub oak (*Quercus berberidifolia*) is a rounded leaf without lobes, but has needle-like points along the outer edges of the leaf (Figure 12). Scrub oak is one of the most common species of the chaparral, and is usually a shrubby plant growing about 4.5 m tall.[79] The typical observed moisture content for this species was between 45 and 75% (oven dry basis). The leaf thickness varied between 0.15-0.8 mm, and the length and width varied from approximately 1 to 4 cm.[79]

4.2.2 Manzanita

Manzanita (*Arctostaphylos glandulosa*) foliage is rounded with a slightly pointed tip. A representative sample of a manzanita plant growing in nature is shown in Figure 13. Manzanita is typically a low growing shrub that can attain the height of a small tree (1 to 2.5 m). The moisture content of manzanita as received varied from 45 to 105%. For the experiments performed in this study, the leaf thickness varied from approximately 0.15 to 0.90 mm. The leaf width and length varied from 1.5 to 2.5 cm and 2.5 to 4.0 cm, respectively.

4.2.3 Chamise

Chamise (*Adenostoma fasciculatum Hook. & Arn.*), sometimes called greasewood, often forms dense thickets in the California foothills. Shrubs grow to 3.5 m tall, with needle-like blades for foliage. Moisture content varied from 76 to 85%. The blades are 4 to 15 mm long and grouped in clusters along the twigs[80] (Figure 14). Due to the small needle structure of the chamise foliage, thermocouple data were not collected, but qualitative ignition characteristics were observed.

4.2.4 Hoaryleaf Ceanothus

Ceanothus (*Ceanothus crassifolius*) typically has the smallest-sized broadleaf of the species tested. Moisture content varied from 35 to 105%. The majority of the ceanothus samples had a thickness in the range from 0.2 to 0.7 mm, with reported leaf lengths of 2.5 to 6.5 cm.[79] Some ceanothus samples showed a fine-tooth outline, causing some points or spines similar to scrub oak (Figure 15).

Figure 12. Image of scrub oak.[81]

Figure 13. Image of manzanita. © Dave Hildebrand[82] used with permission.

Figure 14. Image of chamise. © Gary Monroe[83] used with permission.

Figure 15. Image of hoaryleaf ceanothus.[84]

4.3 Experimental Fuels - Utah Samples:

4.3.1 Gambel Oak

Gambel oak (*Quercus gambelii Nutt.*) is abundant on the mountain slopes near Provo, Utah. The majority of the gambel oak used in this study was collected at the mouth of Rock Canyon in Provo, Utah. This oak species can grow as tall as 20 m, but is usually observed to be less than 6 m in height and growing in bunches. The observed moisture content varied from 50 to 125%. The leaves were typically 0.1 to 0.36 mm in thickness, and 5 to15 cm in length, with 5 to 9 lobes[79] (Figure 16). Generally small-to medium-sized leaves were studied here, due to the small size of the flat flame burner (FFB).

4.3.2 Canyon Maple

Canyon maple (*Acer grandidentatum Nutt.*) is also a common species found in Utah's Wasatch Mountains. It grows to about 12 m in height. Canyon maple samples were also collected from Rock Canyon in Provo, Utah, and had moisture contents from 80 to 100%. The leaves have a few large blunt teeth,[79] and vary in thickness from 0.1 to 0.5 mm. Leaves were 5.0 to 11.5 cm long and wide (Figure 17).

4.3.3 Utah Juniper

Common in dry climates, Utah juniper (*Juniperus osteosperma (Torr.) Little*) is one of the most abundant trees in Utah. Juniper samples were collected in Diamond Fork Canyon near Spanish Fork, Utah. Juniper trees vary in size from bush-like up to 6 m[79] (Figure 18a). Moisture content varied from 40-70%. The leaves are small, needle or scale-like, (Figure 18b) and are quick to ignite in wildfires. Juniper leaves are 1 to 3 mm in diameter and of varying lengths (1 to 5cm) with leaves branching off of leaves.

Limited quantitative experiments were performed with this species, but observations were made pertaining to the qualitative ignition characteristics.

4.3.4 Big Sagebrush

Big Sagebrush (*Artemesia tridentata Nutt.*) is found in the mountains and valleys of Utah. It is characterized by small bushes, usually 1.0 to 1.5 m in height, but sometimes growing as tall as 6 m.[79, 80] Sagebrush leaves have three lobes, as shown in Figure 19. The leaves are very high in moisture content (typically above 150%). These leaves are approximately 5.0 cm long and 1.2 cm wide. Experiments were performed on individual leaves.

Figure 16. Image of gambel oak.[85]

Figure 17. Representative sample of canyon maple. © Naturesongs.com[86] used with permission

Figure 18. Images of Utah juniper (a) whole tree © J.S. Peterson[83] (used with permission) and (b) representative sample size used in experiments.

Figure 19. Representative image of big sagebrush. © J.S. Peterson[83] used with permission

5. Results

The experimental apparatus was largely assembled, and preliminary results were obtained and published by Engstrom and coworkers.[67] Measured surface-temperature-versus-time data followed the logical trend that increasing sample thickness leads to increased heat-up time (see Figure 20).

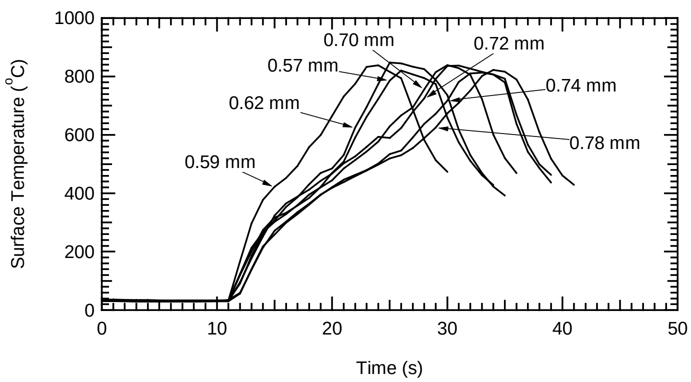


Figure 20. Temperature profiles for horizontally-oriented manzanita of varying thicknesses. (from Engstrom et al.[67])

Ignition temperature and time to ignition for dry samples were also measured. Engstrom and coworkers performed 42 experiments on dead fuels and 50 experiments on live forest fuels. Preliminary results from experiments on live fuel samples by Engstrom and coworkers indicated that the average T_{ig} increased with moisture content (see Figure 21) for both manzanita and scrub oak, although this report was never published. This thesis project has expanded the database to a total of nearly 1000 experiments on forest fuels, the data for which have been stored on DVDs.

This chapter is divided into two major sections. Qualitative observations are described first (Section 5.1), followed by quantitative analysis (Section 5.2).

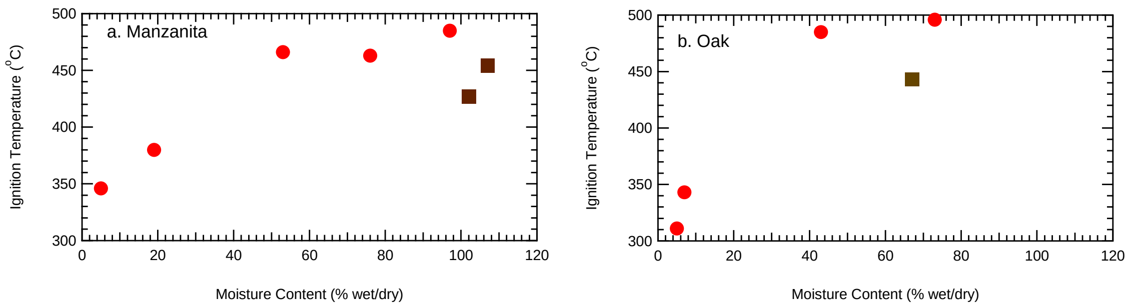


Figure 21. Effect of moisture content on ignition temperature for (a) manzanita and (b) scrub oak. Points represent an average for the moisture content (5-15 experiments per point). Squares represent samples sealed in bags for approximately 1 week.

5.1 Qualitative Results

Events that occurred during heat-up and ignition were observed and recorded using a Minolta 8-918 HI-8 camcorder. Each species had different characteristics in this process. These characteristics were carefully observed so that a better understanding of the ignition process would lead to a better qualitative evaluation. The following section highlights the different qualitative ignition characteristics of the observed species. The observations made are the first of live vegetation at this scale.

5.1.1 California Scrub Oak

The surface of scrub oak leaves would often turn from a dusty appearance to a shiny waxy appearance during heat-up. This is likely caused by the melting of a waxy layer on the surface of the leaf. This color change was not observed with dry samples (moisture content $< 10\%$), suggesting that this waxy layer may be fairly volatile in nature. Bubbles were observed on or just beneath the surface of some scrub oak samples with moisture contents near 60%. Scrub oak typically ignited along the outer edge, flaring up first at the points (see Figure 22), and then igniting along the perimeter of the leaf. The points were often explosively ejected from the leaf creating small brands, burning fuel lofted away that can produce additional fires.

Figure 22. Ignition on the points of California scrub oak followed by explosive branding of the points. The moisture content of this sample was 79%.

Audible crackling was observed during combustion of the oak leaves. Observations were also made on leaves burned in an upside-down position. Crackling, color change, and bubbling were observed when the leaves were placed right-side-up over the FFB. When the leaves were placed upside-down, the surface only went through a color change from a light, dusty color to a dark, wet color. The different characteristics from upside-down to right-side-up are believed to be caused by differences in cell structure between the upper and lower surfaces of the leaves.

Figure 23 shows the progression of the bubbles for this scrub oak, with a moisture content of 60%. It is difficult to see the individual bubbles in Figure 23; however, the change on the leaf surface to a lighter color indicates the presences of bubbles (see video in Appendix CD for better resolution). It wasn't clear whether these bubbles were due to moisture on the surface or if they were bubbles underneath the surface, causing the surface to change colors. More discussion regarding the occurrence of bubbles on the surface is included with the manzanita data.

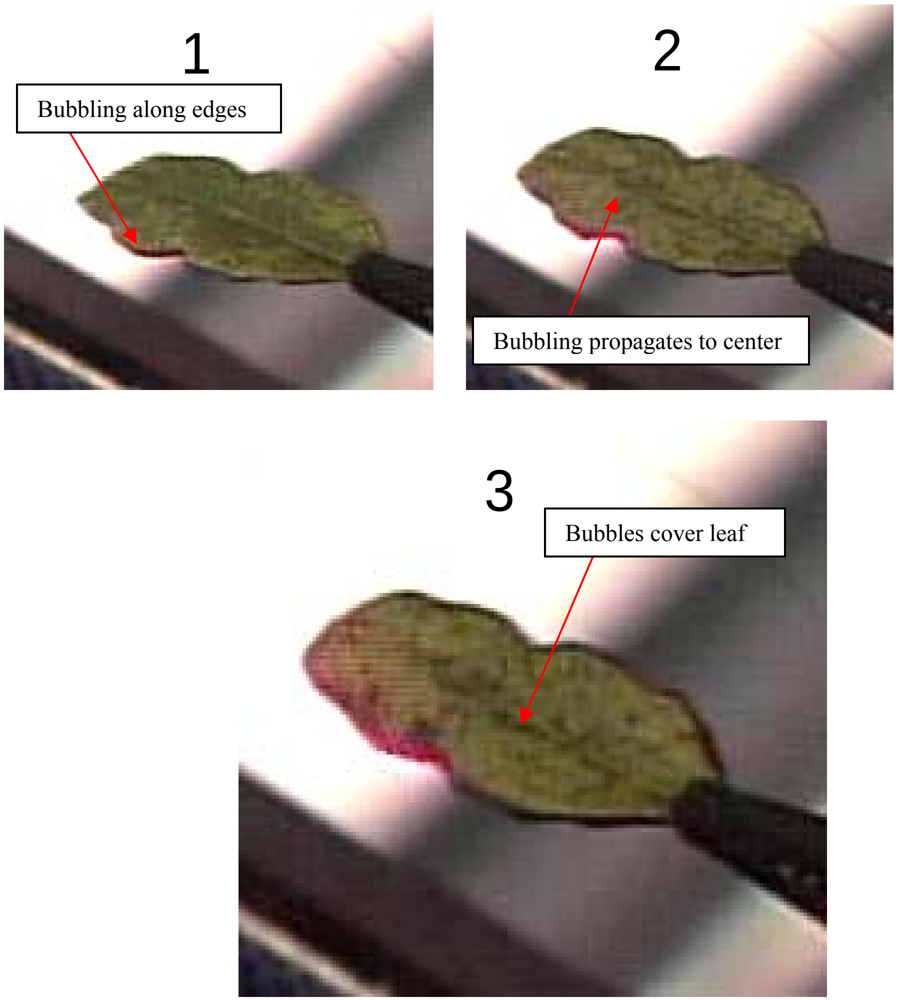


Figure 23. Progression of bubbles forming on the surface of scrub oak. The moisture content of this sample was 60%.

5.1.2 Manzanita

Manzanita foliage is rounded with a slightly pointed tip. During heat-up, the manzanita leaves also changed color from a light, dusty green color to a dark, wet green appearance. This color change was not observed for dry samples of manzanita. Like the scrub oak, this color change is believed to be caused by the melting of the waxy layer on the leaf surface. For higher moisture contents (near 75%), a liquid was observed on the surface of the leaf. The liquid appears first along the perimeter, and then towards the middle of the leaf (Figure 24). As these samples were heating up, the liquid formed droplets that danced on the surface like drops of water on a hot skillet.

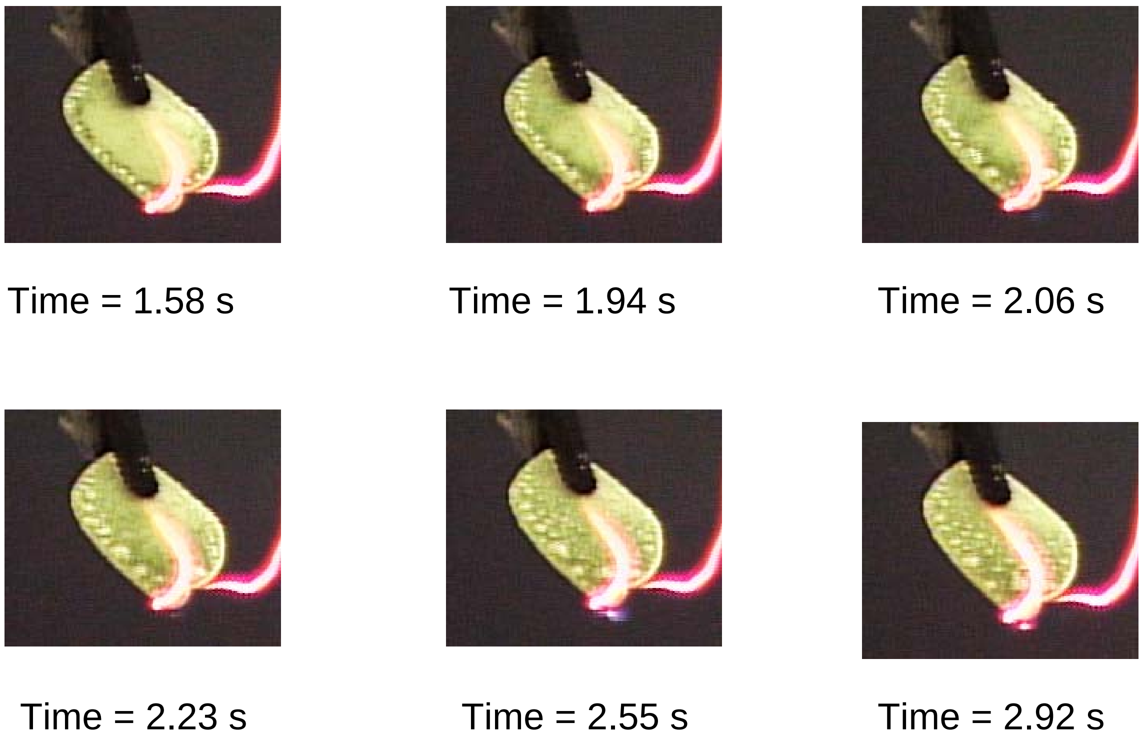


Figure 24. Sequence of bubbling manzanita with moisture content of 73%

At moisture contents near 100%, the manzanita leaves experienced an explosive release of moisture. It is believed that the moisture vaporized inside the leaf structure, and the vapor pressure increased until it exceeded the surface tension of the leaf. At this point, the vapor burst out of the leaf, leaving pockmarks, as shown in Figure 25. When this bursting was observed, there was also a loud audible crackling during the heat-up and combustion of the leaf. As seen in Figure 25, the thermocouple was sometimes ejected from the leaf during bursting. This is likely because the pinhole allows a path of least resistance for vapors to escape as the pressure rises within the leaf.

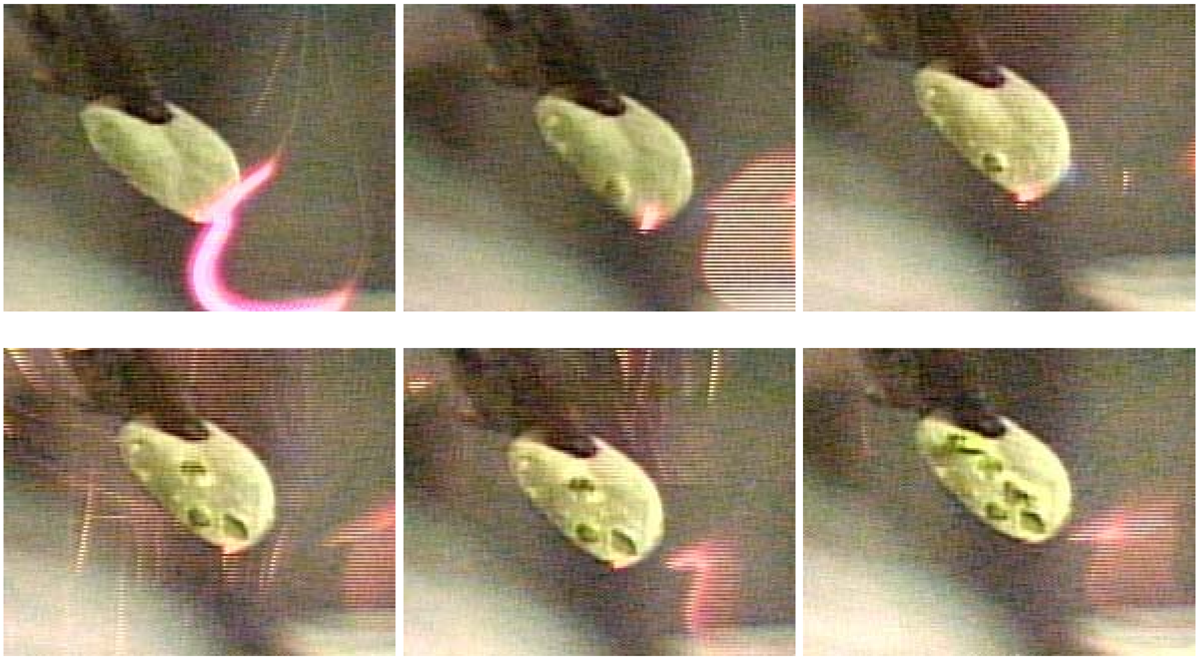


Figure 25. Bursting Manzanita with moisture content near 100%

Figure 26 represents the cellular structure of a typical leaf. Examining the cell structure provided insights and led to a proposed theory for how the bubbling and pockmarks appeared on the surface of manzanita leaves. When a leaf is heated from the underside, vaporized moisture will naturally escape through the top of the surface. There are two ways the water escapes the leaf interior: (1) through the stomata (small pores on the surface of the leaf) or (2) through the epidermal layers. The path of least resistance is for the moisture to evaporate into air spaces around the spongy mesophyll cells. From the air spaces, the vapor diffuses through the stoma into the atmosphere. Guard cells, located near the stoma, open and close the stoma to allow diffusion of gases to and from the atmosphere. Stomata are found on the upper and lower epidermis, but are generally more numerous, and sometimes exclusively found on the underside of leaves.[87]

The hissing noise that was observed when leaves were burned right side up would suggest that the vapor inside the leaf could not exit through the stoma quickly enough. However, when the leaves were burned upside down, little or no hissing was observed, indicating that the vapor was exiting through the more numerous stomata located on the underside of the leaf, that is, the top of an upside-down leaf. If the leaf heats up faster than the moisture can diffuse through the epidermal layer or out the stomata, then the pressure will build up inside the leaf until it exceeds the surface tension of the leaf. When the pressure exceeds the surface strength of the leaf, the moisture will be released by bursting through the leaf surface. This explosion may occur at multiple stomata or at multiple locations of the epidermis, leading to pockmarks as seen in Figure 25.

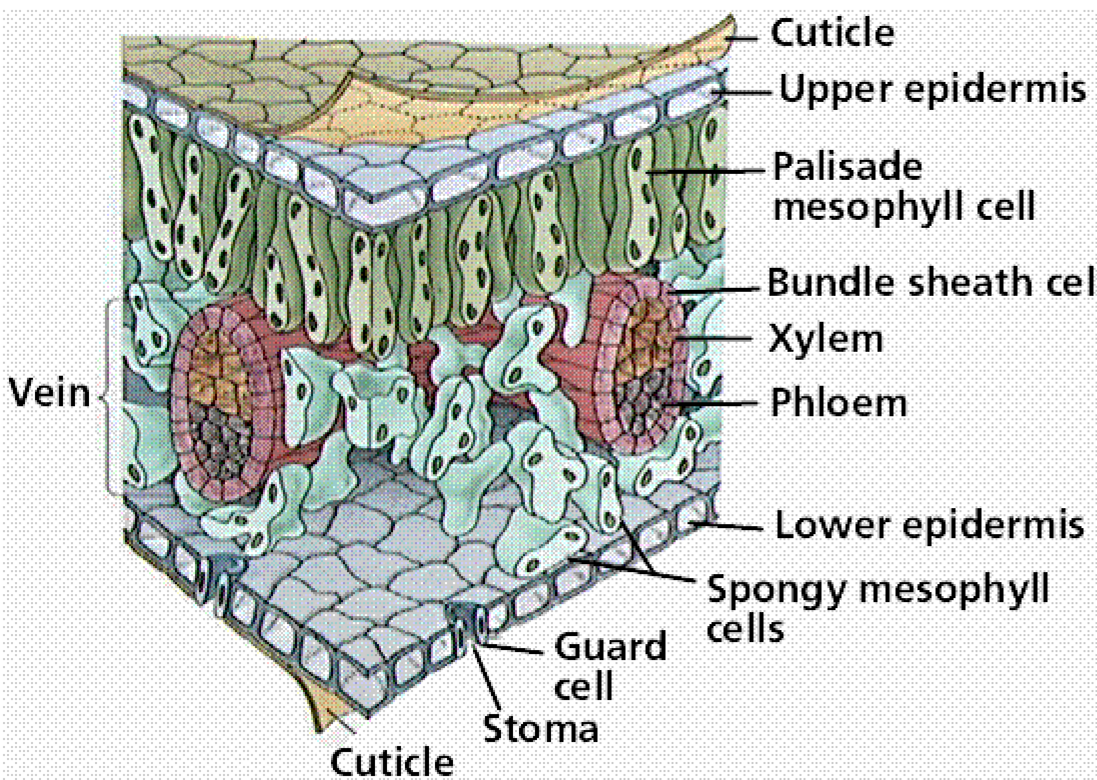


Figure 26. Diagram of leaf structure on a cellular level. Image from Purves et al.[88]

Ignition typically occurs uniformly above the edges of the manzanita leaf, then attaches to the leaf and propagates to the center. When the leaf has sharp points, ignition tends to occur at these points. For example, the leaf will often ignite at the tip opposite the stem. During flaming ignition of the manzanita leaves, the leaf surface changes color from green to black. This color change occurs first on the outside perimeter then propagates towards the center. In the late stages of combustion, this black surface at the center of the leaf appeared wet (most likely pyrolysis gases or heavy waxes were collecting on the leaf surface after exiting either through the epidermis or the stoma). This wet area was only visible for a short time (< 1 sec) and decreased in size as the leaf progressed through burnout.

A summary of the observed surface phenomena that occurred on manzanita samples is shown in Figure 27. This plot is a representative curve taken from one experiment. It is likely that the observed phenomena overlap in different samples. For example, bubbling may overlap with ignition and sometimes even start after ignition.

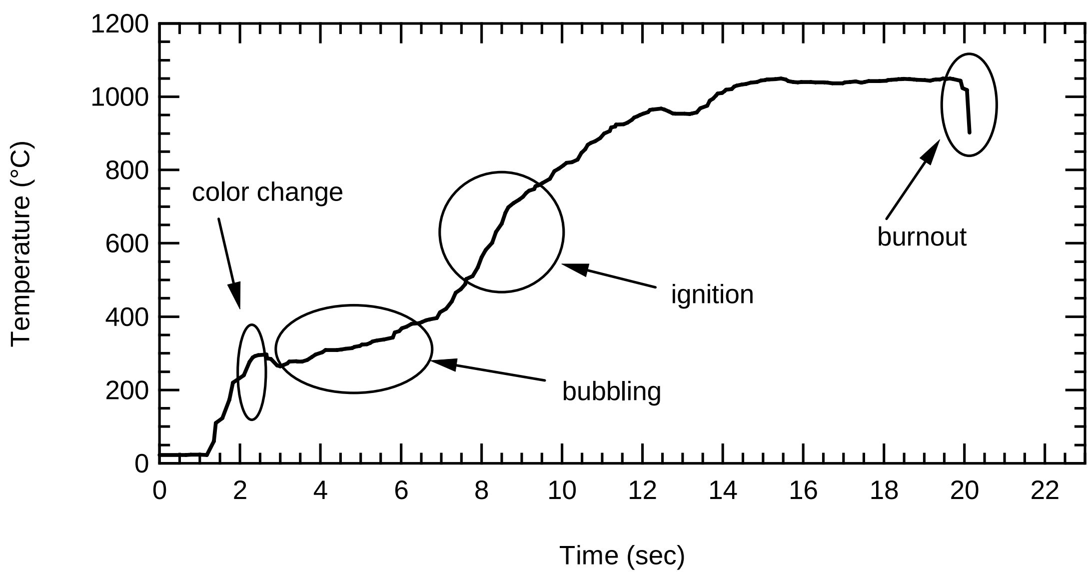
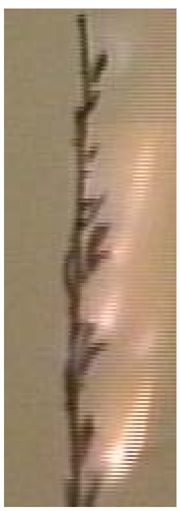


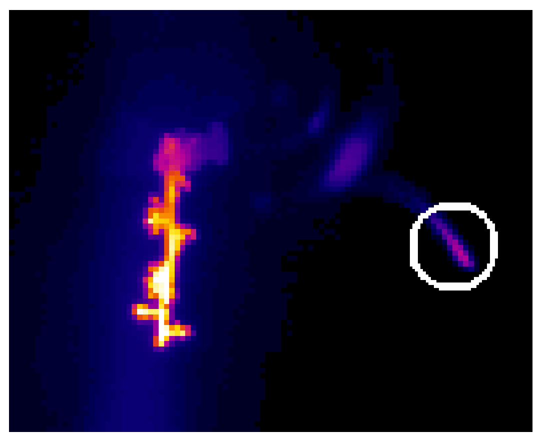
Figure 27. Representative temperature curve showing the observed surface phenomena for a manzanita sample with a moisture content of 73%.

5.1.3 Chamise

Chamise was burned in both the vertical and horizontal orientation. Ignition of chamise samples was always observed to occur at the tips of the needles, followed by flame propagation to the needles and stem. In the vertical orientation, the needles closest to the FFB would ignite first, followed by flame propagation to the top of the stem (Figure 28a). After flaming combustion of the needles neared completion, the stem would begin flaming combustion. When the chamise was burned in the horizontal position, the needles ignited uniformly around the stem, followed by flaming ignition of the stem. In the horizontal position, the flame propagation from the bottom needles to the top was not observed like in the vertical orientation.



(a)



(b)

Figure 28. (a) Combustion photo of chamise burning in the vertical orientation. (b) IR image of burning chamise (bright yellow) with a burning brand (circled).

As the chamise burned, occasionally a brand would be lofted from the main stem and float away from the FFB, entrained in the hot gases (Figure 28b). The image of Figure 28b was recorded using an IR camera, and the brand is circled. Of the fuels studied, chamise, scrub oak, sagebrush, and juniper were the ones that generated brands.

The chamise brands were produced by the stem burning through, causing the stem to divide. The sizes of the brands generated from chamise were significant in proportion to the initial mass of the sample.

5.1.4 Hoaryleaf Ceanothus

Ceanothus was the smallest broadleaf sample studied; however it was relatively thick. The leaf surface did not undergo significant changes prior to ignition like those observed in the oak and manzanita samples. However, ceanothus samples appeared to change color slightly at the beginning of heat-up from a light green to a dark green color. This color change is believed to be caused by the melting of the waxy layer on the leaf surface, as described previously. The samples generally took longer to ignite and were fairly resistant to ignition. When the ceanothus did ignite, ignition occurred first along the perimeter of the leaf before propagating to the center (see video in Appendix).

Figure 29. Ignition of ceanothus sample.

5.1.5 Gambel Oak

The leaf surface of the gambel oak showed a slight color change, but much less than observed with other broadleaf samples. Prior to and during ignition, bubbles formed just beneath the leaf surface, similar to those seen with scrub oak in Figure 23. Also similar to scrub oak, small brands were ejected from the leaf surface. The bubbling can be seen in Figure 30. Ignition occurred at the tip of one of the numerous lobes, and often at multiple locations.

