Project 11-1-4-19

# Determination of the Effects of Heating Mechanisms and Moisture Content on Ignition of Live Fuels

# Final Report


*David R. Weise, USDA Forest Service, PSW Research Station, Riverside, CA*

*Thomas Fletcher, Brigham Young University*

*Shankar Mahalingam, University of Alabama in Huntsville*

*Sara McAllister, USDA Forest Service, Rocky Mountain Research Station*

*Babak Shotorban, University of Alabama in Huntsville*

*Matt Jolly, USDA Forest Service, Rocky Mountain Research Station*

# Abstract

Effect of moisture content and heat flux type on ignition of foliage from 10 live fuels was examined over the course of a year using two apparatuses: a flat-flame burner coupled with a radiant panel and a Forced Ignition and flame Spread Test (FIST) apparatus. Results of the experiments were compared to predictions made with the GPyro/FDS coupled models. A radiant heat flux of 50 kW/m$^2$ was not sufficient to cause spontaneous ignition of the live samples. A pilot ignition or additional convective heating was needed for successful ignition. The dead fuel ignition model using fuel moisture did not work well in these fuels. Detailed 3D modeling of a live fuel particle showed that the fuel contained significant water at ignition which agreed with experimental data. Live fuel particles such as leaves and needles cannot be viewed as thermally-thin fuels.


# Project Background and Purpose

A majority of wildland surface fires occurs in dead fuel beds such as litter and cured grass. However, the majority of crown fires and other large fires in the U.S., and often the greatest acreages, burn in live fuels. Fires in wetlands and in tropical grasses also burn in fuel beds with a large component of live vegetation. In addition to the local effects of fuel moisture on combustion and heat transfer, the vaporized moisture also contributes to the water vapor in the fire plume. If combustion is complete, when the moisture content contained in living vegetation exceeds 56%, the majority of the plume's water vapor comes from vaporization of water and not the water produced by the combustion reaction (Byram 1959). Most living vegetation will burn at moisture contents exceeding 56%. We must understand the role of moisture in the pyrolysis, ignition, and combustion dynamics in these living fuels in order to understand better the fire dynamics of these large fires and lower intensity prescribed fires in these same fuel types.

Ignition of cellulose and wood has been studied extensively given that most homes are constructed of wood and contain numerous items that contain cellulose (paper, fabric, drywall, etc.). Much of the literature and current knowledge about ignition has been compiled (Babrauskas 2003). The basic steps leading to ignition of wood and cellulose are as follows. A fuel particle is subjected to heating by an external source. As the particle heats, it begins to break down chemically releasing gaseous products called pyrolyzates which are composed primarily of small molecular weight hydrocarbons, CO and $CO_2$. If conditions are favorable, the pyrolyzates mix with $O_2$ and when the mixture reaches a critical composition and temperature, the pyrolyzates oxidize and a flame is formed. This is generally defined as ignition; however, this brief description lacks many details.

In order to determine ignition properties of materials, a variety of techniques has been devised, modeled, and evaluated. These techniques can be separated into two broad categories: those based on thermal radiation and those based on convective heating. Thermal radiation techniques provide a heat flux that causes pyrolysis. Ignition of the pyrolyzates is then achieved by either an external source such as a spark or flame (piloted ignition) or through autoignition. Convective heating techniques place a sample in a hot environment or blow hot gases over the sample which results in pyrolysis and ignition through autoignition. In the chapter on ignition of solids (Chapter 7), Babrauskas (2003) presents comprehensive theories and equations developed from first principles for ignition by thermal radiation and by convective heating; however, solution of these equations requires significant computational effort. He notes that even though ignition of most solids is a gas-phase event, the details of gas-phase ignition have not been studied extensively. Engineering solutions to the theories have been devised for thermally-thick and thermally-thin materials. In the context of wildland fuels, fine fuels have been thought of as thermally-thin (no temperature gradient within the fuel particle when heated) and most other fuels are thermally-thick (temperature gradient within the fuel particle).

It is currently unclear whether foliage and small branches < 0.63 cm diameter of live vegetation are thermally-thin or thermally-thick. Albini (1980) in his theoretical model to generate the gaseous fuel for the spreading flame in wildland fuels suggested that the foliage of shrubs and trees was thermally-thin. Moisture has been observed to be still present in small leaves even as the edges of the leaf are igniting (Fletcher *et al.* 2007). The fact that dry horizontal manzanita leaves (10% MC) ignited only on the edges in the hot convective environment of the flat flame burner (FFB) could be due to the flow of the gases around the leaf sample or because the leaf may be thermally thick. The recent work of Finney et al (2010) in deep, vertical fuel beds of wood excelsior suggested that flame contact was necessary for ignition of these fuel particles. Bartoli et al (2011) studied ignition of dead pine needles in the Fire Propagation Apparatus (a piloted ignition thermal radiation apparatus) and found that forced convection of ambient air retarded ignition of the needles by the dilution of pyrolysis gases and convective cooling. Autoignition was observed in some of the tests performed. While Susott (1982) found little difference in the pyrolysis behavior of several dried and ground live fuels, Liodakis et al (2002) found that ignition delay for ground and pelletized samples of five Mediterranean species was related to the amount of cellulose pyrolyzed between 320-370 °C. Susott (1982) also reported that most of the pyrolysis of cellulose, hemicellulose, and lignin occurs in the 300-400 °C range and Rogers et al (1986) identified the compounds associated with the strong peaks in the Susott (1982) thermal decomposition curves. The foliage from gallberry (*Ilex glabra* (L.) A. Gray) and ponderosa pine (*Pinus ponderosa* Lawson & C. Lawson) contained