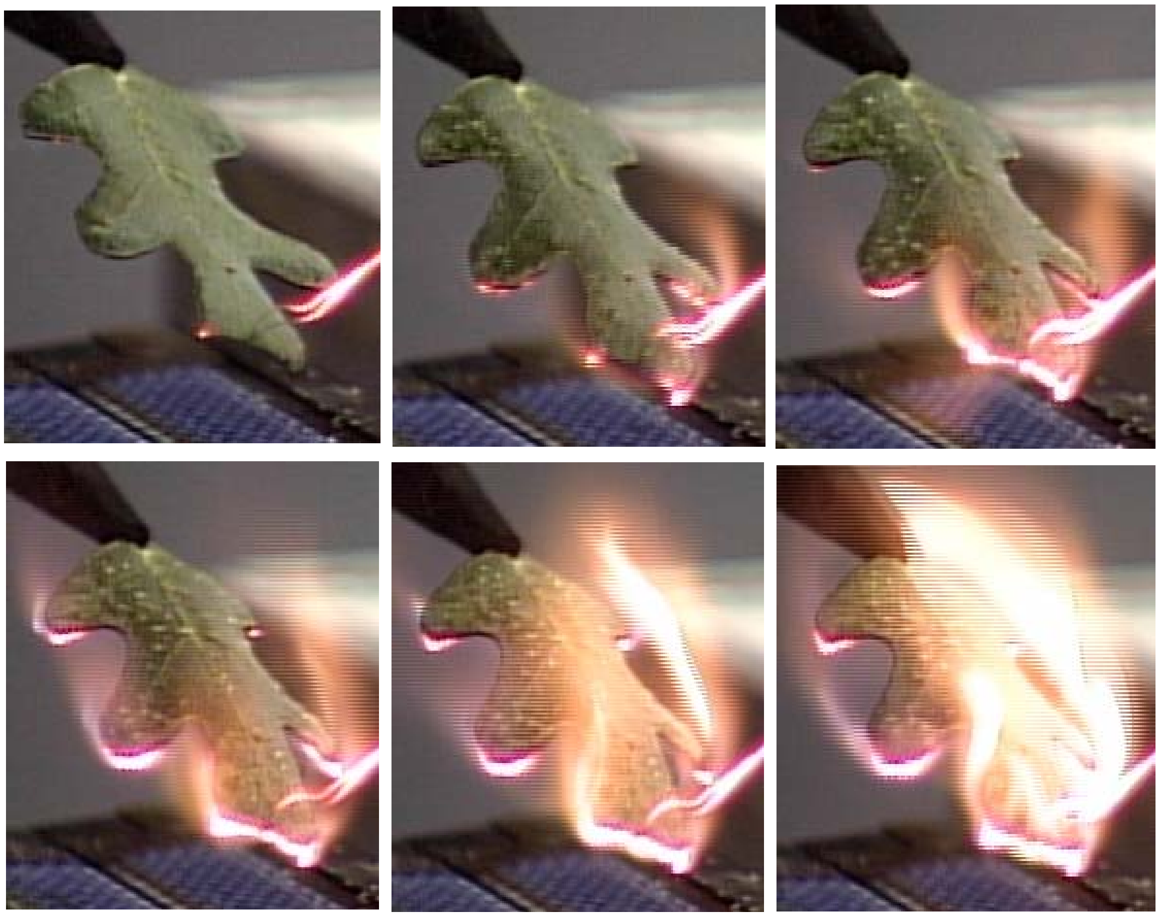


Figure 30. Sequence showing ignition and bubbling on the surface of gambel oak. The moisture content of this sample was 52%.

5.1.6 Canyon Maple

As canyon maple samples were suspended over the FFB, the lobes of the leaf curled into the flame. The surface of the leaves underwent some texture and color changes as bubbles appeared on the surface (see Figure 31). These bubbles were similar to those observed in scrub oak (Figure 23), but did not propagate over the entire leaf surface. The bubbles mainly formed around the edge of the leaf following ignition.

Once ignition took place, it was difficult to observe the leaf surface due to soot formation within the flame (orange flame), but bubbles did appear on the surface.

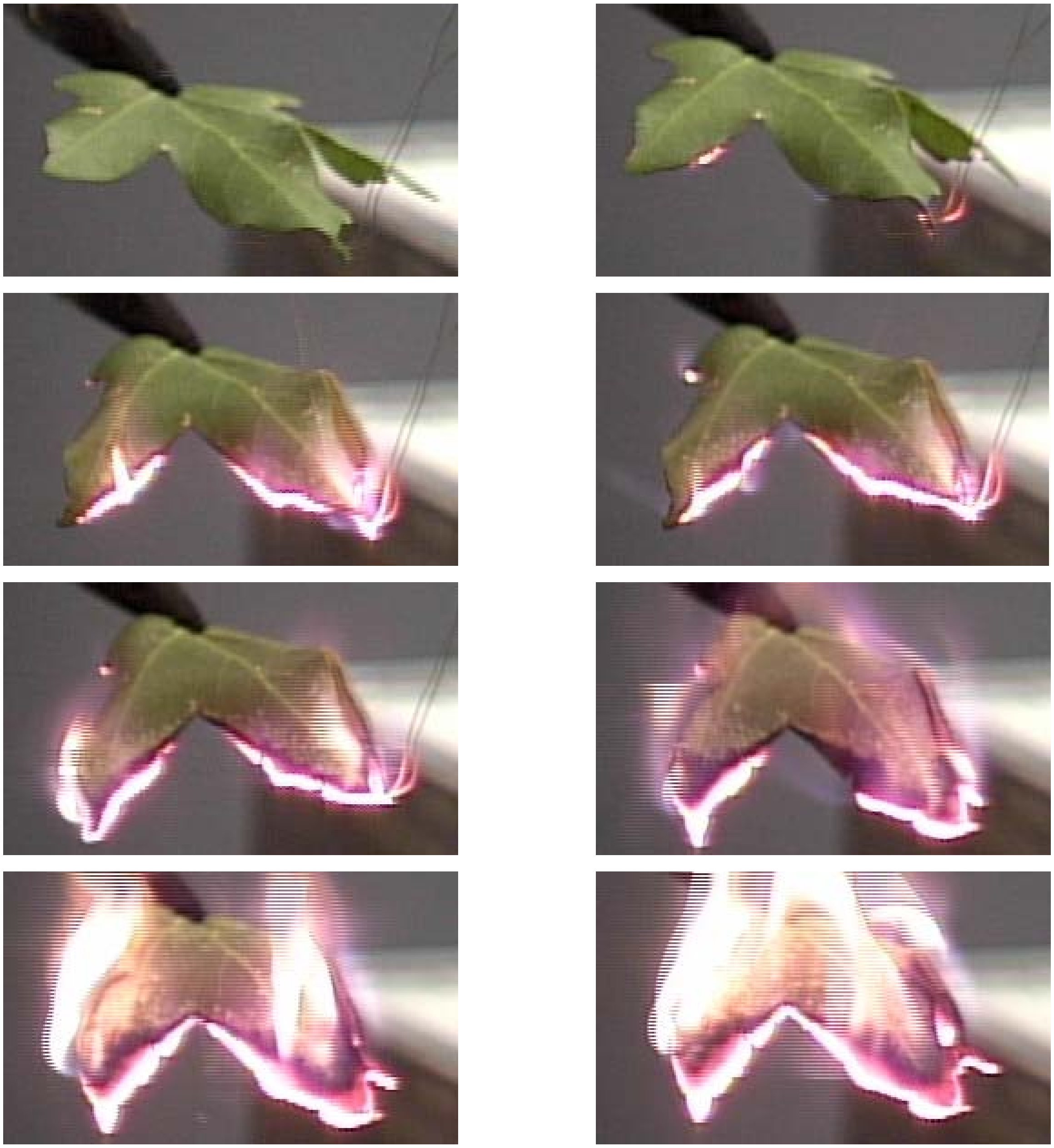


Figure 31. Curling and bubbling of a canyon maple sample over the FFB. This sample had moisture content of 86%

5.1.7 Utah Juniper

The small needle or scale-like leaves of Utah Juniper are quick to ignite in wildfires. Limited experiments were performed with this species, but observations of the ignition characteristics were recorded. When the juniper needles ignited, the first flames occurred on the tips of the leaves before the flame engulfed the entire sample (Figure 32). There was a large flame because of the large surface area/volume ratio of the fuel. The small leaves tended to ignite quickly and burn violently. The organization of the juniper leaves allowed mixing of the pyrolysis gases to occur more readily with oxygen in the hot gas stream, thus leading to increased flaming ignition. Notice in Figure 32 that the separate flames originated from different twig branches, and then combined to form one large flame. A wax-like substance was observed seeping out of the juniper needles and dripping onto the FFB during the heating and ignition of the samples. This phenomenon was observed but not captured on camera. No further analysis was performed to identify the substance; this will be left for future researchers.

5.1.8 Big Sagebrush

Fresh sagebrush had a high moisture content, often near 150%. The sagebrush leaves were less rigid (pliable) than the other samples, perhaps due to lower lignin content or woody structure. Although high in moisture content, sagebrush was fairly quick to ignite. Ignition would usually first occur on one or more of the lobes. Not long after ignition, the opposite end would ignite near the base of the leaf, followed by engulfing flames over the entire leaf (Figure 33). The early burning of the base of the leaf caused the leaf to break away from the clip late in burnout. This could create brands approximately the size of the leaves.

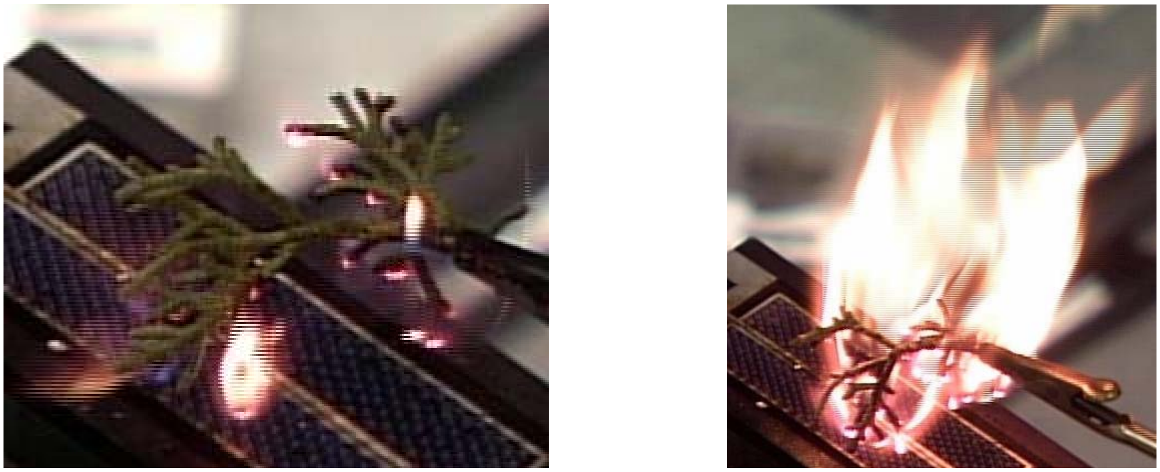
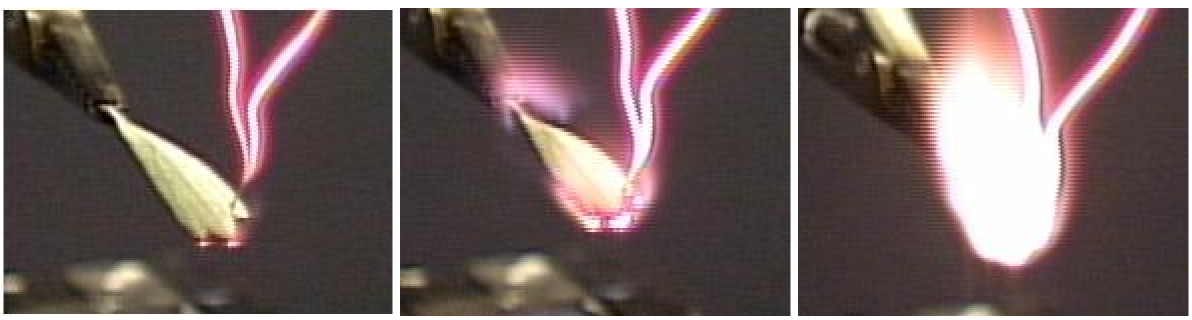


Figure 32. Juniper leaves igniting over FFB (a) just after ignition and (b) during complete flaming. The moisture content of this sample was 41%.



41.3 sec 42.23 sec 42.92 sec

Figure 33. Photos of ignition of Big Sagebrush. These samples had a moisture content of 113%.

5.2 Quantitative Results

The results in the previous section were qualitative, based mainly on video observations. This section describes experiments intended to be more quantitative in nature. As described in Chapter 4, quantitative measurements were made of temperature, point of ignition, duration of flame, and mass. The quantitative experiments were performed on the four California chaparral species and the four Utah species. Table 6 is a summary of the number of experiments performed per species. Average values and 95% confidence intervals of T_{ig} and t_{ig} for each species are shown in Table 7. The 95%

confidence intervals indicate that the T_{ig} values are different for different species. The average ignition temperatures ranged from 231 °C for gambel oak up to 473 °C for ceanothus.

Table 6. Number of Experiments Performed per Species

Species	# of Experiments	Species	# of Experiments
Manzanita	256	Gambel Oak	104
Scrub Oak	204	Canyon Maple	69
Ceanothus	139	Sagebrush	90
Chamise	32	Juniper	66

Table 7. Average T_{ig} and t_{ig} Values for Each Species

Species	T_{ig} (°C)	±	t_{ig} (sec)	±
Manzanita	409	17	2.83	0.30
Scrub Oak	317	35	1.12	0.21
Ceanothus	473	26	4.93	0.41
Gambel Oak	231	24	0.69	0.08
Canyon Maple	277	28	0.53	0.06
Sagebrush	386	34	1.50	0.16
All Species	355	13	2.11	0.15

* The ± represents the 95% confidence interval for these coefficients

Figure 34 shows the distribution of T_{ig} values for all species. The shape of the distribution could be modeled using a probability density function (PDF), which are common in wildfire models.

5.2.1 Thickness

Physical characteristics of each leaf were recorded prior to ignition, including: thickness, mass, and approximate length and width. The effect of thickness on the ignition temperature was explored for both the chaparral and Utah species (see Figure 35 and Figure 36). The general trend shows that T_{ig} increases with increasing thickness, but the scatter in the data make it difficult to determine the trend.

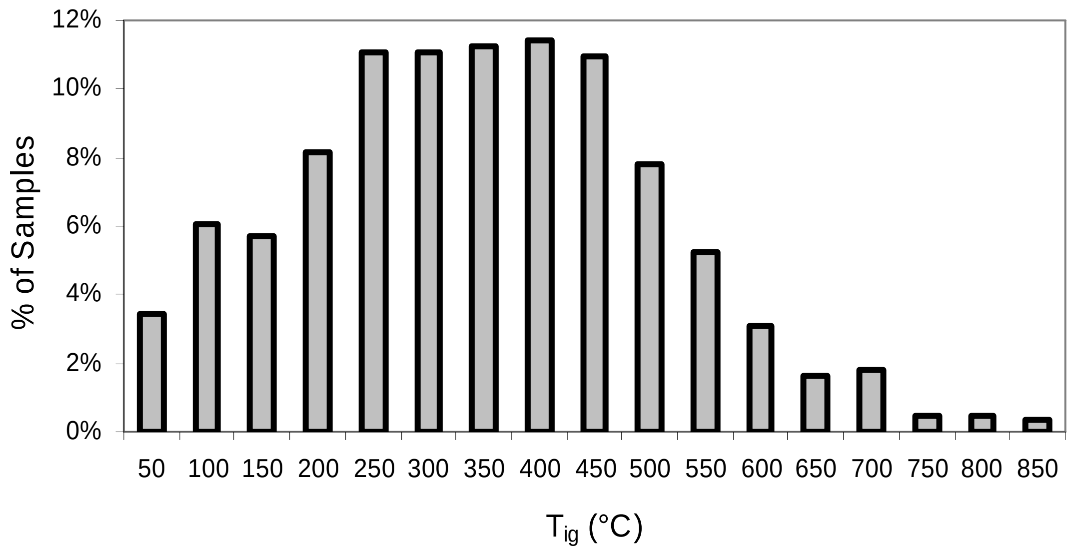


Figure 34. Distribution of T_{ig} for all species.

The effect of thickness on t_{ig} was also explored. Figure 37 and Figure 38 show the effects of thickness on t_{ig} for the California and Utah species. The data scatter makes it difficult to identify trends. There are several variables that may contribute to the scattered results: moisture content, size of the leaf, mass, distance between the FFB and the leaf, and seasonal effects. Attempts were made to identify what factors were contributing to the scatter and to quantify the effects.

The entire data set for each species was fit with a line, and the 95% intervals on the coefficients were determined. The resulting coefficients for the linear fit and the confidence intervals on the coefficients are shown in Table 8. The linear fit (solid line) and 95% confidence intervals (dashed line) are shown in Figure 39. The tight confidence intervals are due to the large number of experimental data points in the regression.

However, the confidence intervals on the coefficients are quite large. Manzanita and ceanothus trends appear to be increasing (Figure 39a & c) while the trend for scrub oak is almost horizontal (Figure 39b).

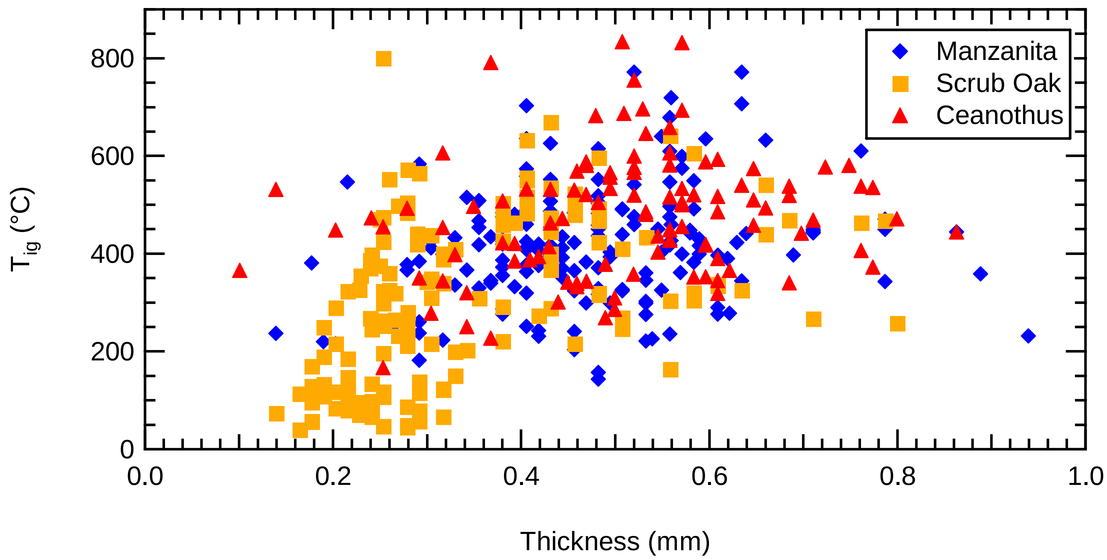


Figure 35. Original data for chaparral species, effect of thickness on T_{ig}.

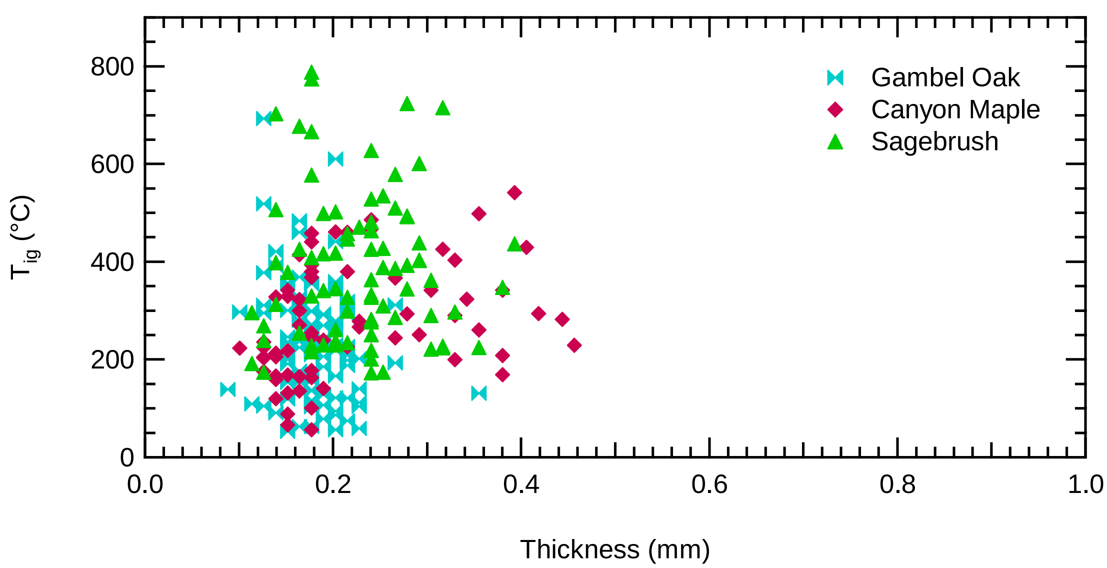


Figure 36. Original data for Utah species, effect of thickness on T_{ig}.

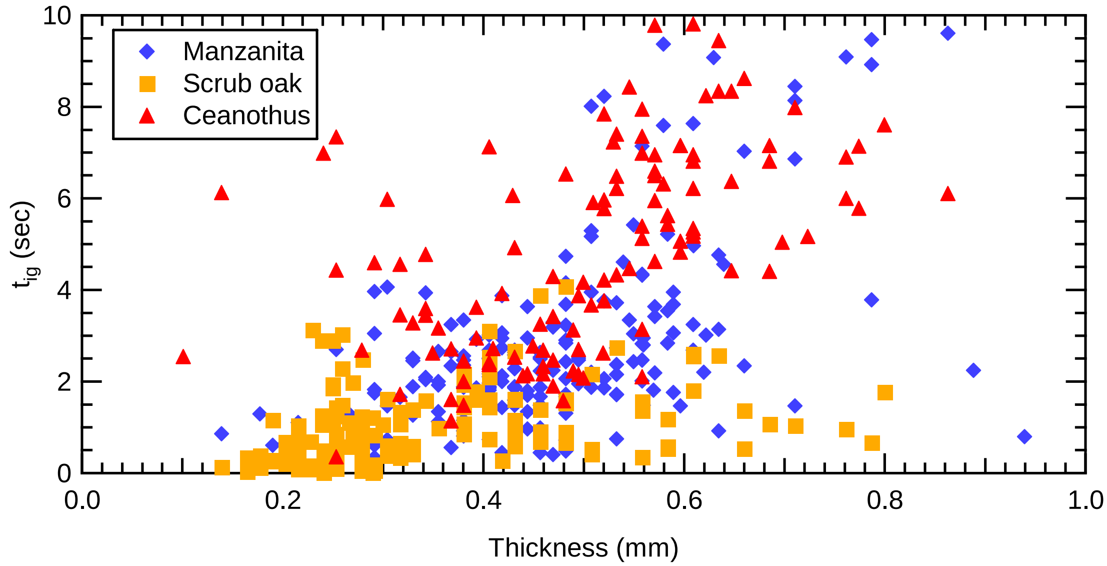


Figure 37. **Original data for chaparral species, effect of thickness on t_{ig}.**

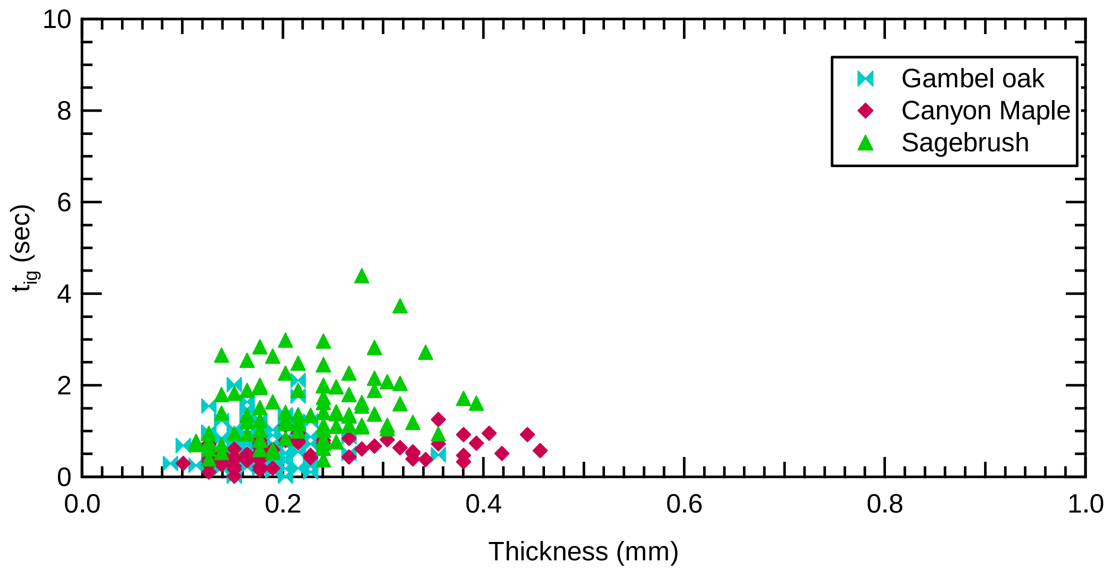


Figure 38. **Original t_{ig} vs. thickness data for Utah species.**

Table 8. Linear Coefficients for Fits of t_{ig} vs. Δx for All Data ($t_{ig} = a + b\,\Delta x$)

Species	a	b
Manzanita	-2.35 ± 2.69	11.31 ± 5.14
Scrub Oak	0.358 ± 0.953	1.548 ± 1.93
Ceanothus	-1.53 ± 3.95	13.75 ± 7.03

* The ± represents the 95% confidence interval for these coefficients

In an attempt to decrease the scatter, the data were separated into bins of common characteristics. The following analysis was performed by sorting the data into bins of thickness. The bins are defined in Table 9. Once the data were binned, the average values of thickness, moisture content, T_{ig}, and t_{ig} were calculated. Figure 40 and Figure 41 show the results of this analysis. The data originally appear scattered, with very little noticeable trends; strong trends are evident in the averaged data.

Table 9. Average Data When Organized by Bins of Thickness for All Chaparral Species

Thickness bins	T_{ig} (°C)			t_{ig} (s)		
	Manzanita	Scrub Oak	Ceanothus	Manzanita	Scrub Oak	Ceanothus
0.1 - 0.2 mm	---	117	---	---	0.31	---
0.2 - 0.3 mm	333	260	396	1.27	0.82	4.99
0.3 - 0.4 mm	392	312	420	1.95	0.99	3.19
0.4 - 0.5 mm	414	463	462	2.13	1.58	3.28
0.5 - 0.6 mm	448	372	515	3.49	0.86	5.62
0.6 - 0.7 mm	440	445	463	5.35	1.38	6.70
0.7 - 0.8 mm	456	---	496	7.01	---	7.11

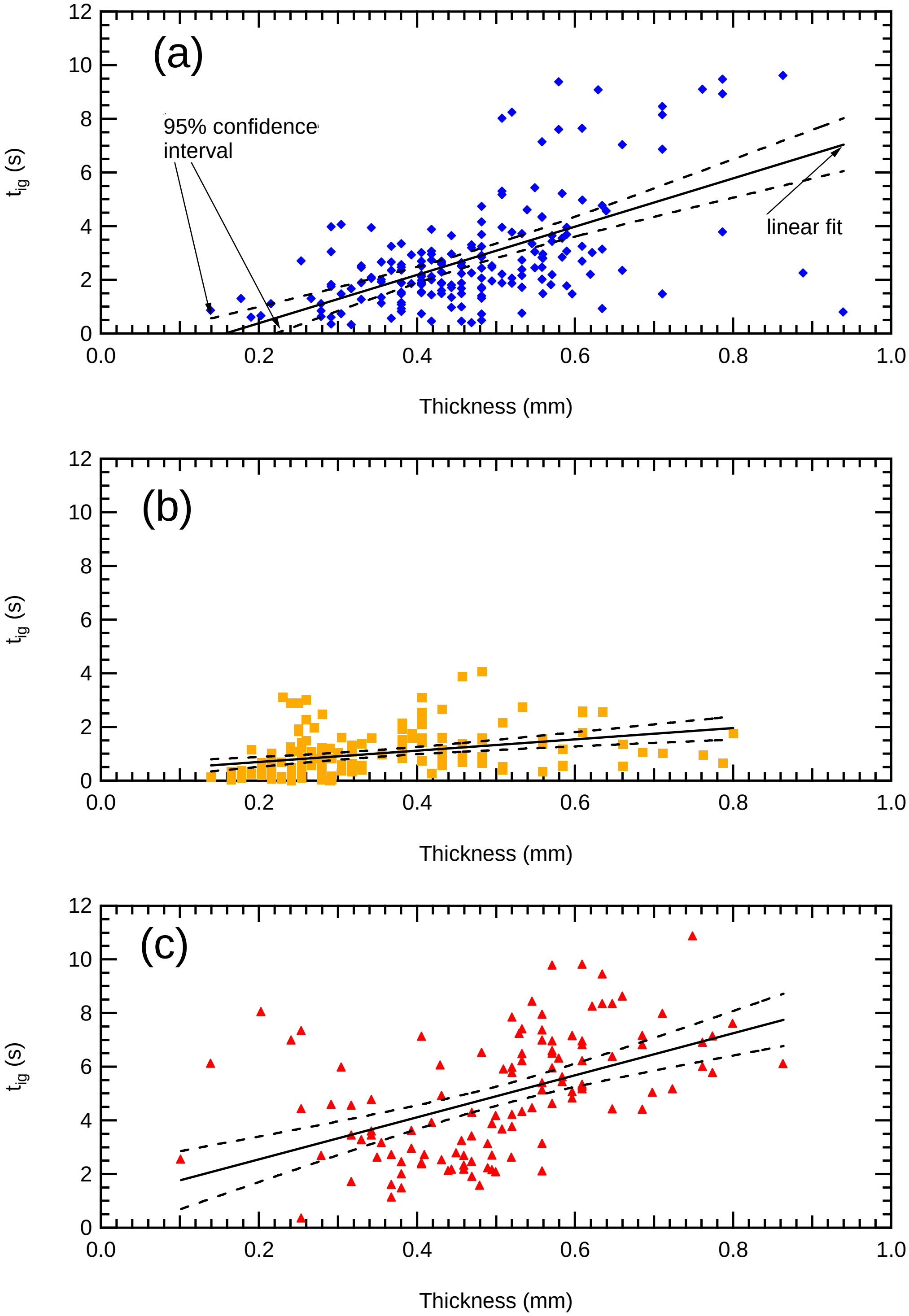


Figure 39. **t_{ig} as a function of thickness for samples of varying moisture content (a) manzanita, (b) scrub oak, and (c) ceanothus. Predicted line fit and 95% confidence interval are also shown.**

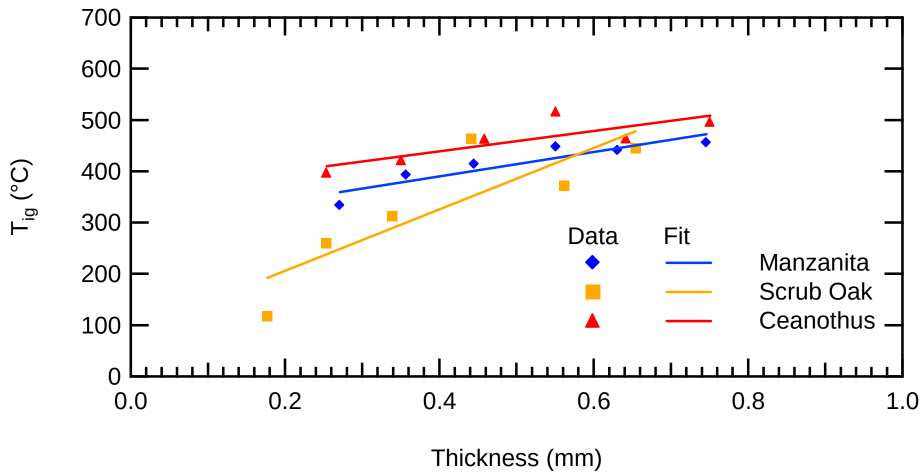


Figure 40. Effect of thickness on T_{ig} for chaparral species binned by thickness. Lines indicate linear fit to the binned data.

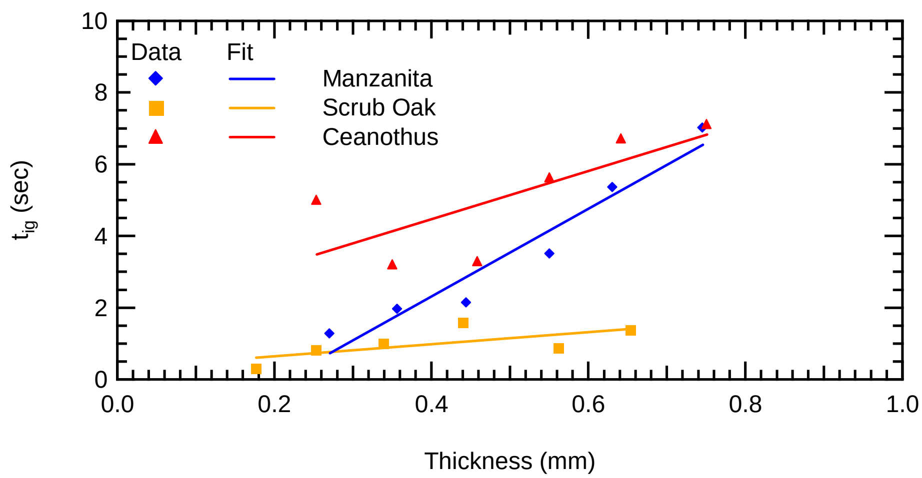


Figure 41. Effect of thickness on t_{ig} for chaparral species binned by thickness. Lines indicate linear fit to the data.

Figure 40 and Figure 41 show a general trend of increasing T_{ig} and t_{ig} with thickness for manzanita, scrub oak and ceanothus. Linear fits are shown for the data, indicating a possible trend. The linear fit to the data appears to be more appropriate for t_{ig} than T_{ig}. It is difficult to determine the effect of thickness on the ignition characteristics because it is difficult, if not impossible, to isolate thickness from the other variables (like moisture content). Time to ignition is believed to be a function of both thickness and moisture content. However, it is difficult to separate these two variables.

It is believed that the scatter could be reduced if the effects of moisture content were included.

5.2.2 Moisture Content

The effect of moisture content on the ignition characteristics was first analyzed by taking the average T_{ig} and t_{ig} values at varying moisture contents. Plots of the T_{ig} analysis are shown in Figure 42a for manzanita data versus moisture content. The T_{ig} data were averaged at each moisture content level, and the 95% confidence interval was calculated. The average values were misleading when analyzed only as a function of moisture content (see Figure 42b), since both thickness and mass were varying within a constant moisture content region. To observe the differences from sample to sample, T_{ig} was plotted versus the mass of moisture in the leaf (m_{H2O}), as shown in Figure 42c. The mass of moisture was calculated from the original mass of the leaf and the moisture content. By using m_{H2O}, the size variations were accounted for in the analysis. The results of this m_{H2O} analysis seemed more accurate than using moisture content; the other species were therefore analyzed using m_{H2O} as well.

Plots of T_{ig} versus m_{H2O} are shown in Figure 43 and Figure 44 for California chaparral and Utah species, respectively. Similar plots for t_{ig} versus m_{H2O} are shown in Figure 45 and Figure 46. The linear fits to the data are shown as a solid line, and the 95% confidence intervals are shown as a dotted line. The slope and intercept values for the linear fits are summarized in Table 10. The slopes in the T_{ig} versus m_{H2O} curves, indicated by b in Table 10, have sufficient scatter for most species that no trend was determined. However, the manzanita data indicate an increasing T_{ig} versus m_{H2O}, and a decreasing T_{ig} versus m_{H2O} was indicated by the canyon maple data. There may also be a negative slope of T_{ig} versus m_{H2O} for the scrub oak data. Time to ignition increases with m_{H2O} for four of the six species analyzed (manzanita, ceanothus, gambel oak, and sagebrush). The t_{ig} data for scrub oak decreases with increasing m_{H2O} and t_{ig} data for canyon maple is constant over the range.

Table 10. Coefficients for Linear Fit of T_{ig} and t_{ig} as a Function of m_{H2O} ($y = a + b\ m_{H2O}$)

	T_{ig} (°C)		t_{ig} (sec)	
Species	a	b	a	b
Manzanita	354 ± 38	539 ± 385	1.64 ± 0.55	12.43 ± 5.6
Scrub Oak	336 ± 40	-371 ± 380	1.23 ± 0.20	-3.24 ± 1.87
Ceanothus	476 ± 46	-129 ± 1320	2.95 ± 0.60	70.65 ± 17.4
Gambel Oak	218 ± 43	164 ± 435	0.42 ± 0.14	3.42 ± 1.38
Canyon Maple	363 ± 61	-924 ± 589	0.57 ± 0.14	-0.52 ± 1.34
Sagebrush	432 ± 81	-2620 ± 4170	0.84 ± 0.39	35.6 ± 19.9

* The ± represents the 95% confidence interval for these coefficients

5.2.3 Combined Correlation

The previous two subsections described efforts to correlate T_{ig} and t_{ig} versus either thickness or m_{H2O}; both variables seemed important. A simple combined correlation was therefore made to predict T_{ig} and t_{ig} for the different species, separately and together, as a function of moisture content and thickness. The T_{ig} and t_{ig} data were curve-fit using the following linear equations:

$$T_{ig} = a \cdot \Delta x + b \cdot m_{H2O} + c \qquad (8)$$

$$t_{ig} = a \cdot \Delta x + b \cdot \Delta H_{vap} \cdot m_{H2O} \qquad (9)$$

where *a*, *b*, and *c* are species-specific constants (see Table 11), Δx is the leaf thickness

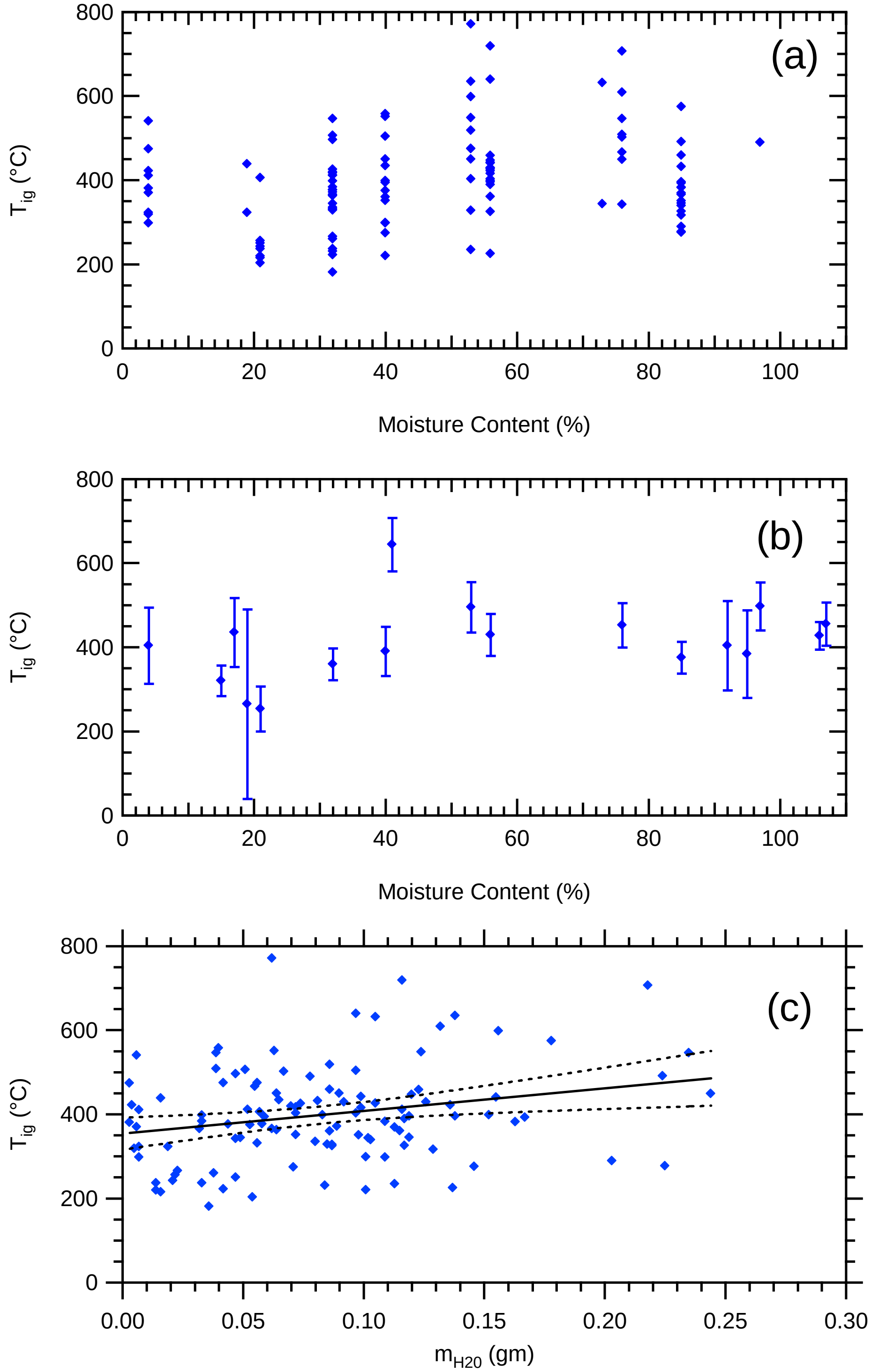


Figure 42. Effect of moisture on T_{ig} data for (a) raw data, (b) average T_{ig} with 95% confidence interval, and (c) as a function of m_{H2O}.

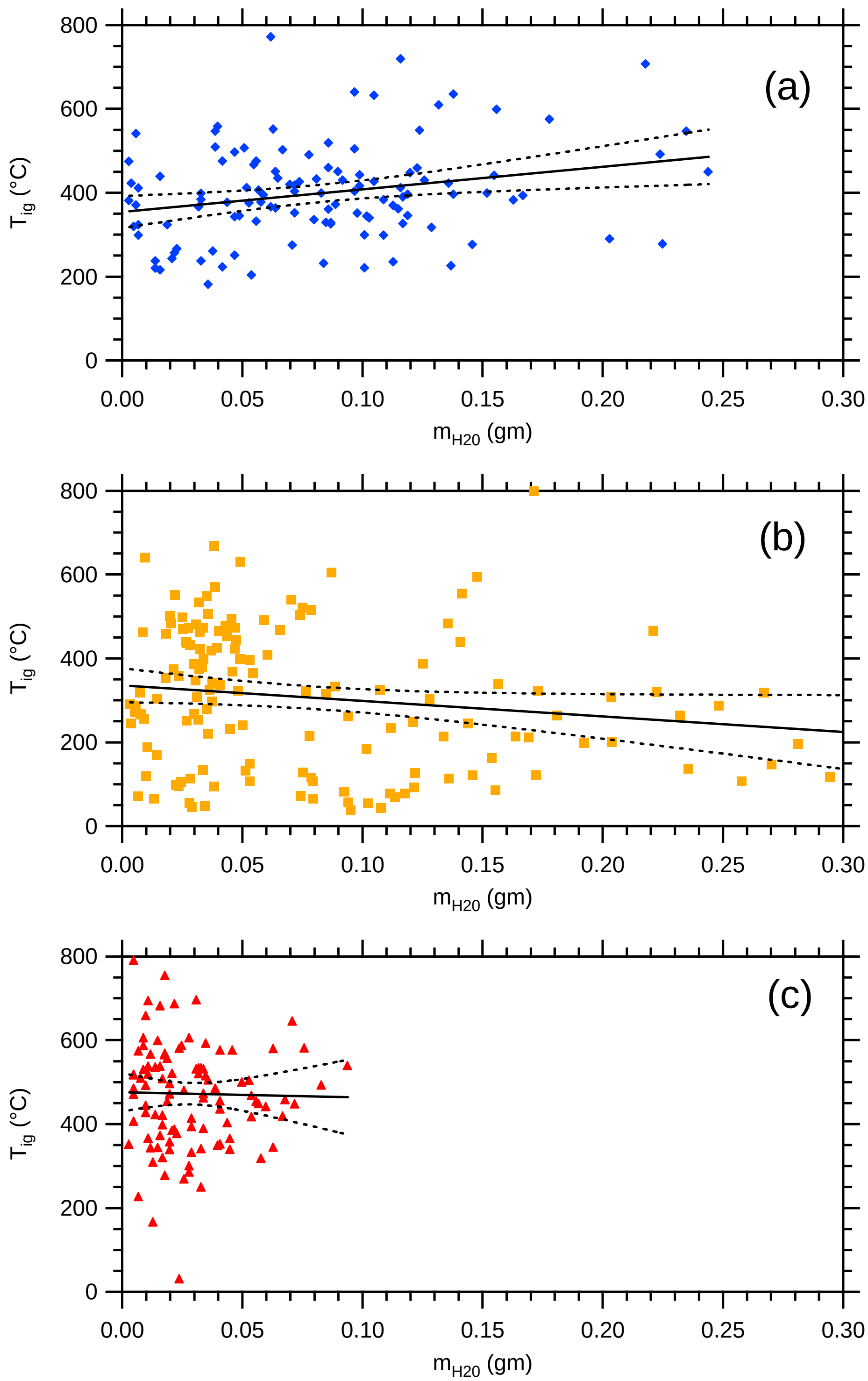


Figure 43. T_{ig} **versus** m_{H2O} **for California species (a) manzanita, (b) scrub oak, and (c) ceanothus.**

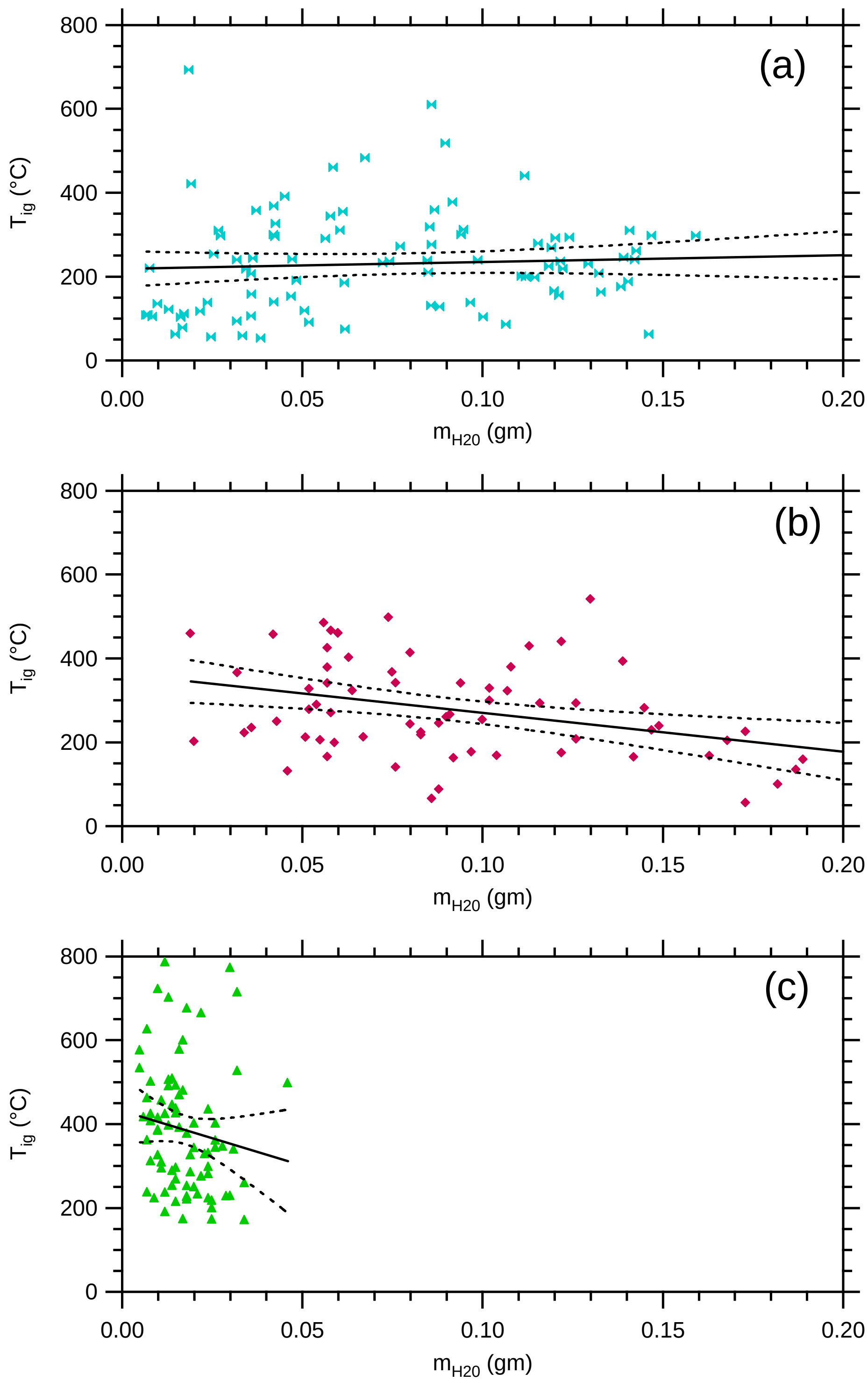


Figure 44. T_{ig} **versus** m_{H2O} **for Utah species (a) gambel oak, (b) canyon maple, and (c) sagebrush.**

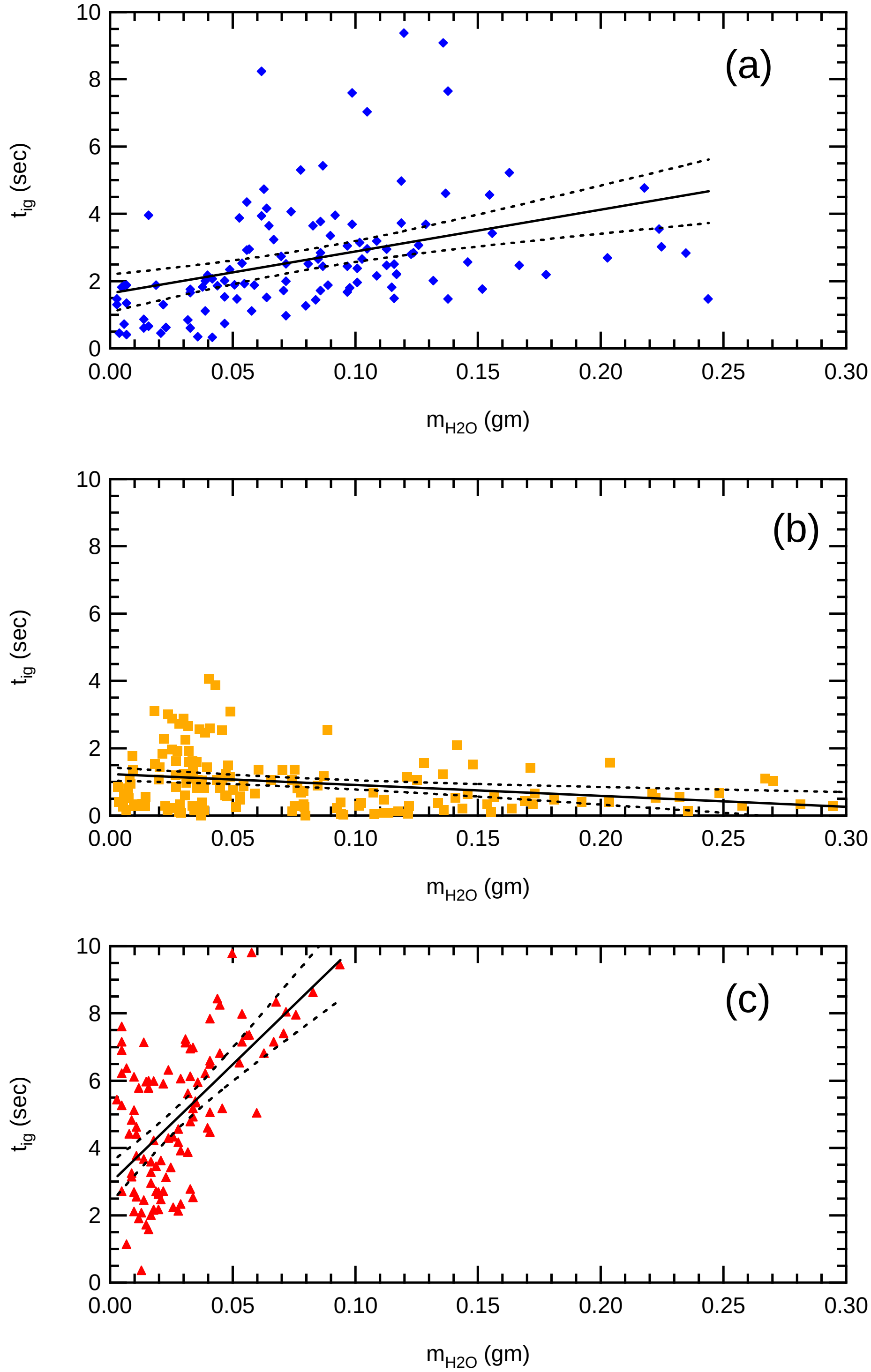


Figure 45. t_{ig} **versus** m_{H2O} **for California species (a) manzanita, (b) scrub oak, and (c) ceanothus.**

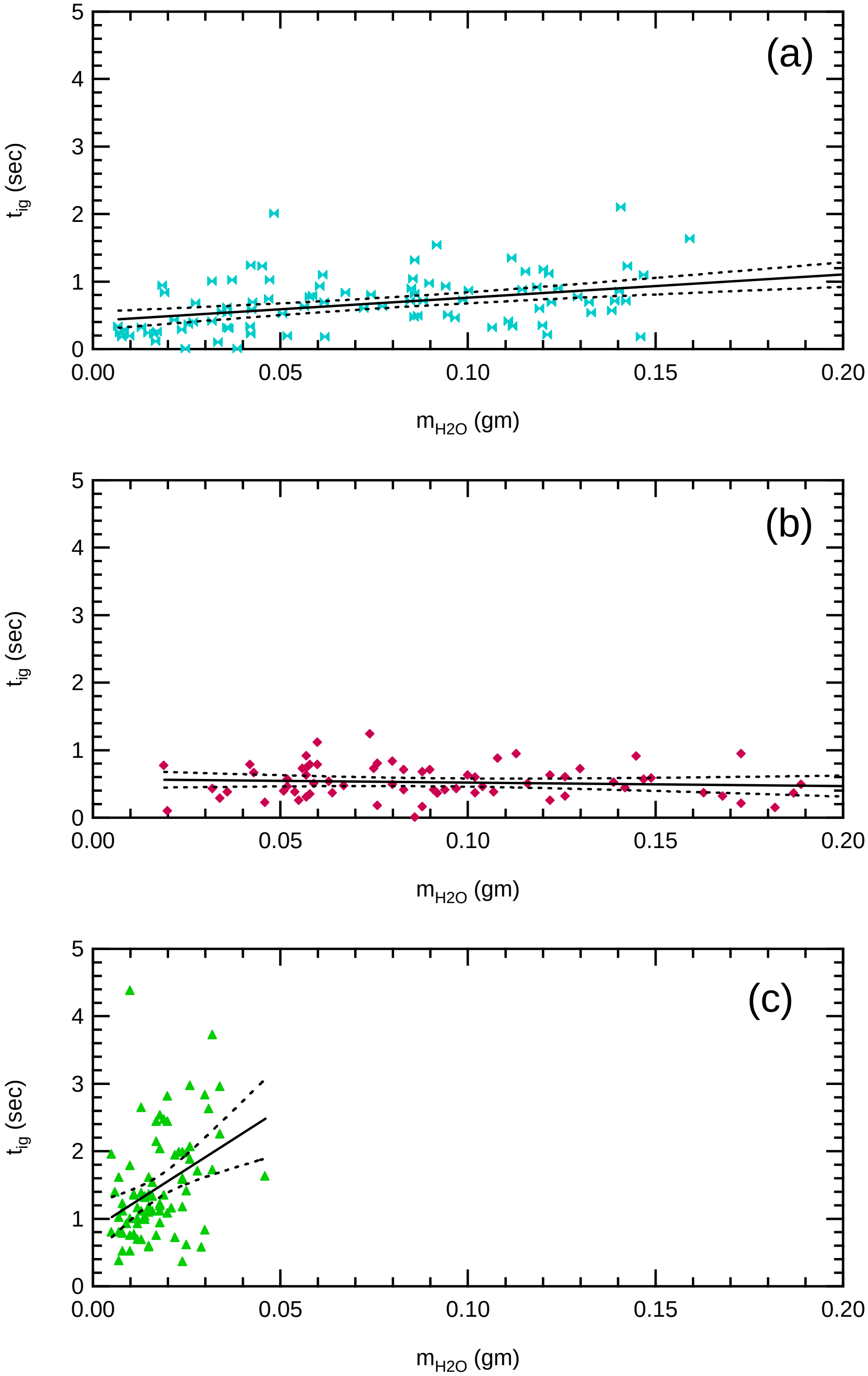


Figure 46. t_{ig} **versus** m_{H2O} **for Utah species (a) gambel oak, (b) canyon maple, and (c) sagebrush.**

(mm), ΔH_{vap} is the heat of vaporization for water (2256.9 kJ/kg), and m_{H2O} is the mass of the moisture (gm). The results of this curve-fit are shown in Figure 47 and Figure 48. The t_{ig} data appear to correlate better than T_{ig} for both the California and Utah species.

Table 11. Coefficients Used in Predicting T_{ig} from Equation 8 for the Different Species

	T_{ig} (°C)			t_{ig} (sec)	
Species	a	b	c	a	b
Manzanita	387 ± 223	-27 ± 496	221 ± 85	5.2 ± 1.35	1.55 ± 2.9
Scrub Oak	526 ± 174	-219 ± 346	144 ± 73	3.01 ± 0.46	-0.64 ± 0.72
Ceanothus	157 ± 180	-296 ± 1340	401 ± 98	6.1 ± 0.95	29.9 ± 6.43
Gambel Oak	-858 ± 685	353 ± 446	359 ± 120	1.97 ± 0.81	1.68 ± 0.68
Canyon Maple	424 ± 269	-940 ± 554	270 ± 82	1.91 ± 0.44	0.33 ± 0.46
Sagebrush	83 ± 562	-2715 ± 4250	414 ± 142	3.61 ± 1.49	15.9 ± 8.1
All Species	452 ± 65	-541 ± 189	229 ± 28	7.10 ± 0.43	2.63 ± 0.84

* The ± represents 95% confidence interval for these coefficients

The coefficients in Table 11 indicate that both moisture and thickness increase the T_{ig} except for manzanita. The negative *b* coefficient indicates that moisture has a decreasing effect on T_{ig} for all species except gambel oak. However the confidence intervals on these coefficients suggest the coefficients are not significantly different than zero. The thickness coefficients for fitting t_{ig} are clearly positive for all species, whereas the m_{H2O} coefficient is positive for some (ceanothus, gambel oak, and sagebrush), essentially zero for others (manzanita and canyon maple), and possibly negative for scrub oak. The moisture coefficient for fitting t_{ig} is negative for scrub oak, indicating a decreasing effect of moisture on t_{ig}. However, the large confidence intervals for the scrub oak t_{ig} *b*

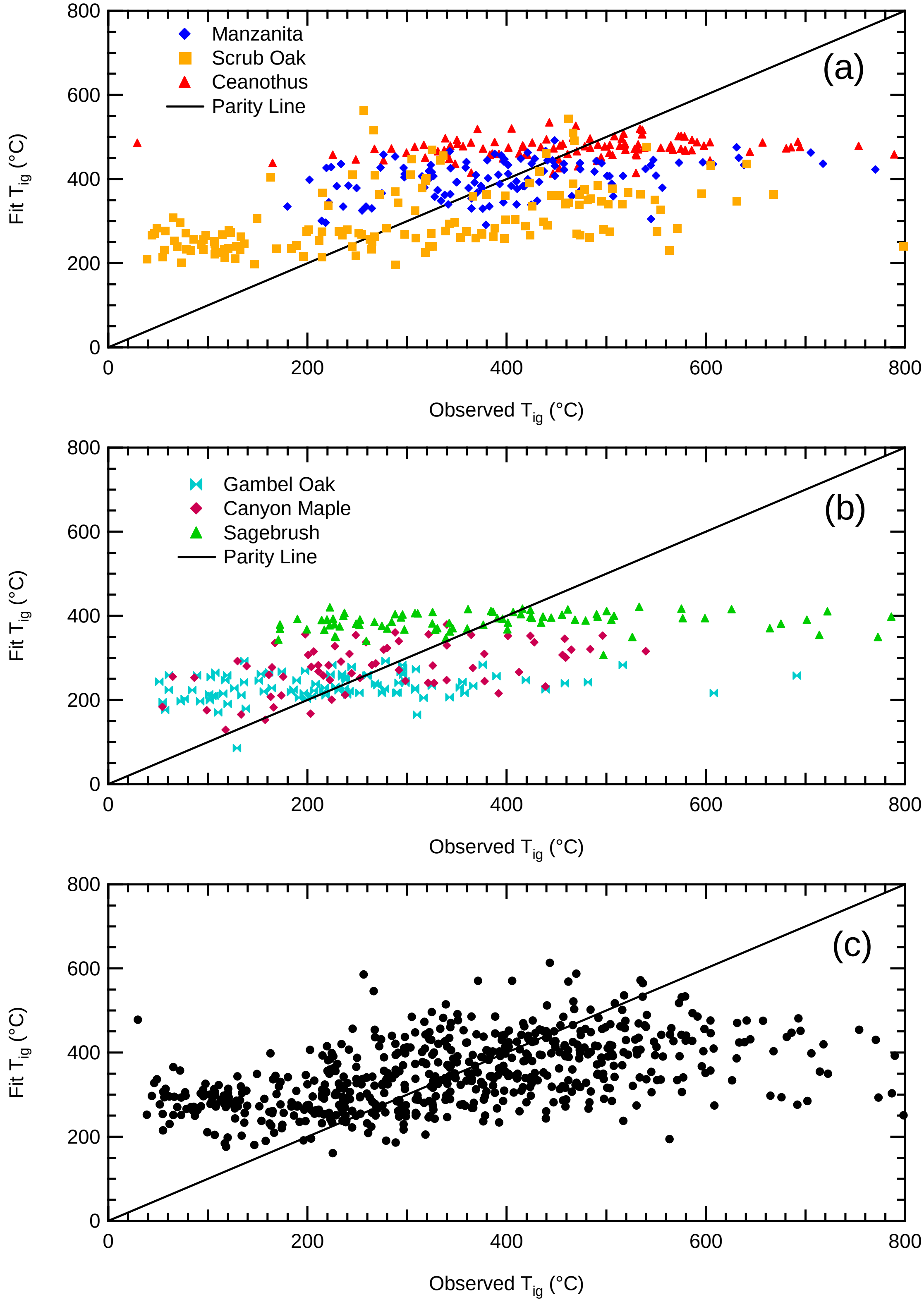


Figure 47. **Comparison of observed T_{ig} data to the fit for (a) California chaparral, (b) Utah species, and (c) for all species combined.**

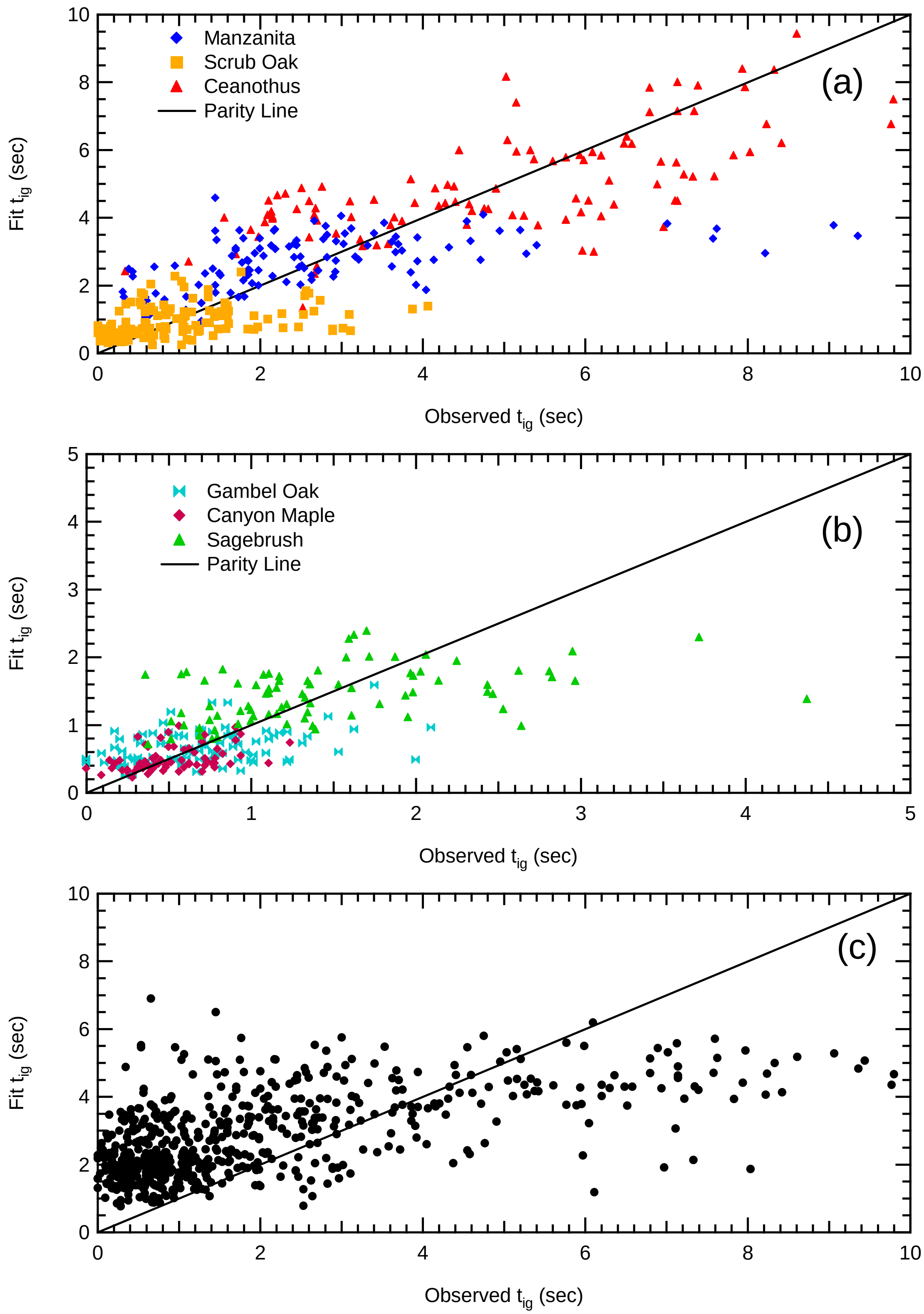


Figure 48. Comparison of observed t_{ig} data to the fit for (a) California chaparral, (b) Utah species, and (c) all species combined.

coefficient indicate that these decreasing effects may not actually occur. The confidence intervals on the coefficients for the two-variable linear fit using all species indicated that both Δx and m_{H2O} are significant for both T_{ig} and t_{ig}. This is different than observed for the fits with individual species.

Additional analysis was performed using Equation 8 and average binned values of T_{ig} and t_{ig} from Table 9. The average t_{ig} data were then curve-fit using Equation 8, and average T_{ig} data were curve-fit using Equation 9. The coefficient values resulting from this analysis are summarized in Table 12. The confidence intervals are large because the data have been compressed into 6 bins. Because the confidence intervals are so large, it is difficult to make any conclusions as to the sign of the coefficients.

Table 12. Coefficients Used in Predicting t_{ig} and T_{ig} from Equations 8 and 9 for the Different Species Binned by Thickness

Species	T_{ig}			t_{ig}	
	a	b	c	a	b
Manzanita	103 ± 651	286 ± 1330	305 ± 106	2.78 ± 20.8	11.8 ± 50.9
Scrub Oak	636 ± 679	-513 ± 2860	161 ± 508	2.11 ± 2.71	0.59 ± 6.57
Ceanothus	205 ± 254	-356 ± 2610	380 ± 200	4.78 ± 4.4	41.1 ± 33.1

Figure 49 and Figure 50 represent the match of the predicted vs. the averaged values for T_{ig} and t_{ig}. Notice the general fit to the 45° line for both T_{ig} and t_{ig}, which indicates good agreement.

Figure 51 and Figure 52 show how the fitted T_{ig} and t_{ig} values calculated using Equations 8 and 9, compare to the binned average T_{ig} and t_{ig} values as a function of thickness. Notice that even though the t_{ig} data for ceanothus do not follow a straight line, the prediction still matches the data fairly well. This is due to the mass of moisture factor, which varies for each bin.

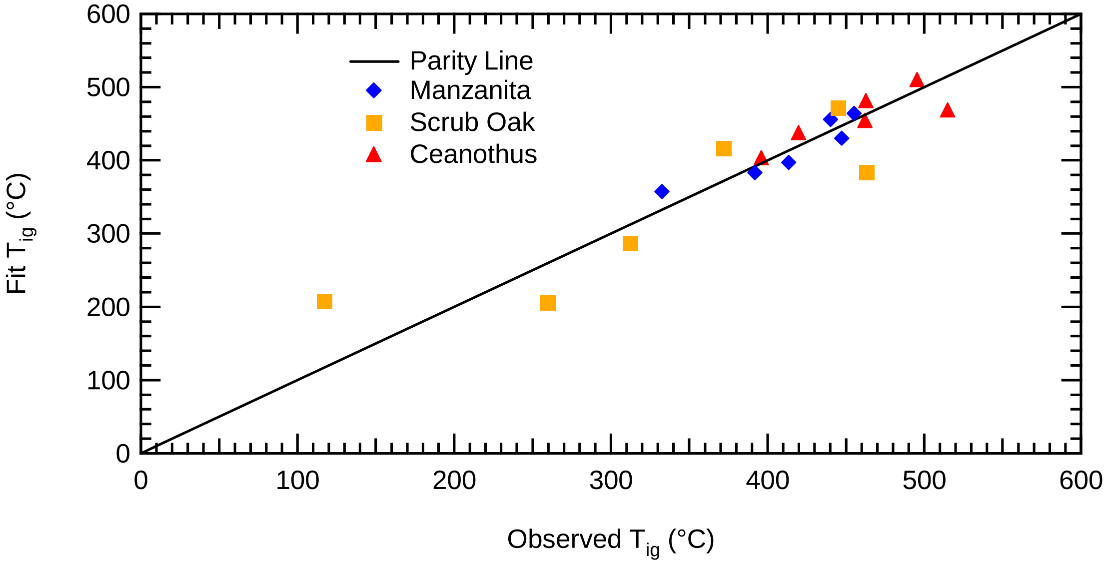


Figure 49. Parity plot for the predicted vs. observed average T_{ig}.

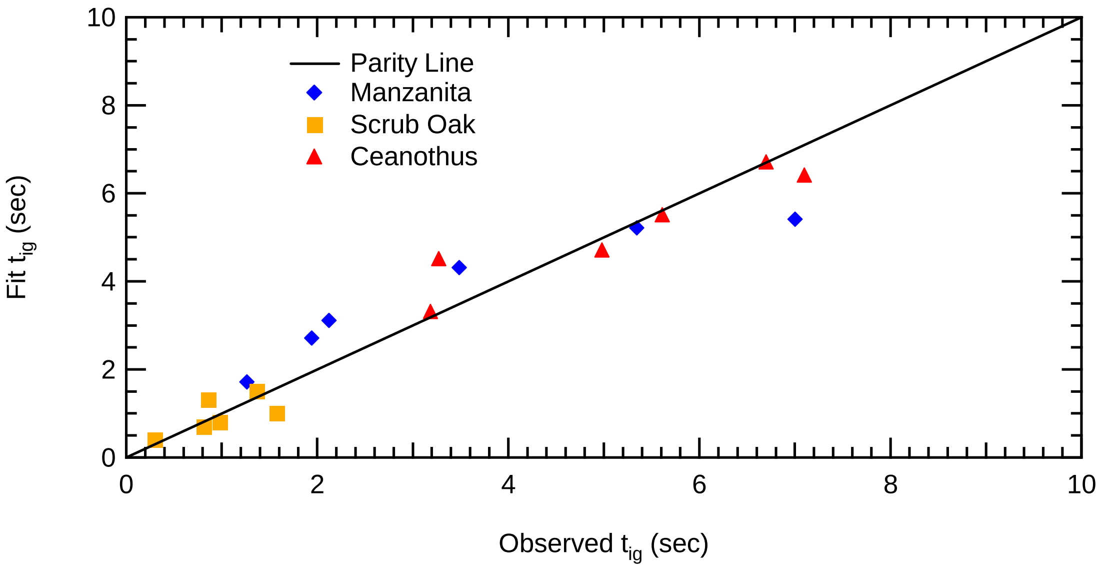


Figure 50. Parity plot for the predicted vs. observed average t_{ig}.

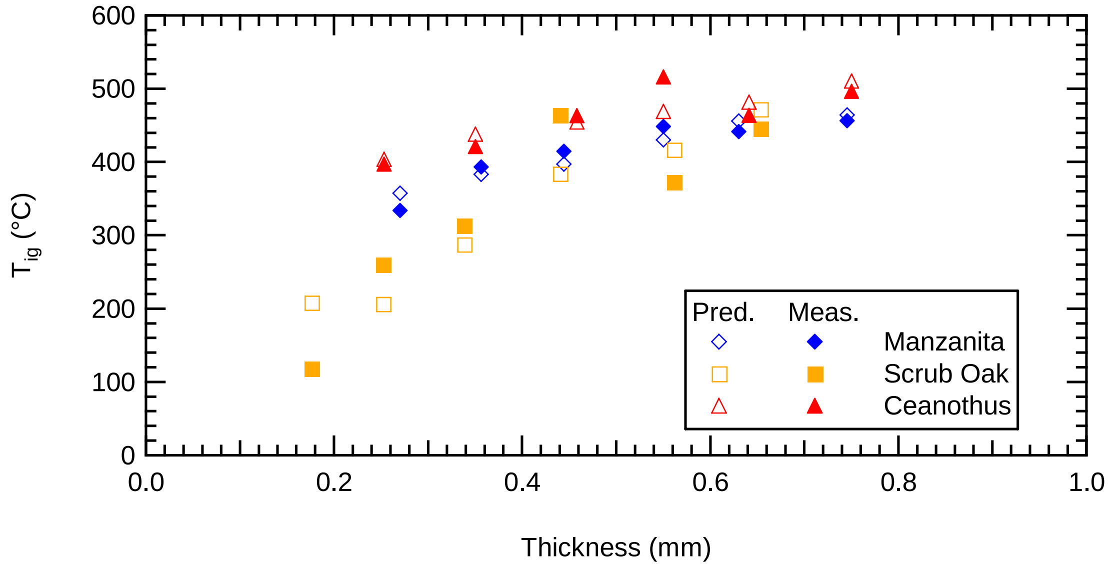


Figure 51. Plots of the predicted and actual T_{ig} from the parity analysis.

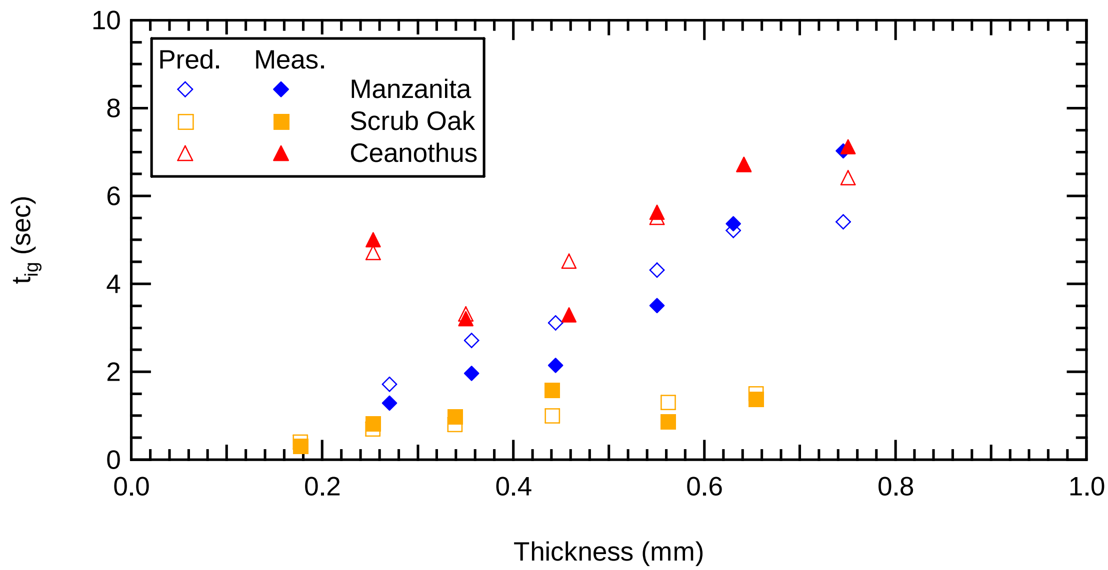


Figure 52. Plots of the predicted and actual t_{ig} from the parity analysis.

5.2.4 Mass

A new Mettler Toledo XS-204 balance was integrated into the experiment and preliminary data were obtained. Figure 53 represents a typical mass versus time curve obtained using this balance, along with corresponding thermocouple temperature data.

As seen in the figure, once the FFB moves under the sample, there is an upward force caused by the hot gases. This upward force, referred to as a buoyancy force, is significant, and varies from leaf to leaf. This force is likely a function of sample surface area. The mass release data was limited to less than 40 runs; additional work in this area will be left to future researchers.

The amount of time that a flame was visible was called the burnout time, or t_{flame}. Burnout time was analyzed for all of the species, except chamise. Burnout time was expected to correlate with the amount of fuel available. Figure 54 shows the correlation of t_{flame} with the initial mass of the sample (m_0). The amount of fuel (m_0) correlates well with the burnout time, although the correlation differs from species to species. The data for each species tend to fall on a line, especially for the Utah species (sagebrush, gambel oak, and canyon maple). The burnout time data for the chaparral species (ceanothus, scrub oak, and manzanita) show a little more scatter, but also exhibit trends unique to each species. The scattered data observed for California chaparral species may be due to the wider variation in moisture content compared to the Utah samples.

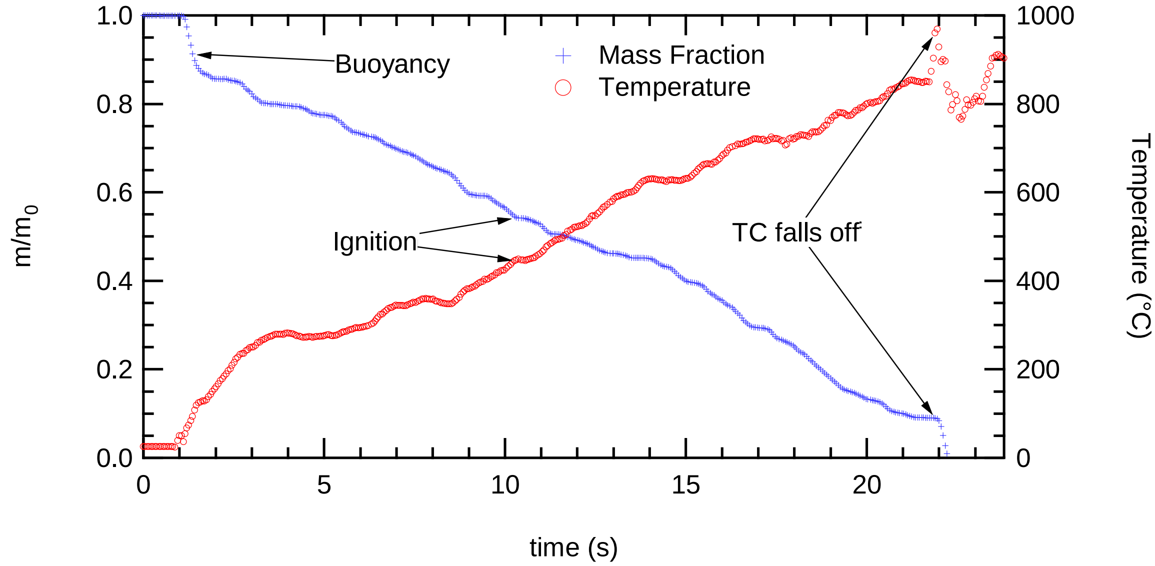


Figure 53. Mass release curve and temperature profile for representative sample of manzanita. The moisture content of this sample was 56%.

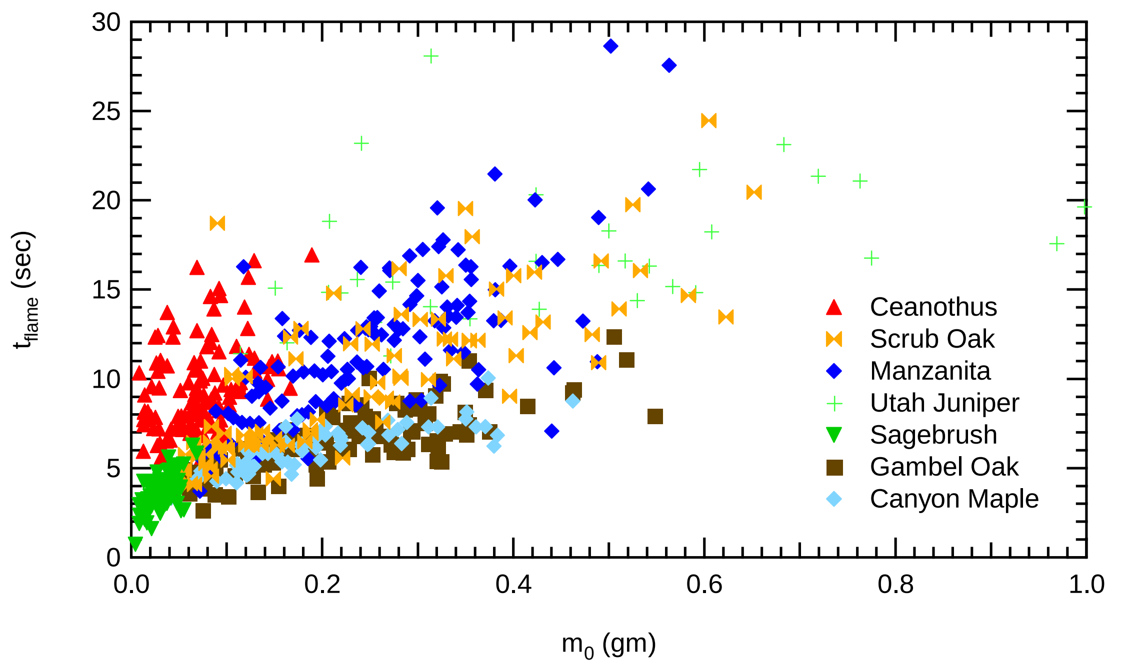


Figure 54. Burnout time (t_{flame}) vs. the initial sample mass (m_0) for California chaparral and Utah species.

5.2.5 Error Analysis

There are a number of factors that would cause variability in the data reported in this project. The most significant source of error is likely due to variability in the visual identification of the ignition time. The assignment of the time where the samples have ignited is somewhat arbitrary; independent researchers analyzing the same data may assign the ignition point to different times. It was especially difficult to define ignition for the scrub oak samples, which had thorn-like points that would explosively ignite but often would not provide a sustained ignition. Bias in determining the time of ignition from visual observation caused a variation in t_{ig} that also affected T_{ig} and t_{flame}. Attempts were made to define ignition as specifically as possible, but there was still some user interpretation in assigning the exact time.

Another source of error could be the location of the thermocouple bead. There are two effects of placing the thermocouple poorly, (1) the thermocouple may not be near the point of ignition and (2) the bead may poke through the leaf and be exposed to the hot gases. The result of ignition occurring at a location far from the thermocouple will cause inaccurate T_{ig} data if there is a significant temperature difference across the sample. In the second case, if the thermocouple bead is exposed to the hot post combustion gases, the temperature data will be higher than the actual temperature of the sample due to convective heat transfer from the hot gases directly to the thermocouple bead.

In addition to the ignition measurements, the leaf thickness and moisture content data were also subject to error. The thickness can vary from point to point on a leaf. Depending on the procedure used to measure the leaf, it is possible to have thicknesses that vary by ±50%. Although a specific method was used, as described earlier, there was still an observed variability of approximately ±5%.

As was described before, the moisture content was determined by using a sample of approximately 2 grams. Depending on the species, anywhere from 5-40 leaves would be required to get a sample weight of 2 grams. The moisture content was therefore an average for all the foliage that was placed in the analyzer. The moisture content of foliage can vary from branch to branch, and possibly from sample to sample on the same branch. Observed variation in moisture content from batch to batch on the same day was usually small (< 5 to 10%), but sometimes ranged over 20%. It is possible that the variation from leaf to leaf was even larger than 20% on occasion.

6. Modeling

This chapter focuses on using fundamental principles to validate a subsample of the data presented in this thesis. The subsample used for this chapter was the manzanita data binned by thickness. The following sections show the consistency of the data with theory for t_{ig} and for the observed temperature history.

6.1 Consistency of t_{ig}

Several simple correlations were investigated to describe the trends in t_{ig} and T_{ig} with moisture content and thickness. The lumped capacitance method[75] was used to predict the time to ignition as a function of thickness. To use the lumped capacitance method, it is necessary to calculate a Biot number (Bi). The Biot number is a dimensionless parameter that relates the resistance to conduction and the resistance to convection for a solid:

$$Bi = \frac{h\Delta x}{k} \tag{10}$$

where *k* is the thermal conductivity of the sample, taken as an average value for several wood species, (0.12 W/m/°C), h is the heat convection coefficient (100 $W/m^2/°C$), and Δx is the leaf thickness (0.4 mm). For Bi values much less than one, a uniform temperature for the solid can be assumed. Using the values previously stated, Bi = 0.3, which is fairly small. For this condition, the lumped capacitance method should be fairly accurate, and therefore a uniform temperature can be assumed for the leaf sample.

The first step in using the lumped capacitance method was to determine the temperature at ignition for varying thicknesses (from the data). The linear fit of manzanita data from Figure 40a was used for T_{ig}. The thickness ranged up to 1 mm but the last bin was omitted because there were only three data points in that range. The lumped capacitance method was then used to predict the time it would take for the leaf to reach this average T_{ig}:

$$t_{ig} = \frac{\rho \Delta x C_p}{h} \cdot \ln\left(\frac{T_i - T_{gas}}{T_{ig} - T_{gas}}\right) \tag{11}$$

where T_i is the initial leaf temperature (°C) and Δx results from the Volume/Surface Area ratio.

In addition to the lumped capacitance method, a correlation from Di Blasi et al.[62] was investigated to predict the t_{ig} based on the hot gas temperature, the experimental T_{ig}, and the gas velocity.

$$t_{ig} = 14000 \cdot U_\infty^{-1.2} \cdot \left(T_{gas} - T_{ig}\right)^{-1.5} \tag{12}$$

where U_∞ was the gas velocity (m/s) and T_{ig} was a function of thickness as explained above.

These two correlations were combined to create a new correlation. The new correlation is dependent on thickness, T_{ig}, and m_{H2O}:

$$t_{ig} = a\Delta x \cdot \left[\ln\left(\frac{T_i - T_{gas}}{T_{ig} - T_{gas}}\right)\right]^b + c\Delta H_{vap} m_{H2O} \tag{13}$$

where a, b, and c are species specific constants solved by minimizing the sum of the errors squared.

This new correlation is shown in Figure 55 compared to the actual binned data, a linear fit, the lumped capacitance model, and the Di Blasi model. One weakness of these correlations is the dependence on T_{ig} data, which is more scattered than t_{ig}.

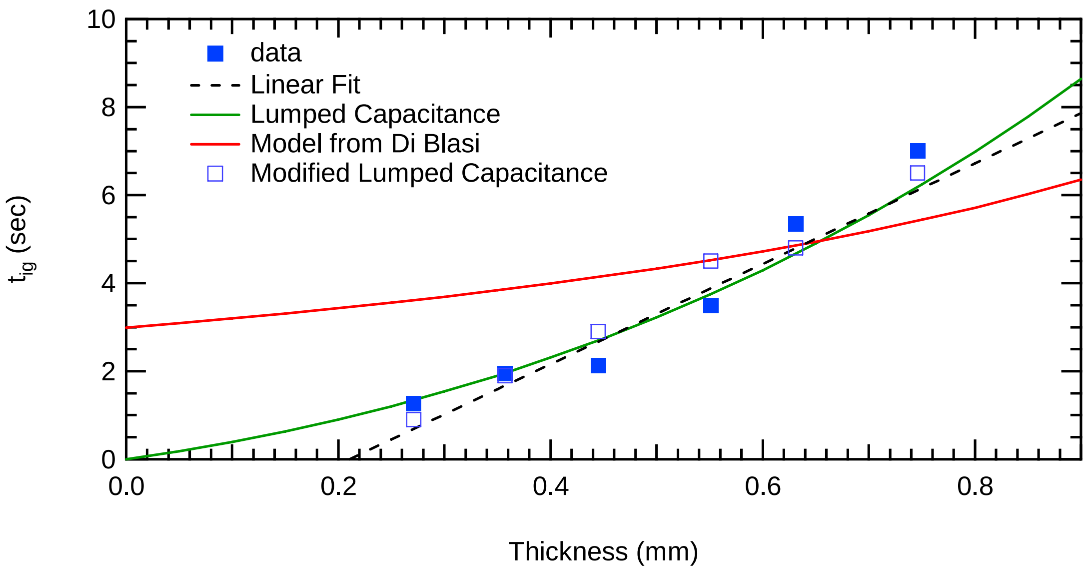


Figure 55. Model predictions of t_{ig} compared to data for manzanita binned by thickness.

The new correlation (Equation 13) fits the data well; as thickness increases, t_{ig} increases exponentially. The new correlation fits the t_{ig} data for the thinner samples (Δx < 0.3 mm), but not quite as well as the lumped capacitance model. However as sample thickness increases, the lumped capacitance model is unable to follow the non-linear increase in t_{ig}, whereas the new correlation follows the observed trend. The nonlinear part of the curve at thickness above 0.6 mm is caused by the significance of internal temperature gradients inside the leaf. As the sample thickness is increased to 0.6 mm, the Biot number increases to 0.5, meaning that the uniform temperature assumption becomes less valid as thickness is increased. It is recognized that this analysis only applies to this set of data, and cannot be generally applied. However, the analysis helps to confirm that the data are consistent with physical mechanisms.

6.2 Consistency of Temperature History

A version of a model developed in C++ by Lu and coworkers[48] was used to model heat transfer to the leaf. This model was used to account for temperature gradients inside and around the leaves. The model described heat and mass transfer to biomass particles with shapes such as spheres, cylinders and flakes and included combustion, devolatilization, and moisture vaporization reactions. The model simulated a particle reacting in hot gas cross-flow heated by both convection and radiation, similar to a boiler environment. A two-stage model for wood (see Figure 56) was used to model the pyrolysis of biomass to light gases, tar, and char. An Arrhenius expression was used to model the drying of moisture in the biomass particle.

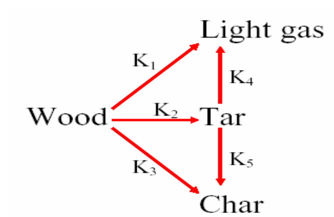


Figure 56. Two stage wood pyrolysis model

Three assumptions were made to develop the model:[48]

1. A one dimensional model applies, which means gradients of temperature, pressure, and concentration exist only in one direction;
2. Local thermal equilibrium exists between the solid and gas phase in the particle;
3. The ideal gas law applies for the gas phase inside the particle;

The main equation (shown below) solved in this model is a conservation of energy equation. The energy equation was used in conjunction with conservation of mass and momentum equations to solve for the species concentrations. The seven main species in this model are: (1) biomass, (2) char, (3) moisture, (4) light gases, (5) inerts, (6) tar, and (7) water vapor.

$$\frac{\partial}{\partial t}\left[\rho_s \hat{H}_s + \varepsilon \rho_g \hat{H}_g\right] + \frac{\partial}{\partial x}\left[\varepsilon \rho_g u \hat{H}_g\right] = \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial x}\left[\rho_g \varepsilon \left(\sum_j D_{eff,j} \hat{H}_j\right)_g\right] \quad (14)$$

The equation was solved in one dimension. For the case of a leaf, modeled as a flat plate, this dimension was through the thickness of the leaf. The model predicted temperature profiles through the thickness of the leaf but not radial temperature gradients. The model also accounted for the surface area by modifying the heat and mass transfer effects accordingly.

Temperature histories were predicted for the surface and center of the particle. This model was used to predict the temperature history of foliage samples during heat-up, estimated as flake-like particles. Although capable of modeling the pyrolysis reactions, they were not used in these preliminary calculations; therefore the results show only the heat-up and drying of the leaf. To use the model in this application, density was changed to the measured value for manzanita (800 kg/m^3) and heat capacity was changed according to Equation 7.

The model was modified to simulate leaves in cross-flow and compared to manzanita data of slightly varying thickness. The data used in this analysis were for dry (5 to 10% moisture content) samples of manzanita. The model was slightly tuned by changing the moisture content ±5% to get good agreement with the measured temperature. Figure 57 shows the comparison of the prediction of the surface temperature made by the model to the actual data for the temperature vs. time profile. The model predicted the temperature history fairly well for the heat-up and early combustion of the sample. This model took approximately an hour of CPU time to run 5 seconds of simulation at a timestep of 0.001 sec for one leaf exposed to the FFB environment. The model has since been greatly improved in speed but no further analysis has been performed. A model of this detail is not of great value when attempting to modify current firespread models, but does show that fundamental science can accurately describe some of the processes occurring.

Future work with this model should include the pyrolysis reactions and higher moisture content samples. Parameters for the pyrolysis reactions may still need to be modified to more accurately represent the foliage being modeled.

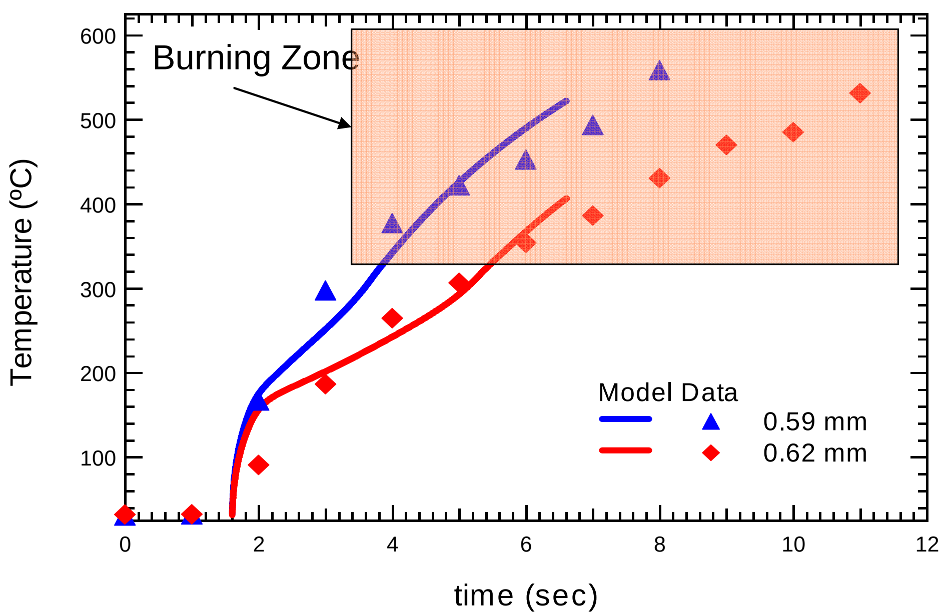


Figure 57 Comparison of representative run for manzanita with surface temperature prediction made by model developed by Lu and coworkers. [48]

7. Conclusions and Recommendations

Experiments were performed on eight different species, four from southern California chaparral and four from Utah locations. Qualitative observations were made for all of the species, whereas quantitative observations were only made for the broadleaf species.

7.1 Conclusions

First ever combustion experiments were performed on nearly live whole leaf samples of California chaparral and Utah species. New surface phenomena were observed during the heat-up, ignition, and burning of the samples. Ignition temperature and ignition time were measured and correlated to thickness and moisture content.

In all of the broadleaf species (both chaparral and Utah), surface changes were observed. All fresh species experienced a change in color from a dusty, light green color to a wet, dark green color. This color change is believed to be caused by the melting of the waxy layer on the leaf surface. Color changes were not observed in samples that had dried in the laboratory for a number of days. In addition to this surface change, many of the broadleaf species experienced bubbling on or beneath the surface. However, no bubbling was observed with sagebrush. At moderate levels of moisture content (40-60%), bubbling was observed on the upper surface of the leaves. No bubbling was observed on the underside of the samples, based on limited observations. For manzanita samples at slightly elevated moisture content levels (near 75%), liquid was observed on the surface of the leaf prior to ignition. Explosions on the surface of the manzanita leaves were observed at higher moisture content levels (~100%), creating pockmarks on the surface of the leaves. These explosions were likely caused by the evaporation of the moisture inside the leaf structure, creating a pressure greater than the surface could withstand. The explosions occurred likely due to the vapor pressure exceeding the surface tension. General leaf structures were studied, and it was concluded that the explosion likely occurs at stoma locations. Explosions and pockmarks were not observed in other species, but may still occur at higher moisture content levels.

Ignition generally occurred at sharp points on the perimeter of the leaves. If the leaves were rounded, ignition occurred in the gas phase uniformly around the perimeter of the leaf. Some scrub oak samples were characterized by having needle-like prickly edges. When heated over the flat flame burner (FFB), these leaves first ignited at the needles. The needles would sometimes ignite and burn out, failing to ignite the leaf, and other times they would be explosively ejected from the leaf.

Juniper and chamise were markedly different from the other species studied due to their needle-like foliage. Juniper would ignite at various locations and create one large flame when placed over the FFB in a horizontal orientation. A liquid, thought to be wax, was also observed seeping out of the juniper foliage and dripping during combustion. Chamise was burned in both the vertical and horizontal orientation. When placed over the FFB in the vertical position, the chamise needles ignited first at the bottom, and then propagated to the top, followed by a second flaming period of the twig. When in the horizontal orientation, the chamise needles ignited uniformly around the sample and propagated to the stem.

Quantitative data were collected and analyzed for the scrub oak, manzanita, ceanothus, gambel oak, canyon maple, and big sagebrush. Temperature curves showed no indication of constant temperature region for moisture evaporation, as has been observed in wood samples. Flaming time (t_{flame}) was found to correlate with the initial mass of the sample. Average ignition temperature (T_{ig}) varied for each species. Ceanothus samples ignited at the highest temperature (an average T_{ig} of 473 °C) while gambel oak ignited at the lowest average temperature (231 °C). T_{ig} and time to ignition (t_{ig}) were influenced by species type, sample thickness, and moisture content. Moisture content and initial mass were used to calculate the mass of moisture per sample (m_{H2O}), which correlated better with T_{ig} and t_{ig} than moisture content. Significant data scatter due to using natural samples was observed. A simple two-variable fit was made using thickness and m_{H2O}. Analysis of the coefficients from the two-variable fit showed that thickness increases T_{ig} for all species, but that m_{H2O} did not have a significant additional effect for any species.

Ignition time showed less scatter than T_{ig}, and correlated better with thickness and m_{H2O}. Ignition time versus m_{H2O} for manzanita, ceanothus, gambel oak, and sagebrush appeared to increase at higher m_{H2O}. Ignition time versus m_{H2O} for canyon maple was relatively constant, and for scrub oak t_{ig} decreased as m_{H2O} increased. The effect of thickness on t_{ig} was linear for all species, with some scatter. A simple two-variable fit, using thickness and mass of moisture in the sample, effectively matched all the t_{ig} data. The coefficients in the two variable fit indicated that t_{ig} increases with thickness for all species and increases with m_{H2O} for all species except scrub oak.

A two-variable fit was also performed on data from all of the species combined. The resulting coefficients indicated that thickness increased T_{ig}, and m_{H2O} decreased T_{ig}. The positive coefficients fitted for t_{ig} indicated that both thickness and m_{H2O} delayed t_{ig}.

The following is a summary of the quantitative conclusions from this project:

- T_{ig} depends on leaf thickness,
- No apparent correlation of T_{ig} with m_{H2O} was observed for individual species,
- t_{ig} depends on m_{H2O} and thickness,
- T_{ig} was correlated by: $T_{ig} = a\Delta x + b\ m_{H2O} + c$
- t_{ig} was correlated by: $t_{ig} = a\Delta x + b\ m_{H2O}$
- The difference between live and dead fuels is still unknown except as this impacts $m_{H2O.}$

7.2 Recommendations for Future Work.

This thesis project has inspired some additional questions. Some of the future work that is planned on this project is to:

- Investigate methods of quantifiably defining the ignition point,
- Implement use of the recently-purchased IR camera to find the temperature of the leaf at ignition,
- Use the IR camera to determine T_{ig} for chamise and juniper,
- Compare the IR temperature data to previous thermocouple data,
- Increase the understanding of the mass release data,
- Investigate the effects of fuel density on T_{ig} and t_{ig},

- Develop a model that can be implemented into fire spread models,
- Vary the flux by using the radiant panel,
- Vary the flux by changing the gas temperature,
- Increase the database,
- Develop correlations for brands, flame height, and burnout,
- Determine what the liquid is on the manzanita surface and dripping from the juniper,
- Measure elemental composition as a function of species, season, and moisture content,
- Study ignition characteristics of stems, branches, twigs and/or bark,
- Scale-up to a bush,
- Determine the real effects of moisture content,
- Determine the heating effects of the thermocouple wires in the flame.

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Appendix

Appendix A

A.1 Summary of Data

Table 13 explains the notation found in the tables summarizing the data collected. Tables 14-21 represent the data collected dating back to initial experiments performed by Engstrom and coworkers. The data were separated by species and ordered by the date of the experiment.

Table 13. Explanation of Variables for Tables 14-21

Variable	Explanation
Date	Date the experiment was performed
Run #	The run # performed on the day
Orientation	Orientation of the sample above the flat flame burner H – Horizontal V – Vertical
MC (%)	Moisture content (oven-dry basis)
Thick	Measured thickness of the leaf sample
Length	Approximate length of the sample
Width	Approximate width of the sample
Mass	Mass of the sample prior to burning
t_{ig}	Ignition time
T_{ig}	Ignition temperature
t_{flame}	Burnout time (time that a visible flame is present)
Data Location	Location of the stored data on CD or DVD media storage
-	Indicates data not available

Table 14. Manzanita Data

Date	Run #	Orientation	MC [%]	Δx (mm)	L [cm]	W [cm]	Mass [gm]	t_{ig} [s]	T_{ig} [°C]	t_{flame} [s]	Data Location
11/14/2002	1	H	17%	-	-	-	0.0370	1.77	374	-	CD
11/14/2002	2	H	17%	-	-	-	0.0391	1.44	411	-	CD
11/14/2002	3	H	17%	-	-	-	0.0388	1.22	-	-	CD
11/14/2002	4	H	17%	-	-	-	0.0390	-	-	-	CD
11/14/2002	4.2	H	17%	-	-	-	0.0508	-	-	-	CD
11/14/2002	5	H	17%	-	-	-	0.0441	2.55	-	-	CD
11/14/2002	6	H	17%	-	-	-	0.0440	1.75	469	-	CD
11/14/2002	7	H	17%	-	-	-	0.0511	1.78	485	-	CD
11/16/2002	1	H	15%	-	-	-	0.1714	6.58	275	-	CD
11/16/2002	2	V	15%	-	-	-	0.1854	1.52	404	-	CD
11/16/2002	3	H	15%	-	-	-	0.3268	10.00	386	-	CD
11/16/2002	4	V	15%	-	-	-	0.2892	2.58	305	-	CD
11/16/2002	5	V	15%	-	-	-	0.1525	0.75	284	-	CD
11/16/2002	6	H	15%	-	-	-	0.1484	2.95	282	-	CD
11/16/2002	7	V	15%	-	-	-	0.1639	2.66	370	-	CD
11/16/2002	8	V	15%	-	-	-	0.2695	0.83	276	-	CD
11/16/2002	9	H	15%	-	-	-	0.2768	4.83	345	-	CD
11/16/2002	10	H	15%	-	-	-	0.2581	1.91	279	-	CD
5/6/2003	1	H	3%	0.76	-	-	0.1177	-	-	-	CD
5/6/2003	2	H	3%	0.69	-	-	0.1279	-	-	-	CD
5/6/2003	3	H	3%	0.79	-	-	0.1200	-	-	-	CD
5/6/2003	4	H	3%	0.85	-	-	0.1276	-	-	-	CD
5/6/2003	5	H	3%	0.86	-	-	0.1418	-	-	-	CD
5/6/2003	6	H	3%	0.71	-	-	0.1413	-	-	-	CD
5/19/2003	1	H	76%	0.56	-	-	0.1668	-	-	-	DVD 1
5/19/2003	2	H	76%	0.89	-	-	0.3704	-	-	-	DVD 1
5/19/2003	3	H	76%	0.64	-	-	0.1755	-	-	-	DVD 1
5/19/2003	4	H	76%	0.86	-	-	0.2786	9.59	443	-	DVD 1
5/19/2003	5	H	76%	0.79	-	-	0.2405	9.45	469	-	DVD 1
5/19/2003	6	H	76%	0.71	-	-	0.2214	8.13	445	-	DVD 1
5/19/2003	7	H	76%	0.79	-	-	0.3368	3.77	448	-	DVD 1
5/19/2003	8	H	76%	0.76	-	-	0.2525	9.08	609	-	DVD 1
5/19/2003	9	H	76%	0.89	-	-	0.3367	2.23	357	-	DVD 1
5/19/2003	10	H	76%	0.71	-	-	0.1907	8.44	442	-	DVD 1
5/19/2003	11	H	76%	0.61	-	-	0.1668	3.23	275	-	DVD 1
5/19/2003	12	H	76%	0.71	-	-	0.2959	6.85	441	-	DVD 1
5/19/2003	13	H	76%	0.79	-	-	0.2234	8.91	342	-	DVD 1
5/19/2003	14	H	76%	0.94	-	-	0.2785	0.78	230	-	DVD 1
5/19/2003	15	H	76%	0.56	-	-	0.1450	7.13	416	-	DVD 1
5/30/2003	1	H	19%	0.48	-	-	0.0688	2.05	156	-	DVD 1
5/30/2003	2	H	19%	0.53	-	-	0.1419	2.72	-	-	DVD 1
5/30/2003	3	H	19%	0.51	-	-	0.1023	3.94	438	8.02	DVD 1
5/30/2003	4	H	19%	0.48	-	-	0.1073	0.47	142	-	DVD 1
5/30/2003	5	H	19%	0.51	-	-	0.1165	1.86	322	7.52	DVD 1
5/30/2003	6	H	19%	0.53	-	-	0.1486	-	-	-	DVD 1
5/30/2003	7	H	19%	0.38	-	-	0.0614	0.80	-	-	DVD 1
5/30/2003	8	H	19%	0.41	-	-	0.0990	-	-	-	DVD 1
5/30/2003	9	H	19%	0.41	-	-	0.1039	-	-	-	DVD 1
6/25/2003	1	-	5%	0.85	-	-	0.1949	-	-	-	-
6/25/2003	2	-	5%	0.51	-	-	0.1369	-	-	-	-
6/25/2003	3	-	5%	0.50	-	-	0.0799	-	-	-	-
6/25/2003	4	-	5%	0.61	-	-	0.1422	-	-	-	-
6/25/2003	5	-	76%	0.48	-	-	0.1511	-	-	-	-
6/25/2003	6	-	5%	0.41	-	-	0.0757	-	-	-	-
6/25/2003	7	-	76%	0.43	-	-	0.1224	-	-	-	-
6/25/2003	8	-	5%	0.38	-	-	0.0631	-	-	-	-
6/26/2003	1	H	4%	0.53	-	-	0.0776	0.73	301	-	DVD 4
6/26/2003	2	H	95%	0.42	-	-	0.1176	3.05	-	-	DVD 4
6/26/2003	3	H	95%	0.38	-	-	0.1029	1.14	286	-	DVD 4
6/26/2003	4	H	95%	0.33	-	-	0.1178	-	-	-	DVD 4
6/26/2003	5	V	4%	0.46	-	-	0.0666	0.97	240	-	DVD 4
6/26/2003	6	V	95%	0.36	-	-	0.1090	1.11	417	-	DVD 4
6/26/2003	7	V	95%	0.33	-	-	0.0945	1.88	408	-	DVD 4
6/26/2003	8	V	95%	0.38	-	-	0.1504	1.52	423	-	DVD 4
6/26/2003	9	H	4%	0.64	-	-	0.1877	0.91	770	-	DVD 4
6/26/2003	10	H	92%	0.38	-	-	0.1110	1.06	385	-	DVD 4
6/26/2003	11	H	92%	0.36	-	-	0.0977	1.33	452	-	DVD 4

Date	Run #	Orientation	MC [%]	Δx (mm)	L [cm]	W [cm]	Mass [gm]	t_{ig} [s]	T_{ig} [°C]	t_{flame} [s]	Data Location
6/26/2003	12	H	92%	0.43	-	-	0.0793	2.67	372	-	DVD 4
7/31/2003	1	H	97%	0.37	-	-	0.1124	0.55	433	-	DVD 8
7/31/2003	2	-	97%	0.36	-	-	0.1067	-	-	-	DVD 8
7/31/2003	3	H	97%	0.42	-	-	0.1680	2.11	-	-	DVD 8
7/31/2003	4	H	97%	0.33	-	-	0.1040	2.44	-	-	DVD 8
7/31/2003	5	H	97%	0.32	-	-	0.0659	-	-	-	DVD 8
7/31/2003	6	H	97%	0.38	-	-	0.0931	0.91	483	-	DVD 8
7/31/2003	7	H	97%	0.25	-	-	0.0632	2.69	-	-	DVD 8
7/31/2003	8	H	97%	0.41	-	-	0.0847	0.72	572	-	DVD 8
7/31/2003	9	-	97%	0.36	-	-	0.0681	-	-	-	DVD 8
7/31/2003	10	H	97%	0.43	-	-	0.1525	1.84	551	-	DVD 8
7/31/2003	11	H	97%	0.51	-	-	0.1587	5.28	489	13.34	DVD 8
7/31/2003	12	H	97%	0.43	-	-	0.1808	1.47	453	-	DVD 8
8/5/2003	1	H	107%	0.46	-	-	0.1626	2.49	482	-	DVD 8
8/5/2003	2	H	107%	0.41	-	-	0.1189	-	-	-	DVD 8
8/5/2003	3	H	107%	0.48	-	-	0.0983	1.70	481	-	DVD 8
8/5/2003	4	H	107%	0.34	-	-	0.0983	2.08	-	-	DVD 8
8/5/2003	5	H	107%	0.43	-	-	0.1714	2.56	486	-	DVD 8
8/5/2003	6	H	107%	0.48	-	-	0.1950	1.30	435	-	DVD 8
8/5/2003	7	H	107%	0.44	-	-	0.1253	1.69	391	-	DVD 8
8/5/2003	8	H	107%	0.56	-	-	0.1461	4.31	-	-	DVD 8
8/18/2003	1	H	106%	0.46	-	-	0.1731	1.47	-	-	DVD 8
8/18/2003	2	H	106%	0.38	-	-	0.0786	2.45	418	-	DVD 8
8/18/2003	3	H	106%	0.37	-	-	0.0959	3.23	-	-	DVD 8
8/18/2003	4	H	106%	0.46	-	-	0.1728	2.63	483	-	DVD 8
8/18/2003	5	H	106%	0.48	-	-	0.1673	1.38	457	-	DVD 8
8/18/2003	6	H	106%	0.41	-	-	0.1888	1.53	459	-	DVD 8
8/18/2003	7	H	106%	0.46	-	-	0.2203	2.22	364	-	DVD 8
8/18/2003	8	H	106%	0.38	-	-	0.1760	3.33	354	-	DVD 8
8/18/2003	9	H	106%	0.51	-	-	0.2607	5.16	410	-	DVD 8
8/18/2003	10	H	106%	0.51	-	-	0.2939	8.00	490	-	DVD 8
8/18/2003	11	H	106%	0.43	-	-	0.1512	2.63	416	-	DVD 8
8/18/2003	12	H	106%	0.41	-	-	0.1544	2.67	423	-	DVD 8
10/31/2003	1	H	53%	0.56	-	-	0.3958	2.45	677	-	DVD 8
10/31/2003	2	H	53%	0.43	-	-	0.4434	2.27	396	-	DVD 8
10/31/2003	3	H	53%	0.41	-	-	0.3900	1.95	407	-	DVD 8
10/31/2003	4	H	53%	0.41	-	-	0.3731	1.88	488	-	DVD 8
10/31/2003	5	H	53%	0.33	-	-	0.2361	-	-	-	DVD 8
10/31/2003	6	H	53%	0.36	-	-	0.1941	-	-	-	DVD 8
10/31/2003	7	H	53%	0.33	-	-	0.1739	-	-	-	DVD 8
10/31/2003	8	H	53%	0.36	-	-	0.2207	2.64	-	-	DVD 8
10/31/2003	9	H	53%	0.39	-	-	0.2112	1.84	479	-	DVD 8
10/31/2003	10	H	53%	0.38	-	-	0.2188	1.88	427	-	DVD 8
10/31/2003	11	H	53%	0.34	-	-	0.2370	2.03	514	-	DVD 8
10/31/2003	12	H	53%	0.29	-	-	0.2070	3.95	582	-	DVD 8
11/1/2003	1	H	41%	0.41	-	-	0.2151	-	-	-	DVD 8
11/1/2003	2	H	41%	0.38	-	-	0.1720	2.34	-	-	DVD 8
11/1/2003	3	H	41%	0.41	-	-	0.1689	2.50	702	-	DVD 8
11/1/2003	4	H	41%	0.39	-	-	0.1762	-	-	-	DVD 8
11/1/2003	5	H	41%	0.43	-	-	0.1656	1.58	625	-	DVD 8
11/1/2003	6	H	41%	0.46	-	-	0.1741	1.66	-	-	DVD 8
11/1/2003	7	H	41%	0.41	-	-	0.2433	3.00	634	-	DVD 8
11/1/2003	8	H	41%	0.48	-	-	0.3366	2.89	614	-	DVD 8
11/4/2003	1	H	22%	0.30	-	-	0.1356	-	-	-	DVD 8
11/4/2003	2	H	22%	0.34	-	-	0.1630	-	-	-	DVD 8
11/4/2003	3	H	22%	0.47	-	-	0.3051	-	-	-	DVD 8
11/4/2003	4	H	22%	0.30	-	-	0.1330	-	-	-	DVD 8
11/5/2003	1	H	20%	0.36	-	-	0.1836	-	-	-	DVD 8
11/5/2003	2	H	20%	0.33	-	-	0.1621	-	-	-	DVD 8
11/5/2003	3	H	20%	0.53	-	-	0.2785	-	-	-	DVD 8
11/5/2003	4	H	20%	0.32	-	-	0.1386	-	-	-	DVD 8
1/20/2004	1	H	73%	0.66	-	-	0.2942	-	-	-	DVD 8
1/20/2004	2	H	73%	0.66	-	-	0.2090	-	-	-	DVD 8
1/20/2004	3	H	73%	0.66	-	-	0.2474	7.01	631	10.66	DVD 8
1/20/2004	4	H	73%	0.64	-	-	0.2410	3.13	343	16.20	DVD 8
1/20/2004	5	H	73%	0.64	-	-	0.2110	-	-	-	DVD 8
1/20/2004	6	H	73%	0.66	-	-	0.2157	-	-	-	DVD 8
1/20/2004	7	H	73%	0.64	-	-	0.2360	-	-	-	DVD 8
1/20/2004	8	H	73%	0.66	-	-	0.2225	-	-	-	DVD 8

Date	Run #	Orientation	MC [%]	Δx (mm)	L [cm]	W [cm]	Mass [gm]	t_{ig} [s]	T_{ig} [°C]	t_{flame} [s]	Data Location
5/4/2004	1	H	76%	0.56	-	-	0.5421	2.81	545	20.59	DVD 10
5/4/2004	2	H	76%	0.36	-	-	0.1269	1.91	466	9.00	DVD 10
5/4/2004	3	H	76%	0.48	-	-	0.1543	3.22	501	10.64	DVD 10
5/4/2004	4	H	76%	0.71	-	-	0.5637	1.45	449	27.53	DVD 10
5/4/2004	5	H	76%	0.64	-	-	0.5026	4.75	706	28.61	DVD 10
5/4/2004	6	H	76%	0.36	-	-	0.0894	1.99	508	8.16	DVD 10
5/4/2004	7	H	76%	0.30	-	-	0.1075	0.72	342	7.80	DVD 10
5/4/2004	8	H	76%	0.56	-	-	0.3058	2.00	608	17.20	DVD 10
5/6/2004	1	H	21%	0.42	-	-	0.1184	0.44	242	16.24	DVD 12
5/6/2004	2	H	21%	0.42	-	-	0.3235	2.93	405	9.59	DVD 12
5/6/2004	3	H	21%	0.20	-	-	0.0936	0.64	215	5.63	DVD 12
5/6/2004	4	H	21%	0.46	-	-	0.3083	2.52	203	11.06	DVD 12
5/6/2004	5	H	21%	0.19	-	-	0.0818	0.59	219	6.00	DVD 12
5/6/2004	6	H	21%	0.41	-	-	0.2646	1.52	250	10.50	DVD 12
5/6/2004	7	H	21%	0.27	-	-	0.1251	1.28	255	7.47	DVD 12
5/6/2004	8	H	21%	0.14	-	-	0.0789	0.85	236	4.75	DVD 12
5/10/2004	1	H	4%	0.47	-	-	0.2055	0.39	298	8.45	DVD 12
5/10/2004	2	H	4%	0.44	-	-	0.1857	1.33	410	5.50	DVD 12
5/10/2004	3	H	4%	0.41	-	-	0.1391	1.80	318	5.84	DVD 12
5/10/2004	4	H	4%	0.46	-	-	0.1046	0.44	421	6.31	DVD 12
5/10/2004	5	H	4%	0.52	-	-	0.1745	1.85	540	7.89	DVD 12
5/10/2004	6	H	4%	0.38	-	-	0.0730	1.45	474	5.55	DVD 12
5/10/2004	7	H	4%	0.46	-	-	0.1940	1.86	323	8.69	DVD 12
5/10/2004	8	H	4%	0.48	-	-	0.1700	0.70	370	10.11	DVD 12
5/10/2004	9	H	4%	0.17	-	-	0.0589	-	-	-	DVD 12
5/10/2004	10	H	4%	0.18	-	-	0.0725	1.28	380	3.67	DVD 12
5/24/2004	1	H	32%	0.29	-	-	0.1558	1.81	259	7.08	DVD 19
5/24/2004	1	H	85%	0.57	-	-	0.3878	2.17	574	13.24	DVD 19
5/24/2004	2	H	85%	0.58	-	-	0.4886	3.53	490	10.92	DVD 18
5/24/2004	2	H	32%	0.42	-	-	0.2926	1.98	417	8.72	DVD 19
5/24/2004	3	H	85%	0.44	-	-	0.2471	2.94	368	12.88	DVD 18
5/24/2004	3	H	32%	0.42	-	-	0.3418	1.42	230	14.08	DVD 19
5/24/2004	4	H	85%	0.61	-	-	0.4432	2.67	288	10.58	DVD 18
5/24/2004	4	H	32%	0.37	-	-	0.2011	2.33	344	10.19	DVD 19
5/24/2004	5	H	85%	0.33	-	-	0.1767	2.50	431	12.69	DVD 18
5/24/2004	5	H	32%	0.39	-	-	0.2281	2.91	331	9.97	DVD 19
5/24/2004	6	H	85%	0.48	-	-	0.2808	3.67	316	12.73	DVD 18
5/24/2004	6	H	32%	0.38	-	-	0.3630	1.86	371	9.67	DVD 19
5/24/2004	7	H	85%	0.53	-	-	0.2603	3.70	344	14.88	DVD 18
5/24/2004	7	H	32%	0.30	-	-	0.2124	1.45	411	8.84	DVD 19
5/24/2004	8	H	85%	0.58	-	-	0.3564	5.20	381	16.25	DVD 18
5/24/2004	8	H	32%	0.28	-	-	0.0924	0.61	265	5.81	DVD 19
5/24/2004	9	H	85%	0.52	-	-	0.1887	3.75	458	12.28	DVD 18
5/24/2004	9	H	32%	0.29	-	-	0.1462	0.33	180	8.33	DVD 19
5/24/2004	10	H	85%	0.61	-	-	0.3007	7.63	395	15.47	DVD 18
5/24/2004	10	H	32%	0.56	-	-	0.1924	2.00	496	10.41	DVD 19
5/24/2004	11	H	85%	0.50	-	-	0.3644	2.45	392	10.47	DVD 18
5/24/2004	11	H	32%	0.29	-	-	0.1343	1.74	383	7.50	DVD 19
5/24/2004	12	H	85%	0.37	-	-	0.2240	2.64	338	12.22	DVD 18
5/24/2004	12	H	32%	0.41	-	-	0.2628	1.50	362	12.44	DVD 19
5/24/2004	13	H	85%	0.29	-	-	0.2994	3.03	-	14.61	DVD 18
5/24/2004	13	H	32%	0.42	-	-	0.2851	2.72	419	12.77	DVD 19
5/24/2004	14	H	85%	0.38	-	-	0.3185	2.55	275	13.22	DVD 18
5/24/2004	14	H	32%	0.36	-	-	0.3486	2.64	328	11.45	DVD 19
5/24/2004	15	H	85%	0.34	-	-	0.1345	3.92	365	9.25	DVD 18
5/24/2004	15	H	32%	0.41	-	-	0.1811	1.85	376	10.35	DVD 19
5/24/2004	16	H	85%	0.62	-	-	0.4900	3.00	277	19.00	DVD 18
5/24/2004	16	H	32%	0.32	-	-	0.1701	0.31	222	7.11	DVD 19
5/24/2004	17	H	85%	0.47	-	-	0.2377	3.17	382	12.67	DVD 18
5/24/2004	17	H	32%	0.29	-	-	0.1364	0.59	236	6.55	DVD 19
5/24/2004	18	H	85%	0.51	-	-	0.2561	2.19	325	12.47	DVD 18
5/24/2004	18	H	32%	0.28	-	-	0.1310	0.83	365	5.48	DVD 19
5/24/2004	19	H	85%	0.57	-	-	0.3236	-	-	-	DVD 18
5/24/2004	19	H	32%	0.41	-	-	0.4735	2.48	411	13.20	DVD 19
5/24/2004	20	H	85%	0.44	-	-	0.2145	1.78	350	8.72	DVD 18
5/24/2004	20	H	32%	0.22	-	-	0.1585	1.09	546	8.72	DVD 19
5/24/2004	21	H	32%	0.43	-	-	0.2101	1.88	506	10.38	DVD 19
5/24/2004	22	H	32%	0.33	-	-	0.3279	1.25	335	12.83	DVD 19
5/24/2004	23	H	32%	0.30	-	-	0.3044	4.05	425	8.77	DVD 19

Date	Run #	Orientation	MC [%]	Δx (mm)	L [cm]	W [cm]	Mass [gm]	t_{ig} [s]	T_{ig} [°C]	t_{flame} [s]	Data Location
5/24/2004	24	H	32%	0.28	-	-	0.2355	1.09	377	8.50	DVD 19
5/24/2004	25	H	32%	0.32	-	-	0.1332	1.64	397	9.72	DVD 19
8/4/2004	1	H	53%	0.52	3.30	2.03	0.2778	-	-	-	DVD 30
8/4/2004	2	H	53%	0.52	2.79	1.73	0.1794	8.22	770	7.95	DVD 30
8/4/2004	3	H	53%	0.57	3.56	2.64	0.4472	3.41	597	16.66	DVD 30
8/4/2004	4	H	53%	0.48	3.20	1.93	0.2460	2.83	517	12.81	DVD 30
8/4/2004	5	H	53%	0.60	3.56	2.54	0.3969	1.45	634	16.28	DVD 30
8/4/2004	6	H	53%	0.58	3.56	2.54	0.3565	2.83	548	15.53	DVD 30
8/4/2004	7	H	53%	0.47	3.05	2.16	0.2369	3.28	-	10.91	DVD 30
8/4/2004	8	H	53%	0.52	2.41	1.27	0.1207	2.05	474	10.05	DVD 30
8/4/2004	9	H	53%	0.55	3.05	2.03	0.2584	3.33	449	13.39	DVD 31
8/4/2004	10	H	53%	0.48	3.05	1.93	0.2508	2.42	327	12.75	DVD 31
8/4/2004	11	H	53%	0.56	3.56	2.44	0.3260	2.45	234	15.11	DVD 31
8/4/2004	12	H	53%	0.66	3.81	2.41	0.4409	2.33	-	7.03	DVD 31
8/4/2004	13	H	53%	0.47	2.03	1.70	0.1154	2.23	-	11.02	DVD 31
8/4/2004	14	H	53%	0.56	2.54	1.52	0.1612	4.33	474	12.36	DVD 31
8/4/2004	15	H	53%	0.50	3.18	2.03	0.2064	2.50	402	11.24	DVD 31
8/5/2004	1	H	40%	0.57	3.30	1.96	0.2926	3.63	398	14.13	DVD 31
8/5/2004	2	H	40%	0.53	3.56	2.54	0.3533	2.36	220	13.69	DVD 31
8/5/2004	3	H	40%	0.42	3.20	1.98	0.1860	3.86	375	8.11	DVD 31
8/5/2004	4	H	40%	0.53	3.99	2.46	0.3818	2.14	297	14.95	DVD 31
8/5/2004	5	H	40%	0.53	3.56	2.36	0.3028	1.70	359	12.33	DVD 31
8/5/2004	6	H	40%	0.41	2.54	1.78	0.1414	2.16	557	9.49	DVD 31
8/5/2004	7	H	40%	0.41	2.51	1.70	0.1361	2.09	-	10.60	DVD 31
8/5/2004	8	H	40%	0.44	3.30	2.26	0.2514	0.95	350	12.89	DVD 31
8/5/2004	9	H	40%	0.50	3.66	2.54	0.3550	1.94	298	14.31	DVD 31
8/5/2004	10	H	40%	0.48	3.07	2.08	0.2205	4.72	550	9.72	DVD 31
8/5/2004	11	H	40%	0.48	3.12	2.13	0.2240	4.14	449	9.88	DVD 31
8/5/2004	12	H	40%	0.43	3.15	2.13	0.2079	1.86	393	12.08	DVD 31
8/5/2004	13	H	40%	0.48	4.14	2.41	0.3409	1.66	504	13.42	DVD 31
8/5/2004	14	H	40%	0.53	3.05	2.21	0.2490	1.70	274	12.72	DVD 31
8/5/2004	15	H	40%	0.44	3.00	2.24	0.2270	3.63	433	10.50	DVD 31
2/4/2005	1	H	56%	0.54	3.75	2.50	0.3813	4.59	224	21.44	PC
2/4/2005	2	H	56%	0.69	3.07	1.98	0.3326	16.50	396	13.48	PC
2/4/2005	3	H	56%	0.64	3.84	2.41	0.4309	4.55	440	16.47	PC
2/4/2005	4	H	56%	0.64	3.43	2.40	0.4114	-	-	-	PC
2/4/2005	5	H	56%	0.56	3.43	2.38	0.3224	1.47	718	17.38	PC
2/4/2005	6	H	56%	0.59	3.60	2.46	0.4236	1.75	398	19.98	PC
2/4/2005	7	H	56%	0.55	3.28	2.05	0.2709	2.42	639	16.17	PC
2/4/2005	8	H	56%	0.56	3.05	2.00	0.2922	2.94	426	16.86	PC
2/4/2005	9	H	56%	0.59	3.34	2.18	0.3510	3.05	429	16.33	PC
2/4/2005	10	H	56%	0.55	3.20	2.12	0.2713	3.03	402	16.03	PC
2/4/2005	11	H	56%	0.56	2.87	2.50	0.3430	2.78	458	17.20	PC
2/4/2005	12	H	56%	0.59	3.24	1.69	0.2550	3.94	429	13.38	PC
2/4/2005	13	H	56%	0.61	3.35	2.03	0.3317	4.95	395	13.98	PC
2/4/2005	14	H	56%	0.55	3.23	1.91	0.2435	5.41	324	10.59	PC
2/4/2005	15	H	56%	0.57	3.50	2.29	0.3212	1.80	360	19.55	PC
2/4/2005	16	H	56%	0.59	2.41	2.29	0.2760	3.67	415	13.00	PC
2/4/2005	17	H	56%	0.62	3.38	2.18	0.3272	2.19	389	17.75	PC
2/4/2005	18	H	56%	0.63	3.43	2.14	0.3800	9.06	422	13.22	PC
2/4/2005	19	H	56%	0.58	3.35	2.27	0.3350	9.36	447	11.58	PC
2/4/2005	20	H	56%	0.58	3.05	1.88	0.2760	7.58	441	12.13	PC

Table 15. Scrub Oak Data

Date	Run #	Orientation	MC [%]	Δx (mm)	L [cm]	W [cm]	Mass [gm]	t_{ig} [s]	T_{ig} [°C]	t_{flame} [s]	Data Location
11/14/2002	1	H	26%	-	-	-	0.0192	-	-	-	CD
11/14/2002	2	H	26%	-	-	-	0.0252	-	-	-	CD
11/14/2002	3	H	26%	-	-	-	0.0187	-	-	-	CD
11/14/2002	4	H	26%	-	-	-	0.0254	-	-	-	CD
11/14/2002	5	H	26%	-	-	-	0.0185	-	-	-	CD
11/19/2002	1	V	21%	-	-	-	0.0419	0.55	316	-	CD
11/19/2002	2	H	21%	-	-	-	0.0406	5.69	215	-	CD
11/19/2002	3	H	21%	-	-	-	0.0580	13.13	307	-	CD
11/19/2002	4	V	21%	-	-	-	0.0363	-	-	-	CD
11/19/2002	5	H	21%	-	-	-	0.0610	2.38	225	-	CD
11/19/2002	6	V	21%	-	-	-	0.0422	0.91	290	-	CD

Date	Run #	Orientation	MC [%]	Δx (mm)	L [cm]	W [cm]	Mass [gm]	t_{ig} [s]	T_{ig} [°C]	t_{flame} [s]	Data Location
11/19/2002	7	V	21%	-	-	-	0.0525	0.45	197	-	CD
11/19/2002	8	H	21%	-	-	-	0.0681	1.69	2247	-	CD
11/19/2002	9	V	21%	-	-	-	0.0430	1.30	260	-	CD
11/19/2002	10	H	21%	-	-	-	0.0427	1.84	326	-	CD
5/20/2003	1	H	43%	0.66	-	-	0.2335	1.36	541	-	DVD 1
5/20/2003	2	H	43%	0.69	-	-	0.2180	1.06	468	-	DVD 1
5/20/2003	3	H	43%	0.51	-	-	0.1166	-	-	-	DVD 1
5/20/2003	4	H	43%	0.58	-	-	0.2895	1.17	605	-	DVD 1
5/20/2003	5	H	43%	0.61	-	-	0.2945	2.55	333	-	DVD 1
5/20/2003	6	H	43%	0.48	-	-	0.1076	1.59	423	-	DVD 1
5/20/2003	7	H	43%	0.58	-	-	0.2182	-	-	-	DVD 1
5/20/2003	8	H	43%	0.46	-	-	0.1813	-	-	-	DVD 1
5/20/2003	9	H	43%	0.56	-	-	0.1691	-	-	-	DVD 1
5/21/2003	1	H	34%	0.51	-	-	0.1155	-	410	-	DVD 4
5/21/2003	2	-	34%	0.53	-	-	0.1091	-	-	-	-
5/21/2003	3	-	34%	0.48	-	-	0.0822	-	-	-	-
6/3/2003	1	H	7%	0.48	-	-	0.1187	0.81	319	-	DVD 4
6/3/2003	2	H	7%	0.56	-	-	0.1533	1.36	641	6.25	DVD 4
6/3/2003	3	H	7%	0.58	-	-	0.2361	0.56	305	-	DVD 4
6/3/2003	4	V	7%	0.42	-	-	0.0844	0.27	272	7.28	DVD 4
6/3/2003	5	V	7%	0.76	-	-	0.1366	0.95	462	6.45	DVD 4
6/3/2003	6	H	7%	0.80	-	-	0.1494	1.76	256	4.38	DVD 4
6/3/2003	7	H	7%	0.51	-	-	0.1244	0.52	268	-	DVD 4
6/3/2003	8	H	7%	0.61	-	-	0.1366	1.80	-	6.24	DVD 4
6/3/2003	9	H	7%	0.38	-	-	0.0539	0.85	291	4.81	DVD 4
6/3/2003	10	H	7%	0.46	-	-	0.0908	-	-	18.69	DVD 4
6/25/2003	1	-	8%	0.76	-	-	0.2137	-	-	-	-
6/25/2003	2	-	8%	0.51	-	-	0.1368	-	-	-	-
6/25/2003	3	-	8%	0.58	-	-	0.1687	-	-	-	-
6/25/2003	4	-	8%	0.61	-	-	0.1794	-	-	-	-
6/25/2003	5	-	8%	0.48	-	-	0.1269	-	-	-	-
6/25/2003	6	-	8%	0.57	-	-	0.2110	-	-	-	-
6/25/2003	7	-	8%	0.66	-	-	0.2480	-	-	-	-
6/25/2003	8	-	8%	0.46	-	-	0.0867	-	-	-	-
6/25/2003	9	-	5%	0.56	-	-	0.1619	-	-	-	-
6/25/2003	10	-	81%	0.38	-	-	0.0993	-	-	-	-
6/25/2003	11	-	5%	0.56	-	-	0.1767	-	-	-	-
6/25/2003	12	-	81%	0.33	-	-	0.0560	-	-	-	-
6/26/2003	1	H	6%	0.71	-	-	0.1409	1.03	266	-	DVD 4
6/26/2003	2	H	63%	0.48	-	-	0.1037	4.06	467	-	DVD 4
6/26/2003	3	H	63%	0.38	-	-	0.0709	2.16	-	-	DVD 4
6/26/2003	4	H	63%	0.46	-	-	0.1110	3.88	478	-	DVD 4
6/26/2003	5	V	6%	0.51	-	-	0.0661	0.41	245	-	DVD 4
6/26/2003	6	V	63%	0.61	-	-	0.1046	2.59	336	-	DVD 4
6/26/2003	7	V	63%	0.53	-	-	0.0728	2.74	433	-	DVD 4
6/26/2003	8	V	63%	0.64	-	-	0.0936	2.56	325	-	DVD 4
6/26/2003	9	H	6%	0.43	-	-	0.1001	0.64	288	-	DVD 4
6/26/2003	10	H	63%	0.41	-	-	0.0793	2.27	481	-	DVD 4
6/26/2003	11	H	63%	0.36	-	-	0.0802	0.97	308	-	DVD 4
6/26/2003	12	H	63%	0.38	-	-	0.0470	1.53	459	-	DVD 4
8/1/2003	1	-	73%	0.25	-	-	0.0517	-	-	-	DVD 8
8/1/2003	2	H	73%	0.46	-	-	0.0845	0.89	506	-	DVD 8
8/1/2003	3	H	73%	0.43	-	-	0.1155	1.16	399	-	DVD 8
8/1/2003	4	H	73%	0.33	-	-	0.1430	1.38	409	-	DVD 8
8/1/2003	5	H	73%	0.41	-	-	0.1161	3.09	631	-	DVD 8
8/1/2003	6	H	73%	0.38	-	-	0.0469	1.08	502	-	DVD 8
8/1/2003	7	-	73%	0.41	-	-	0.1032	-	-	-	DVD 8
8/1/2003	8	H	73%	0.41	-	-	0.1075	2.53	495	-	DVD 8
8/6/2003	1	H	67%	0.41	-	-	0.0880	1.59	549	-	DVD 8
8/6/2003	2	H	67%	0.38	-	-	0.0686	1.92	473	-	DVD 8
8/6/2003	3	H	67%	0.43	-	-	0.0796	2.66	534	-	DVD 8
8/6/2003	4	H	67%	0.30	-	-	0.0670	1.61	437	-	DVD 8
8/6/2003	5	H	67%	0.43	-	-	0.0833	1.59	380	-	DVD 8
8/6/2003	6	H	67%	0.25	-	-	0.0669	0.84	252	-	DVD 8
8/6/2003	7	H	67%	0.39	-	-	0.0807	1.59	462	-	DVD 8
8/6/2003	8	H	67%	0.43	-	-	0.1085	1.06	453	-	DVD 8
8/6/2003	9	H	67%	0.43	-	-	0.0838	1.61	473	-	DVD 8
8/6/2003	10	H	67%	0.41	-	-	0.0507	1.44	484	-	DVD 8
8/6/2003	11	H	67%	0.38	-	-	0.0987	1.44	426	-	DVD 8

Date	Run #	Orientation	MC [%]	Δx (mm)	L [cm]	W [cm]	Mass [gm]	t_{ig} [s]	T_{ig} [°C]	t_{flame} [s]	Data Location
8/6/2003	12	H	67%	0.32	-	-	0.0845	1.33	399	-	DVD 8
8/20/2003	1	H	52%	0.18	-	-	0.0287	0.33	120	-	DVD 8
8/20/2003	2	-	52%	0.18	-	-	0.0420	0.28	169	-	DVD 8
8/20/2003	3	-	52%	0.33	-	-	0.1558	0.58	149	-	DVD 8
8/20/2003	4	-	52%	0.28	-	-	0.1473	0.77	240	-	DVD 8
8/20/2003	5	-	52%	0.38	-	-	0.1048	1.06	221	-	DVD 8
8/20/2003	6	H	52%	0.46	-	-	0.2285	0.69	215	-	DVD 8
8/20/2003	7	H	52%	0.30	-	-	0.0895	0.59	348	-	DVD 8
8/20/2003	8	-	52%	0.43	-	-	0.1595	0.88	366	-	DVD 8
10/31/2003	1	H	76%	0.30	-	-	0.4712	0.41	309	-	DVD 8
10/31/2003	2	H	76%	0.22	-	-	0.6257	1.03	147	-	DVD 8
10/31/2003	3	H	76%	0.39	-	-	0.5076	1.77	-	-	DVD 8
10/31/2003	4	H	76%	0.25	-	-	0.3968	1.42	799	-	DVD 8
10/31/2003	5	H	76%	0.20	-	-	0.3792	0.20	214	-	DVD 8
10/31/2003	6	H	76%	0.29	-	-	0.7129	0.83	563	-	DVD 8
10/31/2003	7	H	76%	0.19	-	-	0.2806	1.16	249	-	DVD 8
10/31/2003	8	H	76%	0.20	-	-	0.5750	0.67	288	-	DVD 8
11/1/2003	1	H	53%	0.46	-	-	0.2171	1.38	522	-	DVD 8
11/1/2003	2	H	53%	0.43	-	-	0.1371	0.58	445	-	DVD 8
11/1/2003	3	H	53%	0.43	-	-	0.1110	0.83	668	-	DVD 8
11/1/2003	4	H	53%	0.56	-	-	0.4445	0.34	163	-	DVD 8
11/1/2003	5	H	53%	0.56	-	-	0.3701	1.56	303	-	DVD 8
11/1/2003	6	H	53%	0.48	-	-	0.2448	0.89	315	-	DVD 8
11/1/2003	7	H	53%	0.41	-	-	0.2278	0.73	516	-	DVD 8
11/1/2003	8	H	53%	0.48	-	-	0.3213	-	-	-	DVD 8
1/20/2004	1	H	66%	0.51	-	-	0.4219	2.16	-	-	DVD 8
1/20/2004	2	H	66%	0.41	-	-	0.3545	2.09	555	12.09	DVD 8
1/20/2004	3	H	66%	0.33	-	-	0.3741	-	-	-	DVD 8
1/20/2004	4	H	66%	0.48	-	-	0.3702	1.52	596	-	DVD 8
1/20/2004	5	H	66%	0.36	-	-	0.3306	-	-	-	DVD 8
1/20/2004	6	H	66%	0.48	-	-	0.3727	-	-	-	DVD 8
1/20/2004	7	H	66%	0.46	-	-	0.4943	-	-	-	DVD 8
1/20/2004	8	H	66%	0.41	-	-	0.0953	-	-	-	DVD 8
1/27/2004	1	H	4%	0.33	-	-	0.0830	-	-	-	-
1/27/2004	2	H	4%	0.36	-	-	0.3887	-	-	-	-
1/27/2004	3	H	4%	0.38	-	-	0.0820	-	-	-	-
1/27/2004	4	H	4%	0.33	-	-	0.2542	-	-	-	-
1/27/2004	5	H	4%	0.33	-	-	0.2088	-	-	-	-
1/27/2004	6	H	4%	0.28	-	-	0.2426	-	-	-	-
1/27/2004	7	H	4%	0.30	-	-	0.2701	-	-	-	-
1/27/2004	8	H	4%	0.32	-	-	0.2076	-	-	-	-
5/4/2004	1	H	82%	0.58	-	-	0.4925	0.53	319	16.56	DVD 10
5/4/2004	2	H	82%	0.79	-	-	0.4900	0.66	466	10.88	DVD 10
5/4/2004	3	H	82%	0.66	-	-	0.3119	0.53	440	9.92	DVD 10
5/4/2004	4	H	82%	0.48	-	-	0.1309	0.66	491	6.88	DVD 10
5/4/2004	5	H	82%	0.25	-	-	0.6233	0.33	196	13.44	DVD 10
5/4/2004	6	H	82%	0.25	-	-	0.6527	0.28	117	20.42	DVD 10
5/4/2004	7	H	82%	0.28	-	-	0.4010	0.49	265	15.75	DVD 10
5/4/2004	8	H	82%	0.33	-	-	0.4256	0.41	199	-	DVD 10
5/6/2004	1	H	17%	0.24	-	-	0.2254	0.30	133	8.50	DVD 12
5/6/2004	2	H	17%	0.23	-	-	0.2588	0.16	95	9.77	DVD 12
5/6/2004	3	H	17%	0.25	-	-	0.1956	0.09	46	7.69	DVD 12
5/6/2004	4	H	17%	0.18	-	-	0.1883	0.11	56	7.11	DVD 12
5/6/2004	5	H	17%	0.28	-	-	0.2318	0.16	49	9.08	DVD 12
5/6/2004	6	H	17%	0.25	-	-	0.2521	0.39	297	8.95	DVD 12
5/6/2004	7	H	17%	0.22	-	-	0.1642	0.23	106	6.24	DVD 12
5/6/2004	8	H	17%	0.24	-	-	0.1508	0.30	98	6.63	DVD 12
5/10/2004	1	H	5%	0.19	-	-	0.2219	0.28	189	5.53	DVD 13
5/10/2004	2	H	5%	0.29	-	-	0.1380	0.17	72	7.01	DVD 13
5/10/2004	3	H	5%	0.32	-	-	0.2745	0.35	65	8.67	DVD 13
5/19/2004	1	H	93%	0.32	-	-	0.3575	0.33	123	17.94	DVD 16
5/19/2004	2	H	93%	0.34	-	-	0.4227	1.58	201	15.94	DVD 16
5/19/2004	3	H	93%	0.28	-	-	0.2812	1.23	483	16.14	DVD 16
5/19/2004	4	H	93%	0.28	-	-	0.3506	0.44	212	19.50	DVD 16
5/19/2004	5	H	93%	0.28	-	-	0.3222	0.11	86	13.31	DVD 16
5/19/2004	6	H	79%	0.28	-	-	0.1676	1.06	504	12.31	DVD 16
5/19/2004	7	H	79%	0.24	-	-	0.1201	0.49	397	10.08	DVD 16
5/19/2004	8	H	79%	0.25	-	-	0.2127	0.39	262	14.77	DVD 16
5/19/2004	9	H	79%	0.25	-	-	0.5839	0.30	107	14.64	DVD 16

Date	Run #	Orientation	MC [%]	Δx (mm)	L [cm]	W [cm]	Mass [gm]	t_{ig} [s]	T_{ig} [°C]	t_{flame} [s]	Data Location
5/19/2004	10	H	79%	0.18	-	-	0.2762	0.28	127	11.27	DVD 16
5/19/2004	11	H	79%	0.30	-	-	0.3030	0.38	215	13.28	DVD 16
5/19/2004	12	H	79%	0.32	-	-	0.3303	0.64	121	15.75	DVD 16
5/19/2004	13	H	79%	0.20	-	-	0.1786	0.33	116	12.80	DVD 16
5/19/2004	14	H	79%	0.27	-	-	0.5258	0.56	264	19.72	DVD 16
5/19/2004	15	H	79%	0.25	-	-	0.1060	0.61	424	10.20	DVD 16
5/19/2004	16	H	79%	0.25	-	-	0.3920	0.66	323	13.38	DVD 16
5/19/2004	17	H	79%	0.28	-	-	0.2530	0.47	235	11.91	DVD 16
5/19/2004	18	H	79%	0.32	-	-	0.3546	0.55	339	12.13	DVD 16
5/19/2004	19	H	79%	0.22	-	-	0.2302	0.30	184	11.92	DVD 16
5/19/2004	20	H	79%	0.25	-	-	0.1067	1.24	474	9.97	DVD 16
5/19/2004	21	H	79%	0.22	-	-	0.1731	0.81	322	11.09	DVD 17
5/19/2004	22	H	79%	0.23	-	-	0.2433	0.69	326	12.77	DVD 17
5/19/2004	23	H	79%	0.32	-	-	0.2834	1.06	388	13.58	DVD 17
5/19/2004	24	H	79%	0.27	-	-	0.6053	1.09	318	24.44	DVD 17
5/19/2004	25	H	79%	0.29	-	-	0.5339	0.14	137	16.03	DVD 17
5/20/2004	1	H	39%	0.14	-	-	0.2640	0.13	73	7.53	DVD 17
5/20/2004	2	H	39%	0.17	-	-	0.3383	0.03	39	11.09	DVD 17
5/20/2004	3	H	39%	0.22	-	-	0.1889	0.49	107	6.91	DVD 17
5/20/2004	4	H	39%	0.18	-	-	0.3637	0.38	55	12.13	DVD 17
5/20/2004	5	H	39%	0.20	-	-	0.3285	0.22	83	12.20	DVD 17
5/20/2004	6	H	39%	0.18	-	-	0.0833	0.17	95	4.92	DVD 17
5/20/2004	7	H	39%	0.17	-	-	0.1012	0.33	113	6.00	DVD 17
5/20/2004	8	H	39%	0.19	-	-	0.1826	0.25	132	6.44	DVD 17
5/20/2004	9	H	39%	0.24	-	-	0.4440	-	-	-	DVD 17
5/20/2004	10	H	39%	0.24	-	-	0.5113	0.22	245	13.88	DVD 17
5/20/2004	11	H	39%	0.29	-	-	0.4180	0.13	78	12.56	DVD 17
5/20/2004	12	H	39%	0.19	-	-	0.2821	0.25	108	10.13	DVD 17
5/20/2004	13	H	39%	0.24	-	-	0.2832	0.00	66	10.00	DVD 17
5/20/2004	14	H	39%	0.22	-	-	0.3966	0.08	79	9.00	DVD 17
5/20/2004	15	H	39%	0.24	-	-	0.4318	0.06	93	13.14	DVD 17
5/20/2004	16	H	39%	0.29	-	-	0.4834	0.17	114	12.45	DVD 17
5/20/2004	17	H	39%	0.28	-	-	0.3831	0.05	44	15.00	DVD 17
5/20/2004	18	H	39%	0.23	-	-	0.4039	0.08	69	11.27	DVD 17
5/20/2004	19	H	39%	0.29	-	-	0.3348	0.05	57	12.19	DVD 17
5/20/2004	20	H	39%	0.22	-	-	0.2677	0.28	129	8.88	DVD 17
2/4/2005	1	H	61%	0.25	2.58	1.41	0.0669	2.89	470	4.05	PC
2/4/2005	2	H	61%	0.25	2.12	1.43	0.0561	1.84	374	4.86	PC
2/4/2005	3	H	61%	0.25	3.01	1.38	0.0847	1.92	375	4.52	PC
2/4/2005	4	H	61%	0.25	2.97	1.41	0.0837	1.09	254	6.44	PC
2/4/2005	5	H	61%	0.28	2.88	1.44	0.1021	2.47	571	5.41	PC
2/4/2005	6	H	61%	0.26	2.19	1.28	0.0575	2.28	551	5.73	PC
2/4/2005	7	H	61%	0.28	2.92	1.42	0.0930	0.83	279	6.11	PC
2/4/2005	8	H	61%	0.26	2.29	1.42	0.0683	-	-	-	PC
2/4/2005	9	H	61%	0.29	2.82	1.38	0.0978	0.00	419	6.92	PC
2/4/2005	10	H	61%	0.26	2.24	1.29	0.0624	3.02	360	4.09	PC
2/4/2005	11	H	61%	0.29	2.40	1.40	0.0704	1.20	441	5.63	PC
2/4/2005	12	H	61%	0.26	3.48	1.58	0.1270	1.49	324	6.28	PC
2/4/2005	13	H	61%	0.23	2.58	1.25	0.0630	-	-	-	PC
2/4/2005	14	H	61%	0.23	2.13	1.04	0.0474	3.11	354	4.05	PC
2/4/2005	15	H	61%	0.24	2.81	1.47	0.0789	1.25	386	5.73	PC
2/4/2005	16	H	61%	0.27	2.25	1.27	0.0663	1.97	497	6.39	PC
2/4/2005	17	H	61%	0.24	3.54	1.65	0.1208	1.05	369	6.27	PC
2/4/2005	18	H	61%	0.27	3.11	1.69	0.1184	0.83	232	6.81	PC
2/4/2005	19	H	61%	0.30	2.97	1.41	0.0991	1.05	343	6.14	PC
2/4/2005	20	H	61%	0.24	2.73	1.39	0.0790	2.89	267	5.23	PC

Table 16. Ceanothus Data

Date	Run #	Orientation	MC [%]	Δx (mm)	L [cm]	W [cm]	Mass [gm]	t_{ig} [s]	T_{ig} [°C]	t_{flame} [s]	Data Location
6/25/2003	1	-	106%	0.74	-	-	0.1440				-
6/25/2003	2	-	106%	0.56	-	-	0.0697	-	-	-	-
6/25/2003	3	-	106%	0.51	-	-	0.0906	-	-	-	-
6/25/2003	4	-	106%	0.56	-	-	0.1059	-	-	-	-
11/1/2003	1	H	49%	0.58	-	-	0.0986	5.61	519	-	DVD 8
11/1/2003	2	H	49%	0.61	-	-	0.1064	5.33	592	-	DVD 8
11/1/2003	3	H	49%	0.56	-	-	0.1083	5.38	514	-	DVD 8

Date	Run #	Orientation	MC [%]	Δx (mm)	L [cm]	W [cm]	Mass [gm]	t_{ig} [s]	T_{ig} [°C]	t_{flame} [s]	Data Location
11/1/2003	4	H	49%	0.53	-	-	0.0802	4.31	479	-	DVD 8
5/4/2004	1	H	98%	0.56	-	-	0.1541	7.94	580	10.97	DVD 11
5/4/2004	2	H	98%	0.61	-	-	0.0927	6.94	-	11.49	DVD 11
5/4/2004	3	H	98%	0.66	-	-	0.1670	8.61	492	9.44	DVD 11
5/4/2004	4	H	98%	0.53	-	-	0.1435	7.39	645	8.83	DVD 11
5/4/2004	5	H	98%	0.64	-	-	0.1900	9.44	539	16.91	DVD 11
5/4/2004	6	H	98%	0.43	-	-	0.0687	4.91	462	8.56	DVD 11
5/4/2004	7	H	98%	0.57	-	-	0.0836	6.48	454	14.58	DVD 11
5/4/2004	8	H	98%	0.57	-	-	0.0833	6.58	831	7.33	DVD 11
5/6/2004	1	H	35%	0.30	-	-	0.0694	5.97	277	16.20	DVD 12
5/6/2004	2	H	35%	0.34	-	-	0.0671	3.58	319	9.08	DVD 11
5/6/2004	3	H	35%	0.34	-	-	0.1294	4.76	249	16.59	DVD 11
5/6/2004	4	H	35%	0.25	-	-	0.0517	0.34	166	7.64	DVD 11
5/6/2004	5	H	35%	0.37	-	-	0.0271	1.13	226	10.86	DVD 11
5/6/2004	6	H	35%	0.25	-	-	0.0672	4.42	-	10.47	DVD 11
5/6/2004	7	H	35%	0.29	-	-	0.1550	4.58	349	10.53	DVD 11
5/6/2004	8	H	35%	0.10	-	-	0.0426	2.53	365	7.14	DVD 11
5/11/2004	1	H	94%	0.25	-	-	0.1155	7.33	454	9.27	DVD 13
5/11/2004	2	H	94%	0.24	-	-	0.0711	6.97	472	8.05	DVD 13
5/11/2004	3	H	94%	0.20	-	-	0.1480	8.03	447	10.92	DVD 13
5/11/2004	4	H	94%	0.14	-	-	0.0674	6.11	530	8.36	DVD 13
5/11/2004	5	H	94%	0.72	-	-	0.0942	5.16	576	14.63	DVD 13
5/11/2004	6	H	94%	0.75	-	-	0.1297	10.86	579	11.13	DVD 13
5/11/2004	7	H	94%	0.61	-	-	0.1301	6.80	344	10.39	DVD 13
5/11/2004	8	H	94%	0.57	-	-	0.0684	6.94	532	9.20	DVD 13
5/11/2004	9	H	94%	0.60	-	-	0.0838	5.05	351	12.00	DVD 13
5/11/2004	10	H	94%	0.61	-	-	0.0705	5.16	389	10.45	DVD 13
5/11/2004	11	H	94%	0.71	-	-	0.1111	7.97	467	11.78	DVD 13
5/11/2004	12	H	94%	0.57	-	-	0.1033	9.77	499	8.52	DVD 13
5/11/2004	13	H	94%	0.70	-	-	0.1232	5.03	440	15.66	DVD 13
5/11/2004	14	H	94%	0.69	-	-	0.0926	6.80	339	15.03	DVD 13
5/11/2004	15	H	94%	0.61	-	-	0.1192	9.80	317	13.98	DVD 14
5/11/2004	16	H	87%	0.55	-	-	0.0943	8.42	402	7.66	DVD 14
5/11/2004	17	H	87%	0.65	-	-	0.1451	8.33	457	10.66	DVD 14
5/11/2004	18	H	87%	0.55	-	-	0.0873	4.45	435	13.89	DVD 14
5/11/2004	19	H	87%	0.48	-	-	0.1131	6.52	504	9.67	DVD 14
5/11/2004	20	H	87%	0.53	-	-	0.0847	6.20	484	8.83	DVD 14
5/11/2004	21	H	87%	0.52	-	-	0.0877	7.83	576	10.20	DVD 14
5/11/2004	22	H	87%	0.60	-	-	0.1151	7.14	417	9.77	DVD 14
5/11/2004	23	H	87%	0.62	-	-	0.0974	8.23	365	9.63	DVD 14
5/11/2004	24	H	87%	0.41	-	-	0.0666	7.11	531	10.88	DVD 14
5/11/2004	25	H	87%	0.60	-	-	0.1433	7.14	418	9.94	DVD 14
5/11/2004	26	H	87%	0.69	-	-	0.0848	-	-	12.44	DVD 14
5/11/2004	27	H	87%	0.56	-	-	0.1227	7.34	448	12.80	DVD 14
5/11/2004	28	H	87%	0.50	-	-	0.0695	3.86	532	12.66	DVD 14
5/11/2004	29	H	87%	0.57	-	-	0.0778	5.94	504	8.66	DVD 14
5/11/2004	30	H	87%	0.32	-	-	0.0608	4.55	605	9.75	DVD 14
5/13/2004	1	H	38%	0.32	-	-	0.0689	3.44	453	7.08	DVD 15
5/13/2004	2	H	38%	0.39	-	-	0.0763	3.61	384	6.78	DVD 15
5/13/2004	3	H	38%	0.42	-	-	0.0537	-	-	-	DVD 15
5/13/2004	4	H	38%	0.32	-	-	0.0544	1.70	343	7.13	DVD 15
5/13/2004	5	H	38%	0.38	-	-	0.0798	1.47	-	11.77	DVD 15
5/13/2004	6	H	38%	0.36	-	-	0.0834	3.16	-	7.55	DVD 15
5/13/2004	7	H	38%	0.38	-	-	0.0614	1.99	507	7.25	DVD 15
5/13/2004	8	H	38%	0.39	-	-	0.0623	2.94	420	6.91	DVD 15
5/13/2004	9	H	38%	0.38	-	-	0.0521	2.44	421	7.24	DVD 15
5/13/2004	10	H	38%	0.42	-	-	0.1036	3.91	393	8.94	DVD 15
5/13/2004	11	H	38%	0.43	-	-	0.1239	2.52	530	11.34	DVD 15
5/13/2004	12	H	38%	0.47	-	-	0.0921	3.41	586	8.44	DVD 15
5/13/2004	13	H	38%	0.41	-	-	0.0756	2.41	-	10.00	DVD 15
5/13/2004	14	H	38%	0.47	-	-	0.0766	2.45	520	9.06	DVD 15
5/13/2004	15	H	38%	0.33	-	-	0.0632	3.27	397	7.44	DVD 15
5/13/2004	16	H	38%	0.28	-	-	0.0352	2.67	491	5.81	DVD 15
5/13/2004	17	H	38%	0.44	-	-	0.0727	2.16	471	9.84	DVD 15
5/13/2004	18	H	38%	0.41	-	-	0.0731	2.36	-	7.66	DVD 15
5/13/2004	19	H	38%	0.34	-	-	0.0924	3.44	-	7.44	DVD 15
5/13/2004	20	H	38%	0.37	-	-	0.0733	1.59	-	10.95	DVD 15
7/22/2004	1	H	57%	0.51	1.70	-	0.0386	3.66	833	10.69	DVD 25
7/22/2004	2	H	57%	0.56	1.52	-	0.0286	2.09	657	12.39	DVD 25

Date	Run #	Orientation	MC [%]	Δx (mm)	L [cm]	W [cm]	Mass [gm]	t_{ig} [s]	T_{ig} [°C]	t_{flame} [s]	Data Location
7/22/2004	3	H	57%	0.76	1.52	-	0.0446	5.98	537	12.30	DVD 25
7/22/2004	4	H	57%	0.77	1.63	-	0.0384	7.13	534	13.69	DVD 25
7/22/2004	5	H	57%	0.53	1.60	-	0.0180	6.47	-	8.14	DVD 25
7/22/2004	6	H	57%	0.77	1.52	-	0.0448	5.77	371	12.88	DVD 25
7/22/2004	7	H	57%	0.52	1.02	-	0.0415	5.95	599	6.53	DVD 25
7/22/2004	8	H	57%	0.50	2.06	-	0.0532	2.69	555	7.88	DVD 25
7/22/2004	9	H	57%	0.52	1.65	-	0.0497	4.20	754	7.86	DVD 25
7/22/2004	10	H	57%	0.50	1.65	-	0.0490	2.14	564	7.24	DVD 25
7/22/2004	11	H	57%	0.37	1.32	-	0.0134	2.70	790	5.91	DVD 25
7/22/2004	12	H	57%	0.46	1.27	-	0.0242	3.24	529	7.19	DVD 25
7/22/2004	13	H	57%	0.65	1.50	-	0.0220	4.41	508	9.53	DVD 25
7/22/2004	14	H	57%	0.56	1.37	-	0.0259	3.13	605	12.31	DVD 25
7/22/2004	15	H	57%	0.57	2.11	-	0.0302	4.61	693	9.45	DVD 25
7/22/2004	16	H	57%	0.52	1.69	-	0.0308	3.75	519	6.36	DVD 25
7/22/2004	17	H	57%	0.69	1.70	-	0.0314	4.39	537	11.00	DVD 25
7/22/2004	18	H	57%	0.52	1.78	-	0.0324	5.77	565	5.59	DVD 25
7/22/2004	19	H	57%	0.56	1.30	-	0.0281	5.11	426	6.24	DVD 25
7/22/2004	20	H	57%	0.61	1.65	-	0.0144	5.25	516	8.09	DVD 25
7/22/2004	21	H	57%	0.80	1.85	-	0.0148	7.60	470	9.06	DVD 25
7/22/2004	22	H	57%	0.64	2.36	-	0.0213	8.33	-	7.84	DVD 25
7/22/2004	23	H	57%	0.58	2.03	-	0.0090	5.42	351	10.30	DVD 25
7/22/2004	24	H	57%	0.69	1.91	-	0.0137	7.14	518	7.69	DVD 25
7/22/2004	25	H	57%	0.60	1.57	-	0.0261	4.81	586	7.81	DVD 25
7/22/2004	26	H	57%	0.65	1.78	-	0.0187	6.36	573	7.77	DVD 25
7/22/2004	27	H	57%	0.56	2.08	-	0.0298	6.97	-	7.17	DVD 25
7/22/2004	28	H	57%	0.61	1.73	-	0.0139	6.20	484	7.39	DVD 25
7/22/2004	29	H	57%	0.76	1.91	-	0.0147	6.89	405	8.17	DVD 28
7/22/2004	30	H	57%	0.86	1.85	-	0.0286	6.09	443	10.39	DVD 28
2/5/2005	1	H	46%	0.64	2.03	1.26	0.0963	-	-	-	PC
2/5/2005	2	H	46%	0.51	1.35	1.27	0.0708	5.89	686	5.17	PC
2/5/2005	3	H	46%	0.52	1.51	1.04	0.0640	2.61	357	8.64	PC
2/5/2005	4	H	46%	0.44	1.63	1.33	0.0884	2.11	300	8.36	PC
2/5/2005	5	H	46%	0.58	1.29	1.31	0.0758	6.30	30	5.91	PC
2/5/2005	6	H	46%	0.43	1.40	1.40	0.0913	6.05	413	6.98	PC
2/5/2005	7	H	46%	0.46	1.50	1.01	0.0568	2.16	568	7.91	PC
2/5/2005	8	H	46%	0.46	1.99	1.26	0.0926	2.31	331	8.19	PC
2/5/2005	9	H	46%	0.46	1.41	1.08	0.0619	2.67	338	7.97	PC
2/5/2005	10	H	46%	0.47	1.21	0.80	0.0375	1.89	342	6.49	PC
2/5/2005	11	H	46%	0.47	1.46	1.25	0.0758	4.28	580	8.19	PC
2/5/2005	12	H	46%	0.48	1.44	0.88	0.0523	1.56	681	9.31	PC
2/5/2005	13	H	46%	0.45	1.94	1.55	0.1053	2.77	340	9.38	PC
2/5/2005	14	H	46%	0.35	1.75	0.87	0.0625	2.61	495	7.98	PC
2/5/2005	15	H	46%	0.49	1.67	1.28	0.0815	2.22	268	7.64	PC
2/5/2005	16	H	46%	0.49	1.44	1.23	0.0725	3.11	377	8.19	PC
2/5/2005	17	H	46%	0.53	1.76	1.51	0.0995	7.22	695	6.74	PC
2/5/2005	18	H	46%	0.41	1.77	0.91	0.0688	2.70	386	9.44	PC
2/5/2005	19	H	46%	0.50	1.65	1.38	0.0883	4.16	285	9.17	PC
2/5/2005	20	H	46%	0.50	1.13	0.95	0.0399	2.06	308	6.63	PC

Table 17. Chamise Data

Date	Run #	Orientation	MC [%]	Δx (mm)	L [cm]	W [cm]	Mass [gm]	t_{ig} [s]	T_{ig} [°C]	t_{flame} [s]	Data Location
11/19/2002	1	-	18%	-	-	-	9.5260	-	-	-	CD
11/19/2002	2	-	18%	-	-	-	5.6592	-	-	-	CD
11/19/2002	3	-	18%	-	-	-	4.1338	-	-	-	CD
11/19/2002	4	-	18%	-	-	-	4.8421	-	-	-	CD
11/19/2002	5	-	18%	-	-	-	9.0191	-	-	-	CD
6/26/2003	1	-	76%	-	-	-	-	-	-	-	DVD 5
6/26/2003	2	V	76%	-	-	-	-	-	-	19.86	DVD 4
6/26/2003	3	V	76%	-	-	-	-	-	-	13.38	DVD 4
6/26/2003	4	V	76%	-	-	-	-	-	-	16.34	DVD 4
6/26/2003	5	V	76%	-	-	-	-	-	-	23.25	DVD 4
5/21/2003	1	H	81%	-	-	-	-	-	-	-	DVD 2
5/21/2003	2	V	81%	-	-	-	-	-	-	22.34	DVD 2
5/21/2003	3	V	81%	-	-	-	-	-	-	30.91	DVD 2
5/21/2003	4	V	81%	-	-	-	-	-	-	17.39	DVD 2
5/21/2003	5	V	81%	-	-	-	-	-	-	34.89	DVD 2

Date	Run #	Orientation	MC [%]	Δx (mm)	L [cm]	W [cm]	Mass [gm]	t_{ig} [s]	T_{ig} [°C]	t_{flame} [s]	Data Location
5/21/2003	6	H	81%	-	-	-	-	-	-	20.31	DVD 2
5/21/2003	7	V	81%	-	-	-	-	-	-	-	DVD 2
5/21/2003	8	V	81%	-	-	-	-	-	-	31.02	DVD 2
5/21/2003	9	V	81%	-	-	-	-	-	-	-	DVD 2
5/21/2003	10	V	81%	-	-	-	-	-	-	-	DVD 3
5/21/2003	11	H	81%	-	-	-	-	-	-	17.75	DVD 3
5/21/2003	12	H	81%	-	-	-	-	-	-	11.17	DVD 3
5/22/2003	1	V	85%	-	-	-	-	-	-	24.53	DVD 3
5/22/2003	2	V	85%	-	-	-	-	-	-	34.78	DVD 3
5/22/2003	3	H	85%	-	-	-	-	-	-	27.45	DVD 3
5/22/2003	4	H	85%	-	-	-	-	-	-	40.50	DVD 3
5/22/2003	5	V	85%	-	-	-	-	-	-	39.50	DVD 3
5/22/2003	6	H	85%	-	-	-	-	-	-	29.44	DVD 3
5/22/2003	7	V	85%	-	-	-	-	-	-	21.91	DVD 3
5/22/2003	8	H	85%	-	-	-	-	-	-	29.48	DVD 3
5/22/2003	9	H	85%	-	-	-	-	-	-	20.45	DVD 3
5/22/2003	10	V	85%	-	-	-	-	-	-	32.91	DVD 3
5/22/2003	11	V	85%	-	-	-	-	-	-	43.28	DVD 3

Table 18. Gambel Oak Data

Date	Run #	Orientation	MC [%]	Δx (mm)	L [cm]	W [cm]	Mass [gm]	t_{ig} [s]	T_{ig} [°C]	t_{flame} [s]	Data Location
6/9/2004	1	H	71%	0.18	8.64	-	0.3535	1.09	296	7.44	DVD 20
6/9/2004	2	H	71%	0.09	4.06	-	0.0571	0.28	137	4.25	DVD 20
6/9/2004	3	H	71%	0.20	7.37	-	0.2943	0.69	218	7.03	DVD 20
6/9/2004	4	H	71%	0.20	5.59	-	0.1391	0.77	343	5.17	DVD 20
6/9/2004	5	H	71%	0.22	8.00	-	0.3184	0.69	207	9.05	DVD 20
6/9/2004	6	H	71%	0.17	6.35	-	0.2925	1.11	235	7.09	DVD 20
6/9/2004	7	H	71%	0.17	7.11	-	0.2848	0.91	223	6.27	DVD 20
6/9/2004	8	H	71%	0.22	6.60	-	0.2755	0.88	197	5.89	DVD 20
6/9/2004	9	H	71%	0.18	6.35	-	0.2045	0.89	209	8.14	DVD 20
6/9/2004	10	H	71%	0.15	5.84	-	0.1787	0.80	235	6.19	DVD 20
6/9/2004	11	H	71%	0.20	6.35	-	0.2778	1.14	278	8.61	DVD 20
6/9/2004	12	H	71%	0.18	6.86	-	0.2325	0.45	137	7.08	DVD 20
6/9/2004	13	H	71%	0.36	4.32	-	0.2062	0.47	130	8.05	DVD 20
6/9/2004	14	H	71%	0.27	4.32	-	0.2278	0.50	311	8.63	DVD 20
6/9/2004	15	H	71%	0.22	7.37	-	0.2893	1.17	291	6.05	DVD 20
6/9/2004	16	H	71%	0.18	4.06	-	0.0768	1.00	239	3.83	DVD 20
6/9/2004	17	H	71%	0.18	4.70	-	0.0829	0.55	217	4.42	DVD 20
6/9/2004	18	H	71%	0.20	6.35	-	0.2067	0.81	275	5.36	DVD 20
6/9/2004	19	H	71%	0.19	5.84	-	0.1136	1.02	240	4.98	DVD 20
6/9/2004	20	H	71%	0.23	6.35	-	0.2412	0.86	103	8.53	DVD 20
6/9/2004	21	H	71%	0.15	5.08	-	0.1219	0.52	118	6.00	DVD 20
6/9/2004	22	H	71%	0.22	3.81	-	0.1490	0.17	73	5.97	DVD 20
6/9/2004	23	H	71%	0.18	7.62	-	0.3514	0.17	62	6.86	DVD 20
6/9/2004	24	H	71%	0.20	7.37	-	0.3110	0.77	229	8.03	DVD 20
6/9/2004	25	H	71%	0.19	5.59	-	0.2038	0.70	238	6.41	DVD 20
6/9/2004	26	H	71%	0.19	5.72	-	0.1485	0.69	184	5.30	DVD 20
6/9/2004	27	H	71%	0.15	5.72	-	0.1167	2.00	190	6.10	DVD 20
6/9/2004	28	H	71%	0.20	5.72	-	0.2563	0.31	85	6.77	DVD 20
6/9/2004	29	H	71%	0.19	6.10	-	0.2121	0.70	127	6.02	DVD 20
6/9/2004	30	H	71%	0.19	6.10	-	0.2866	0.59	268	8.25	DVD 20
7/12/2004	1	H	126%	0.18	6.60	-	0.2560	1.22	260	7.33	DVD 22
7/12/2004	2	H	126%	0.17	8.13	-	0.2485	0.56	175	7.38	DVD 22
7/12/2004	3	H	126%	0.13	5.08	-	0.1087	0.92	309	4.56	DVD 22
7/12/2004	4	H	126%	0.22	10.41	-	0.5486	1.75	225	7.89	DVD 22
7/12/2004	5	H	126%	0.22	6.35	-	0.2528	2.09	309	5.74	DVD 22
7/12/2004	6	H	126%	0.17	7.37	-	0.2386	0.53	162	6.77	DVD 22
7/12/2004	7	H	126%	0.20	7.87	-	0.3713	0.52	261	9.34	DVD 22
7/12/2004	8	H	126%	0.13	5.84	-	0.1646	1.53	376	6.09	DVD 22
7/12/2004	9	H	126%	0.10	3.81	-	0.0494	0.67	296	4.69	DVD 22
7/12/2004	10	H	126%	0.17	8.13	-	0.3750	1.47	279	7.05	DVD 22
7/12/2004	11	H	84%	0.23	6.86	-	0.4152	1.20	-	8.45	DVD 22
7/12/2004	12	H	84%	0.13	2.79	-	0.0406	0.94	692	3.64	DVD 22
7/12/2004	13	H	84%	0.17	5.08	-	0.1476	0.83	482	5.91	DVD 22
7/12/2004	14	H	84%	0.20	5.59	-	0.1880	1.31	609	5.85	DVD 22
7/12/2004	15	H	84%	0.19	6.60	-	0.2716	0.89	292	6.80	DVD 22

Date	Run #	Orientation	MC [%]	Δx (mm)	L [cm]	W [cm]	Mass [gm]	t_{ig} [s]	T_{ig} [°C]	t_{flame} [s]	Data Location
7/12/2004	16	H	84%	0.22	8.89	-	0.5186	0.77	120	11.06	DVD 22
7/12/2004	17	H	84%	0.20	6.60	-	0.2446	1.34	440	7.89	DVD 22
7/12/2004	18	H	84%	0.13	4.06	-	0.0930	0.58	294	5.47	DVD 22
7/12/2004	19	H	84%	0.27	8.89	-	0.4618	0.86	192	9.22	DVD 22
7/12/2004	20	H	84%	0.22	7.11	-	0.3074	0.85	187	7.50	DVD 22
7/12/2004	21	H	105%	0.17	7.11	-	0.3115	1.63	297	6.34	DVD 22
7/12/2004	22	H	105%	0.22	6.35	-	0.2295	0.53	-	7.52	DVD 22
7/12/2004	23	H	105%	0.18	7.11	-	0.1842	0.92	299	6.83	DVD 22
7/12/2004	24	H	105%	0.15	3.56	-	0.0729	1.02	356	4.20	DVD 22
7/12/2004	25	H	105%	0.17	3.81	-	0.0825	1.23	367	4.77	DVD 22
7/12/2004	26	H	105%	0.14	4.06	-	0.0886	1.22	390	4.92	DVD 22
7/12/2004	27	H	105%	0.13	5.33	-	0.1756	0.97	517	6.05	DVD 22
7/12/2004	28	H	105%	0.15	8.38	-	0.2723	0.70	245	6.30	DVD 22
7/12/2004	29	H	105%	0.17	5.59	-	0.1932	0.72	238	6.84	DVD 22
7/12/2004	30	H	105%	0.19	7.37	-	0.2781	0.70	239	5.89	DVD 22
7/13/2004	1	H	15%	0.20	5.33	-	0.1020	0.31	120	3.39	DVD 23
7/13/2004	2	H	15%	0.18	6.10	-	0.1276	0.22	102	4.53	DVD 23
7/13/2004	3	H	15%	0.23	9.40	-	0.3290	0.22	139	6.91	DVD 23
7/13/2004	4	H	15%	0.20	7.62	-	0.1934	0.00	55	5.17	DVD 23
8/18/2004	1	H	13%	0.20	8.64	6.10	0.2795	-	-	-	DVD 33
8/18/2004	2	H	13%	0.17	10.16	8.64	0.4486	-	-	-	DVD 33
8/18/2004	3	H	13%	0.18	4.62	2.79	0.0697	0.17	219	4.00	DVD 33
8/18/2004	4	H	13%	0.15	10.49	6.60	0.3444	0.00	52	7.05	DVD 33
8/18/2004	5	H	13%	0.19	3.91	4.78	0.1510	0.11	77	6.58	DVD 33
8/18/2004	6	H	13%	0.23	7.06	5.05	0.1544	0.25	111	3.97	DVD 33
8/18/2004	7	H	13%	0.18	5.77	3.20	0.0880	0.19	134	3.51	DVD 33
8/18/2004	8	H	13%	0.19	8.00	6.81	0.3204	0.31	105	6.51	DVD 33
8/18/2004	9	H	13%	0.11	3.89	2.87	0.0650	0.24	108	4.77	DVD 33
8/18/2004	10	H	13%	0.14	10.54	8.97	0.4636	0.19	90	9.38	DVD 33
8/18/2004	11	H	13%	0.18	8.84	5.72	0.3247	0.30	243	5.36	DVD 33
8/18/2004	12	H	13%	0.18	5.99	4.70	0.2282	0.36	253	6.05	DVD 33
8/18/2004	13	H	13%	0.13	5.74	3.63	0.0755	0.28	104	2.61	DVD 33
8/18/2004	14	H	13%	0.18	6.91	2.64	0.1945	0.42	116	4.41	DVD 33
8/18/2004	15	H	13%	0.20	8.48	5.74	0.2845	0.41	93	5.85	DVD 33
8/18/2004	16	H	13%	0.18	8.08	7.29	0.3212	0.53	157	6.19	DVD 33
8/18/2004	17	H	13%	0.19	8.26	5.33	0.3204	0.61	205	5.38	DVD 33
8/18/2004	18	H	13%	0.17	6.20	3.91	0.1331	0.23	61	3.66	DVD 33
8/18/2004	19	H	13%	0.18	3.91	2.87	0.0611	0.33	107	3.55	DVD 33
8/18/2004	20	H	13%	0.23	8.51	5.51	0.2986	0.09	58	8.83	DVD 33
8/19/2004	1	H	52%	0.15	5.36	2.92	0.1587	-	-	-	DVD 33
8/19/2004	2	H	52%	0.19	5.16	3.10	0.1645	0.63	290	7.13	DVD 33
8/19/2004	3	H	52%	0.17	6.15	3.30	0.1711	0.78	459	6.55	DVD 33
8/19/2004	4	H	52%	0.20	7.04	3.45	0.2530	0.48	358	7.75	DVD 33
8/19/2004	5	H	52%	0.20	9.40	4.83	0.5057	0.17	-	12.36	DVD 33
8/19/2004	6	H	52%	0.17	6.78	5.26	0.3536	0.20	154	11.00	DVD 33
8/19/2004	7	H	52%	0.17	3.73	2.84	0.1243	0.69	325	5.66	DVD 33
8/19/2004	8	H	52%	0.23	7.85	3.18	0.3019	0.70	-	8.33	DVD 33
8/19/2004	9	H	52%	0.15	5.87	5.28	0.3264	0.33	198	9.72	DVD 33
8/19/2004	10	H	52%	0.18	7.24	3.81	0.2253	0.63	271	7.11	DVD 33
8/19/2004	11	H	52%	0.19	5.13	3.86	0.2110	0.60	232	7.84	DVD 33
8/19/2004	12	H	52%	0.15	5.23	2.84	0.1228	0.33	299	5.28	DVD 33
8/19/2004	13	H	52%	0.22	5.56	3.86	0.2490	1.03	317	10.03	DVD 33
8/19/2004	14	H	52%	0.18	5.21	2.95	0.1788	1.09	354	6.31	DVD 33
8/19/2004	15	H	52%	0.20	7.87	4.52	0.3496	0.34	165	8.11	DVD 33
8/19/2004	16	H	52%	0.23	7.37	4.14	0.3232	0.41	200	9.85	DVD 33
8/19/2004	17	H	52%	0.17	3.73	2.06	0.0784	0.39	309	5.52	DVD 33
8/19/2004	18	H	52%	0.15	5.64	4.80	0.1370	0.74	152	6.09	DVD 33
8/19/2004	19	H	52%	0.14	3.10	1.57	0.0561	0.83	420	4.89	DVD 33
8/19/2004	20	H	52%	0.18	5.13	3.40	0.2512	-	-	-	DVD 33

Table 19. Canyon Maple Data

Date	Run #	Orientation	MC [%]	Δx (mm)	L [cm]	W [cm]	Mass [gm]	t_{ig} [s]	T_{ig} [°C]	t_{flame} [s]	Data Location
7/15/2004	1	H	87%	0.33	3.68	-	0.1161	0.38	288	5.00	DVD 24
7/15/2004	2	H	87%	0.44	5.08	-	0.3119	0.91	281	7.27	DVD 24
7/15/2004	3	H	87%	0.33	4.06	-	0.1225	-	-	-	DVD 24
7/15/2004	4	H	87%	0.30	4.57	-	0.1624	0.80	341	6.44	DVD 24

Date	Run #	Orientation	MC [%]	Δx (mm)	L [cm]	W [cm]	Mass [gm]	t_{ig} [s]	T_{ig} [°C]	t_{flame} [s]	Data Location
7/15/2004	5	H	87%	0.38	3.30	-	0.1219	0.91	340	5.95	DVD 24
7/15/2004	6	H	87%	0.38	4.83	-	0.2694	0.31	207	7.64	DVD 24
7/15/2004	7	H	87%	0.39	5.08	-	0.2799	0.72	540	7.13	DVD 24
7/15/2004	8	H	87%	0.38	4.95	-	0.2232	0.45	168	-	DVD 24
7/15/2004	9	H	87%	0.29	3.05	-	0.0930	0.66	249	-	DVD 24
7/15/2004	10	H	87%	0.36	3.30	-	0.1585	1.24	497	5.33	DVD 24
7/15/2004	11	H	87%	0.33	3.56	-	0.1257	0.50	198	4.89	DVD 24
7/15/2004	12	H	87%	0.34	4.32	-	0.1381	0.36	322	5.78	DVD 24
7/15/2004	13	H	87%	0.33	4.06	-	0.1345	0.53	402	6.01	DVD 24
7/15/2004	14	H	87%	0.42	4.57	-	0.2493	0.50	292	6.31	DVD 24
7/15/2004	15	H	87%	0.22	2.03	-	0.0406	0.77	459	3.28	DVD 24
7/15/2004	16	H	87%	0.46	5.08	-	0.3144	0.56	228	8.89	DVD 24
7/15/2004	17	H	87%	0.27	3.30	-	0.0681	0.42	365	4.30	DVD 24
7/15/2004	18	H	87%	0.32	4.06	-	0.1228	0.63	424	5.03	DVD 24
7/15/2004	19	H	87%	0.41	4.83	-	0.2426	0.94	428	7.22	DVD 24
7/15/2004	20	H	87%	0.36	4.32	-	0.1942	0.70	259	6.67	DVD 24
7/15/2004	21	H	87%	0.27	4.70	-	0.1716	0.83	243	5.16	DVD 24
7/15/2004	22	H	87%	0.24	3.68	-	0.1210	0.72	484	5.26	DVD 24
7/15/2004	23	H	87%	0.22	3.81	-	0.1217	0.73	378	4.56	DVD 24
7/15/2004	24	H	87%	0.20	4.06	-	0.1281	0.78	459	5.05	DVD 24
7/15/2004	25	H	87%	0.18	3.56	-	0.0902	0.78	457	4.24	DVD 24
7/15/2004	26	H	87%	0.24	3.56	-	0.1237	0.78	465	4.64	DVD 24
7/15/2004	27	H	87%	0.20	3.68	-	0.1294	1.11	460	5.06	DVD 24
7/15/2004	28	H	87%	0.23	4.32	-	0.1943	0.41	265	6.11	DVD 24
7/15/2004	29	H	87%	0.32	4.57	-	0.2493	0.63	-	6.97	DVD 24
7/15/2004	30	H	87%	0.28	5.08	-	0.2704	0.60	292	6.83	DVD 24
8/10/2004	1	H	86%	0.17	4.11	4.72	0.2196	0.36	299	6.23	DVD 32
8/10/2004	2	H	86%	0.14	5.72	7.62	0.4628	0.33	118	8.72	DVD 32
8/10/2004	3	H	86%	0.13	6.10	6.86	0.3615	0.31	204	7.27	DVD 32
8/10/2004	4	H	86%	0.14	4.06	3.05	0.1111	0.56	326	4.14	DVD 32
8/10/2004	5	H	86%	0.10	3.05	2.54	0.0730	0.28	222	4.48	DVD 32
8/10/2004	6	H	86%	0.15	3.53	4.83	0.2195	0.59	328	6.74	DVD 32
8/10/2004	7	H	86%	0.14	3.63	3.81	0.1438	0.47	211	5.78	DVD 32
8/10/2004	8	H	86%	0.15	5.08	6.10	0.3518	0.36	167	8.11	DVD 32
8/10/2004	9	H	86%	0.18	4.83	6.43	0.3742	0.20	55	10.01	DVD 32
8/10/2004	10	H	86%	0.15	4.06	4.83	0.2038	0.41	340	6.83	DVD 32
8/10/2004	11	H	86%	0.15	3.73	3.43	0.1000	0.22	130	4.38	DVD 32
8/10/2004	12	H	86%	0.14	4.01	3.73	0.1108	0.39	211	5.13	DVD 32
8/10/2004	13	H	86%	0.17	3.96	3.66	0.1248	0.35	269	5.78	DVD 32
8/10/2004	14	H	86%	0.15	4.57	5.33	0.1790	0.41	216	6.33	DVD 32
8/10/2004	15	H	86%	0.14	4.50	4.06	0.1223	0.30	165	4.67	DVD 32
8/10/2004	16	H	86%	0.19	5.33	5.84	0.3215	0.58	238	7.26	DVD 32
8/10/2004	17	H	86%	0.18	4.06	4.88	0.1987	0.36	162	5.42	DVD 32
8/10/2004	18	H	86%	0.23	3.56	3.86	0.1123	0.45	277	4.75	DVD 32
8/10/2004	19	H	86%	0.13	2.90	2.54	0.0423	0.09	201	3.28	DVD 32
8/10/2004	20	H	86%	0.19	4.75	5.26	0.1646	0.17	139	5.30	DVD 32
8/12/2004	1	H	97%	0.18	5.59	5.33	0.2838	0.52	392	6.34	DVD 32
8/12/2004	2	H	97%	0.17	4.75	4.32	0.2171	0.38	322	6.94	DVD 32
8/12/2004	3	H	97%	0.13	4.90	4.19	0.1683	0.70	223	4.63	DVD 32
8/12/2004	4	H	97%	0.18	5.84	5.66	0.3712	0.14	99	7.30	DVD 32
8/12/2004	5	H	97%	0.13	5.99	5.21	0.2481	0.25	174	6.28	DVD 32
8/12/2004	6	H	97%	0.14	3.33	4.04	0.1118	0.25	204	5.20	DVD 32
8/12/2004	7	H	97%	0.17	5.44	5.92	0.3805	0.36	134	6.19	DVD 32
8/12/2004	8	H	97%	0.18	3.73	3.76	0.1529	0.72	366	5.75	DVD 32
8/12/2004	9	H	97%	0.14	5.74	7.06	0.3841	0.48	158	6.81	DVD 32
8/12/2004	10	H	97%	0.15	3.84	4.01	0.1794	0.16	87	6.16	DVD 32
8/12/2004	11	H	97%	0.18	4.01	4.57	0.1982	0.42	176	7.02	DVD 32
8/12/2004	12	H	97%	0.18	4.19	4.80	0.2040	0.63	253	7.31	DVD 32
8/12/2004	13	H	97%	0.15	4.06	4.67	0.1745	0.00	65	7.72	DVD 32
8/12/2004	14	H	97%	0.18	4.24	4.88	0.2479	0.63	439	-	DVD 32
8/12/2004	15	H	97%	0.18	4.14	4.95	0.2206	0.88	378	6.56	DVD 32
8/12/2004	16	H	97%	0.22	5.08	7.26	0.3511	0.94	225	7.72	DVD 32
8/12/2004	17	H	97%	0.18	3.56	3.40	0.1795	0.67	245	5.94	DVD 32
8/12/2004	18	H	97%	0.17	3.48	4.27	0.1624	0.48	413	7.28	DVD 32
8/12/2004	19	H	97%	0.13	2.41	3.15	0.0734	0.38	234	4.80	DVD 32
8/12/2004	20	H	97%	0.17	4.93	5.38	0.2891	0.44	164	7.52	DVD 32

Table 20. Big Sagebrush Data

Date	Run #	Orientation	MC [%]	Δx (mm)	L [cm]	W [cm]	Mass [gm]	t_{ig} [s]	T_{ig} [°C]	t_{flame} [s]	Data Location
6/9/2004	1	H	197%	0.19	4.32	-	0.0691	1.63	498	5.80	DVD 21
6/9/2004	2	H	197%	0.13	4.32	-	0.0461	0.94	-	4.88	DVD 21
6/9/2004	3	H	197%	0.18	3.81	-	0.0352	1.98	329	3.11	DVD 21
6/9/2004	4	H	197%	0.15	3.18	-	0.0276	1.81	-	3.66	DVD 21
6/9/2004	5	H	197%	0.17	4.32	-	0.0463	1.88	-	4.06	DVD 21
6/9/2004	6	H	197%	0.22	4.06	-	0.0648	1.88	-	6.25	DVD 21
6/9/2004	7	H	197%	0.20	3.81	-	0.0457	0.83	229	5.14	DVD 21
6/9/2004	8	H	197%	0.17	3.30	-	0.0279	1.19	253	4.75	DVD 21
6/9/2004	9	H	197%	0.18	3.81	-	0.0398	1.50	-	4.20	DVD 21
6/9/2004	10	H	197%	0.20	2.79	-	0.0180	1.16	237	3.23	DVD 21
6/9/2004	11	H	197%	0.30	2.79	-	0.0204	1.03	289	3.41	DVD 21
6/9/2004	12	H	197%	0.36	1.80	-	0.0137	0.92	223	4.22	DVD 21
6/9/2004	13	H	197%	0.30	3.30	-	0.0275	1.11	220	3.99	DVD 21
6/9/2004	14	H	197%	0.24	2.54	-	0.0146	1.00	326	2.89	DVD 21
6/9/2004	15	H	197%	0.22	3.43	-	0.0323	1.16	233	3.97	DVD 21
6/9/2004	16	H	197%	0.33	2.79	-	0.0220	1.17	296	3.41	DVD 21
6/9/2004	17	H	197%	0.24	4.06	-	0.0329	0.72	275	3.86	DVD 21
6/9/2004	18	H	197%	0.24	4.06	-	0.0381	0.61	217	2.98	DVD 21
6/9/2004	19	H	197%	0.24	4.06	-	0.0365	0.36	281	3.78	DVD 21
6/9/2004	20	H	197%	0.19	4.06	-	0.0445	0.58	228	3.72	DVD 21
6/9/2004	21	H	141%	0.11	3.05	-	0.0205	0.69	190	2.83	DVD 21
6/9/2004	22	H	141%	0.13	3.81	-	0.0292	0.75	173	4.02	DVD 21
6/9/2004	23	H	141%	0.11	3.18	-	0.0181	0.77	294	2.67	DVD 21
6/9/2004	24	H	141%	0.13	2.54	-	0.0120	0.38	238	3.18	DVD 21
6/9/2004	25	H	141%	0.15	4.06	-	0.0312	0.94	377	3.53	DVD 21
6/9/2004	26	H	141%	0.14	2.54	-	0.0135	0.52	311	2.92	DVD 21
6/9/2004	27	H	141%	0.18	2.54	-	0.0199	1.00	787	3.25	DVD 21
6/9/2004	28	H	141%	0.14	3.05	-	0.0214	0.69	396	3.69	DVD 21
6/9/2004	29	H	141%	0.19	3.18	-	0.0172	0.52	415	3.19	DVD 21
6/9/2004	30	H	141%	0.13	3.81	-	0.0254	0.59	268	3.44	DVD 21
6/29/2004	1	H	155%	0.20	3.81	-	0.0359	-	-	-	DVD 21
6/29/2004	2	H	155%	0.22	4.06	-	0.0310	2.47	326	2.44	DVD 21
6/29/2004	3	H	155%	0.20	4.06	-	0.0420	2.97	343	3.30	DVD 21
6/29/2004	4	H	155%	0.17	3.30	-	0.0228	1.33	253	3.56	DVD 21
6/29/2004	5	H	155%	0.17	3.05	-	0.0190	0.92	424	4.13	DVD 21
6/29/2004	6	H	155%	0.14	4.06	-	0.0219	1.38	506	2.85	DVD 21
6/29/2004	7	H	155%	0.18	4.06	-	0.0362	1.94	665	2.94	DVD 21
6/29/2004	8	H	155%	0.19	4.06	-	0.0509	2.63	339	3.66	DVD 21
6/29/2004	9	H	155%	0.18	3.81	-	0.0487	2.83	773	3.00	DVD 21
6/29/2004	10	H	155%	0.17	3.56	-	0.0291	2.53	676	3.00	DVD 21
6/29/2004	11	H	155%	0.20	4.06	-	0.0555	2.25	260	5.19	DVD 21
6/29/2004	12	H	155%	0.27	3.56	-	0.0315	1.35	285	4.09	DVD 21
6/29/2004	13	H	155%	0.22	3.43	-	0.0399	1.17	298	5.59	DVD 21
6/29/2004	14	H	155%	0.24	4.57	-	0.0557	2.95	171	2.64	DVD 21
6/29/2004	15	H	155%	0.24	4.32	-	0.0520	1.72	527	3.91	DVD 21
6/29/2004	16	H	155%	0.18	3.56	-	0.0243	0.58	215	3.41	DVD 21
6/29/2004	17	H	155%	0.25	3.56	-	0.0406	1.41	173	4.86	DVD 21
6/29/2004	18	H	155%	0.24	3.43	-	0.0409	1.97	200	4.73	DVD 21
6/29/2004	19	H	155%	0.18	4.06	-	0.0303	1.22	227	3.17	DVD 21
6/29/2004	20	H	155%	0.25	2.54	-	0.0183	1.36	308	3.17	DVD 21
6/29/2004	21	H	155%	0.32	4.83	-	0.0527	3.72	714	2.58	DVD 21
6/29/2004	22	H	155%	0.25	1.78	-	0.0090	1.95	534	2.92	DVD 21
6/29/2004	23	H	155%	0.14	3.81	-	0.0220	2.64	702	1.58	DVD 21
6/29/2004	24	H	155%	0.28	2.54	-	0.0170	4.38	723	1.89	DVD 21
6/29/2004	25	H	155%	0.20	2.79	-	0.0092	1.39	416	2.33	DVD 21
6/29/2004	26	H	155%	0.14	2.29	-	0.0050	1.78	-	0.70	DVD 21
6/29/2004	27	H	155%	0.27	3.30	-	0.0183	2.25	-	-	DVD 21
6/29/2004	28	H	155%	0.24	3.81	-	0.0329	2.44	249	3.75	DVD 21
6/29/2004	29	H	155%	0.32	4.32	-	0.0388	1.58	223	4.80	DVD 21
6/29/2004	30	H	155%	0.32	3.56	-	0.0293	2.03	226	3.19	DVD 21
7/19/2004	1	H	113%	0.29	3.30	-	0.0386	2.81	402	3.91	DVD 24
7/19/2004	2	H	113%	0.29	2.54	-	0.0286	1.36	437	3.63	DVD 24
7/19/2004	3	H	113%	0.39	3.05	-	0.0446	1.59	435	5.09	DVD 24
7/19/2004	4	H	113%	0.28	3.30	-	0.0384	1.08	343	-	DVD 24
7/19/2004	5	H	113%	0.27	2.79	-	0.0180	1.78	385	2.50	DVD 24
7/19/2004	6	H	113%	0.24	4.06	-	0.0448	1.99	331	3.84	DVD 24
7/19/2004	7	H	113%	0.34	3.56	-	0.0415	2.70	-	4.00	DVD 24

Date	Run #	Orientation	MC [%]	Δx (mm)	L [cm]	W [cm]	Mass [gm]	t_{ig} [s]	T_{ig} [°C]	t_{flame} [s]	Data Location
7/19/2004	8	H	113%	0.38	3.30	-	0.0532	1.70	346	-	DVD 24
7/19/2004	9	H	113%	0.29	3.68	-	0.0497	1.88	401	4.28	DVD 24
7/19/2004	10	H	113%	0.30	3.68	-	0.0490	2.06	361	4.91	DVD 24
7/19/2004	11	H	113%	0.24	2.54	-	0.0134	1.02	626	2.45	DVD 24
7/19/2004	12	H	113%	0.28	2.79	-	0.0242	1.11	491	3.47	DVD 24
7/19/2004	13	H	113%	0.24	3.05	-	0.0220	1.39	-	2.97	DVD 24
7/19/2004	14	H	113%	0.27	3.05	-	0.0259	1.31	508	3.56	DVD 24
7/19/2004	15	H	113%	0.23	3.30	-	0.0302	1.33	469	3.91	DVD 24
7/19/2004	16	H	113%	0.28	3.18	-	0.0308	1.53	391	4.31	DVD 26
7/19/2004	17	H	113%	0.29	3.30	-	0.0314	2.14	600	3.80	DVD 26
7/19/2004	18	H	113%	0.24	3.05	-	0.0324	2.44	480	3.45	DVD 26
7/19/2004	19	H	113%	0.28	3.30	-	0.0281	1.61	492	3.63	DVD 26
7/19/2004	20	H	113%	0.20	2.54	-	0.0144	1.22	501	2.70	DVD 26
7/19/2004	21	H	113%	0.24	2.54	-	0.0148	1.11	424	2.09	DVD 26
7/19/2004	22	H	113%	0.22	3.05	-	0.0213	1.34	456	3.22	DVD 26
7/19/2004	23	H	113%	0.18	2.29	-	0.0090	0.80	576	1.86	DVD 26
7/19/2004	24	H	113%	0.24	2.54	-	0.0137	0.80	362	2.61	DVD 26
7/19/2004	25	H	113%	0.22	3.30	-	0.0261	0.99	445	3.25	DVD 26
7/19/2004	26	H	113%	0.25	2.29	-	0.0187	0.75	387	4.22	DVD 26
7/19/2004	27	H	113%	0.27	3.30	-	0.0298	1.11	577	3.55	DVD 26
7/19/2004	28	H	113%	0.24	2.54	-	0.0139	1.61	462	3.03	DVD 26
7/19/2004	29	H	113%	0.18	2.79	-	0.0147	0.78	407	2.25	DVD 26
7/19/2004	30	H	113%	0.25	3.05	-	0.0286	1.09	426	3.97	DVD 26

Table 21. Utah Juniper Data

Date	Run #	Orientation	MC [%]	Δx (mm)	L [cm]	W [cm]	Mass [gm]	t_{ig} [s]	T_{ig} [°C]	t_{flame} [s]	Data Location
7/28/2004	1	H	69%	-	-	-	-	0.17	-	21.25	DVD 28
7/28/2004	2	H	69%	-	-	-	1.0739	1.45	-	27.64	DVD 28
7/28/2004	3	H	69%	-	-	-	1.0497	0.33	-	29.36	DVD 28
7/28/2004	4	H	69%	-	-	-	2.7758	0.66	-	31.44	DVD 28
7/28/2004	5	H	69%	-	-	-	0.4238	0.48	-	20.31	DVD 28
7/28/2004	6	H	69%	-	-	-	0.8775	2.11	-	41.70	DVD 28
7/28/2004	7	H	69%	-	-	-	2.8484	0.31	-	38.58	DVD 28
7/28/2004	8	H	69%	-	-	-	2.2215	0.97	-	36.34	DVD 28
7/28/2004	9	H	69%	-	-	-	3.5966	2.75	-	54.09	DVD 28
7/28/2004	10	H	69%	-	-	-	1.9247	4.70	-	22.02	DVD 28
7/28/2004	11	H	69%	-	-	-	1.5463	3.38	-	29.42	DVD 26
7/28/2004	12	H	69%	-	-	-	0.6077	3.08	-	18.24	DVD 26
7/28/2004	13	H	69%	-	-	-	1.0193	0.83	-	40.52	DVD 26
7/28/2004	14	H	69%	-	-	-	4.2274	2.75	-	55.47	DVD 26
7/28/2004	15	H	69%	-	-	-	2.6548	1.94	-	29.42	DVD 26
7/29/2004	1	H	61%	-	-	-	1.1882	0.49	-	29.42	DVD 29
7/29/2004	2	H	61%	-	-	-	1.9143	1.78	-	30.70	DVD 29
7/29/2004	3	H	61%	-	-	-	0.3140	0.33	-	28.08	DVD 29
7/29/2004	4	H	61%	-	-	-	1.0964	2.27	-	21.80	DVD 29
7/29/2004	5	H	61%	-	-	-	0.6763	0.31	-	-	DVD 29
7/29/2004	6	H	61%	-	-	-	2.0834	0.80	-	-	DVD 29
7/29/2004	7	H	61%	-	-	-	2.3700	3.08	-	-	DVD 29
7/29/2004	8	H	61%	-	-	-	0.6830	0.33	-	23.13	DVD 29
7/29/2004	9	H	61%	-	-	-	0.7192	0.49	-	21.34	DVD 29
7/29/2004	10	H	61%	-	-	-	0.5910	2.89	-	14.83	DVD 29
7/29/2004	11	H	61%	-	-	-	0.7632	0.97	-	21.08	DVD 29
7/29/2004	12	H	61%	-	-	-	0.3546	2.19	212	13.36	DVD 30
7/29/2004	13	H	61%	-	-	-	0.2717	1.80	144	11.28	DVD 30
7/29/2004	14	H	61%	-	-	-	0.5297	0.64	137	14.38	DVD 30
7/29/2004	15	H	61%	-	-	-	0.4272	2.25	389	13.91	DVD 30
7/29/2004	16	H	61%	-	-	-	0.3132	2.52	385	14.05	DVD 30
7/29/2004	17	H	61%	-	-	-	0.5424	2.52	210	16.31	DVD 30
7/29/2004	18	H	61%	-	-	-	2.0394	0.92	172	-	DVD 30
7/29/2004	19	H	61%	-	-	-	0.5667	3.24	171	15.17	DVD 30
7/29/2004	20	H	61%	-	-	-	0.9981	3.09	204	19.63	DVD 30
7/29/2004	21	H	61%	-	-	-	0.7752	1.25	411	16.77	DVD 30
7/29/2004	22	H	61%	-	-	-	3.2138	0.47	58	-	DVD 30
1/18/2005	1	H	54%	-	-	-	0.2367	-	-	15.56	PC
1/18/2005	2	H	54%	-	-	-	0.1508	-	-	15.08	PC
1/18/2005	3	H	54%	-	-	-	0.2736	-	-	15.42	PC

Date	Run #	Orientation	MC [%]	Δx (mm)	L [cm]	W [cm]	Mass [gm]	t_{ig} [s]	T_{ig} [°C]	t_{flame} [s]	Data Location
1/18/2005	4	H	54%	-	-	-	1.1496	-	-	22.06	PC
1/18/2005	5	H	54%	-	-	-	0.4999	-	-	18.28	PC
1/18/2005	6	H	54%	-	-	-	1.0444	-	-	23.69	PC
1/18/2005	7	H	54%	-	-	-	0.5950	-	-	21.73	PC
1/18/2005	8	H	54%	-	-	-	0.9689	-	-	17.58	PC
1/18/2005	9	H	54%	-	-	-	1.7664	-	-	20.27	PC
1/18/2005	10	H	54%	-	-	-	0.1930	-	-	-	PC
1/20/2005	1	H	41%	-	-	-	0.5171	-	-	16.61	PC
1/20/2005	2	H	41%	-	-	-	0.7684	-	-	-	PC
1/20/2005	3	H	41%	-	-	-	0.2409	-	-	23.19	PC
1/20/2005	4	H	41%	-	-	-	0.4607	-	-	-	PC
1/20/2005	5	H	41%	-	-	-	1.5351	-	-	26.53	PC
1/20/2005	6	H	41%	-	-	-	1.0489	-	-	22.94	PC
1/20/2005	7	H	41%	-	-	-	0.2284	-	-	-	PC
1/20/2005	8	H	41%	-	-	-	0.2064	-	-	14.84	PC
1/20/2005	9	H	41%	-	-	-	0.2061	-	-	-	PC
1/20/2005	10	H	41%	-	-	-	0.7291	-	-	-	PC
1/20/2005	11	H	41%	-	-	-	0.8779	-	-	-	PC
1/20/2005	12	H	41%	-	-	-	0.4239	-	-	16.59	PC
1/20/2005	13	H	41%	-	-	-	1.4865	-	-	-	PC
1/20/2005	14	H	41%	-	-	-	0.2614	-	-	-	PC
1/20/2005	15	H	41%	-	-	-	0.1144	-	-	11.41	PC
1/20/2005	16	H	41%	-	-	-	0.2075	-	-	18.83	PC
1/20/2005	17	H	41%	-	-	-	0.1630	-	-	12.02	PC
1/20/2005	18	H	41%	-	-	-	0.2550	-	-	13.16	PC
1/20/2005	19	H	41%	-	-	-	0.4895	-	-	16.36	PC
1/20/2005	20	H	41%	-	-	-	0.2196	-	-	14.81	PC

A.2 Additional Analysis

A.2.1 Additional Correlations for T_{ig}

Different correlations were explored to see if there were strong trends in the ignition temperature, for all species combined, that could be explained by thickness and mass of water in the sample. There were four correlations in particular that were explored. The equations for these fits are shown in Table 22 along with the coefficient values and the sum of the errors squared (SSE). The fits to the data are shown in Figures 58 to 61.

Table 22. Summary of Coefficients and SSE for Four Correlations of T_{ig}

$T_{ig} = a\,\Delta x + b$		$T_{ig} = a\,\Delta x + b\,m_{H2O} + c$		
a	b	a	b	c
452.48 ± 67	193.45 ± 25.5	451.98 ± 65.4	-540.78 ± 189	228.79 ± 27.8

SSE	***12,032,863***		SSE	***11,443,484***
$T_{ig} = a + b/(\cos(0.1/\Delta x))$		$T_{ig} = a + b(1-\exp(-c\,\Delta x))$		
a	b	a	b	c
835.7 ± 110	-442.87 ± 99.1	117.34 ± 90.8	475.57 ± 143	2.1033 ± 2.03
SSE	***13,760,487***		SSE	***11,904,035***

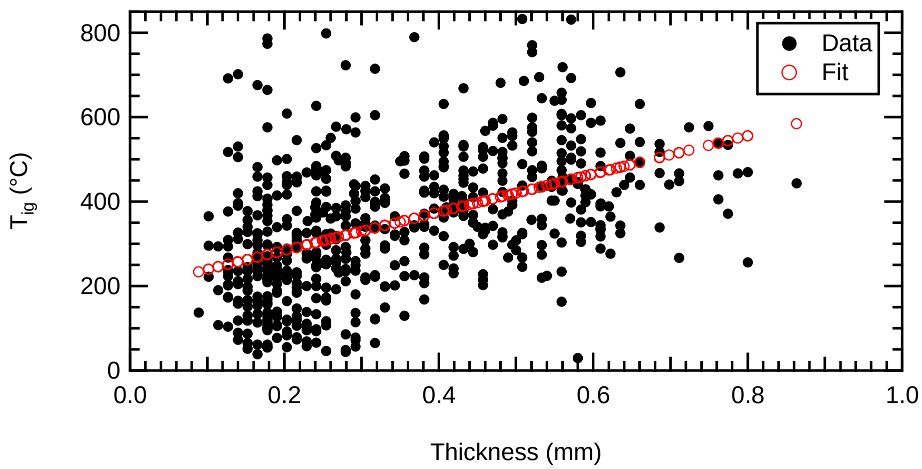

Figure 58. Linear correlation for $T_{ig} = a\,\Delta x + b$

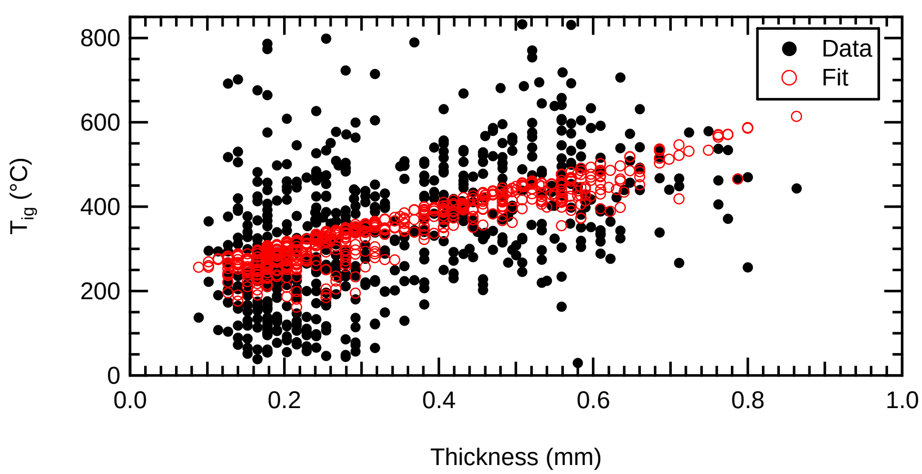

Figure 59. Two-variable linear correlation, $T_{ig} = a\,\Delta x + b\,m_{H2O} + c$

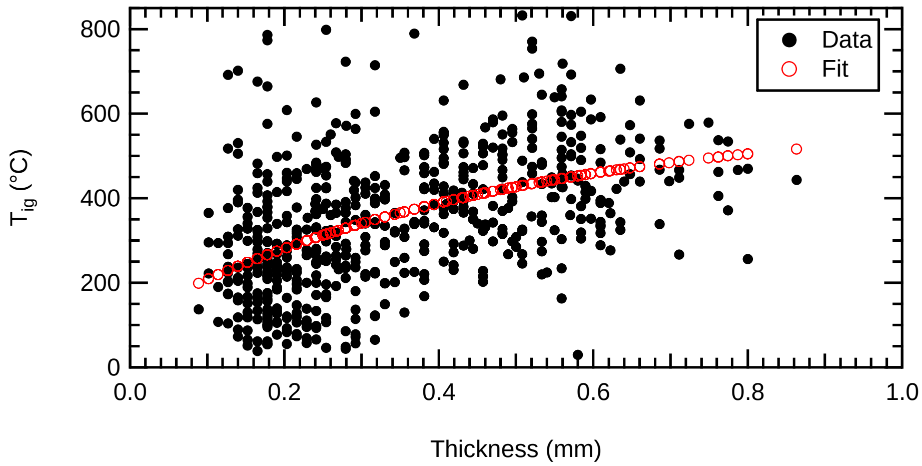

Figure 60. Exponential correlation, $T_{ig} = a + b(1\text{-}\exp(-c\Delta x))$.

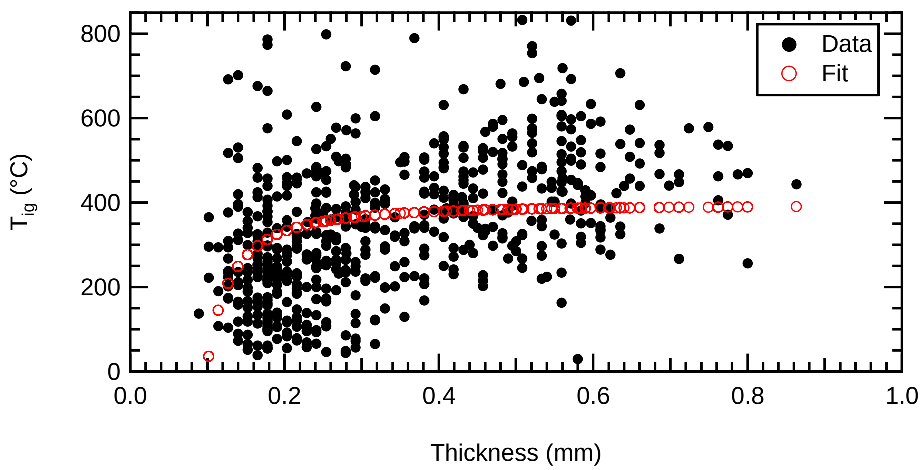

Figure 61. Correlation from theory, $T_{ig} = a + b/(\cos(0.1/\Delta x))$.

A.2.2 Thickness – m_{H2O} Relationship

Thickness and m_{H2O} were first thought to relate linearly. Upon further analysis, there appeared to be a two-pronged relationship between thickness and m_{H2O} for a few species. Figure 62 and Figure 63 show the relationship of thickness and m_{H2O} for the different species.

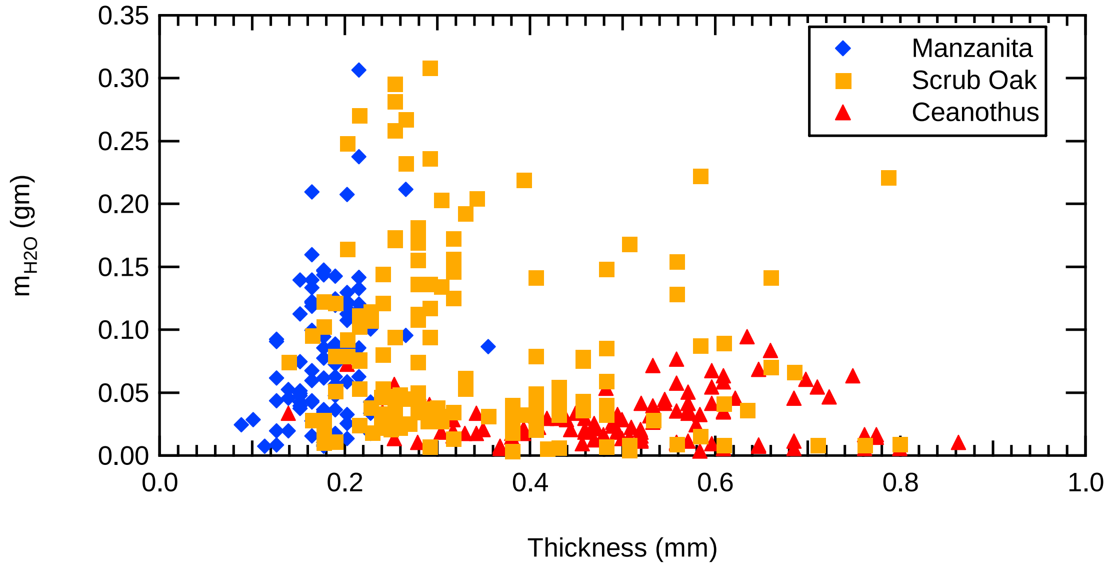

Figure 62. **m_{H2O} versus thickness for California chaparral species.**

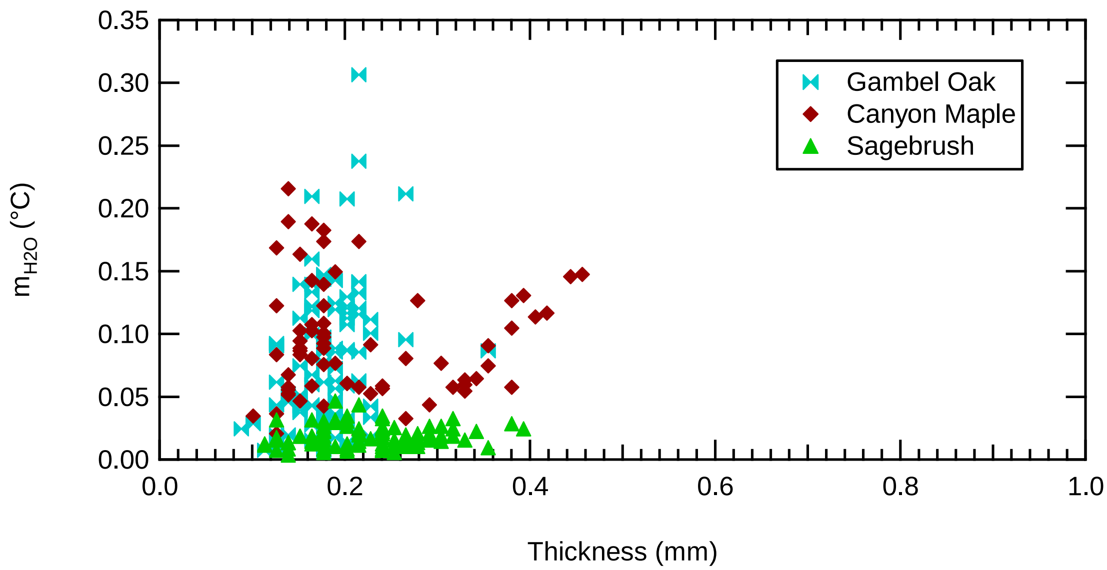

Figure 63. **m_{H2O} versus thickness for Utah species.**

Appendix B (CD)

Additional information was placed in a supplemental appendix on a DVD. Representative videos are found on the DVD along with raw data, the LabVIEW file, Hong Lu model, and the standard operating procedures.

B.1 Representative Videos

The following table is a summary of the representative videos found in Appendix B (DVD).

Table 23. Index of Video Clips in Appendix B

Item #	Descriptive Title	Date	Run #	MC
1.	Bubbling Manzanita	Jan 20, 2004	7	73%
2.	Bursting Manzanita	Jul 31, 2003	4	97%
3.	Manzanita Surface Color Change	Feb 4, 2005	1	56%
4.	Bubbling Scrub Oak	Feb 4, 2005	3	61%
5.	Bursting Scrub Oak at Ignition	May 19, 2004	20	79%
6.	Scrub Oak Surface Change	May 20, 2003	1	43%
7.	IR of Burning Scrub Oak	Feb 4, 2005	12	61%
8.	Burning Ceanothus	May 11, 2004	5	94%
9.	Horizontal Chamise	May 21, 2003	11	81%
10.	Vertical Chamise	May 21, 2003	8	81%
11.	Bubbling Gambel Oak	Aug 19, 2004	14	52%
12	Bubbling Canyon Maple	Aug 10, 2004	10	86%
13.	Burning Sagebrush	Jul 19, 2004	22	113%
14.	Branding Sagebrush	Jul 19, 2004	19	113%
15.	Burning Juniper	Jan 18, 2005	6	54%
16.	IR of Burning Juniper	Jan 18, 2005	6	54%

B.2 Raw Data Summary Sheet

The data from Tables 18-21 can be found in more detail in this spreadsheet.

B.3 LabVIEW Program

A copy of the library of SubVIs used in the LabVIEW program was compiled. The program was originally coded in LabVIEW 5.1, then completely reworked in LabVIEW 7.1.

B.4 Particle Combustion Model

The latest version of the code (as of May 2005) developed by Lu and coworkers[48] is located on the supplemental DVD.

B.5 Standard Operating Procedures for the Equipment Used in the Experiment

The standard operating procedures for operating the flat flame burner and the LabVIEW program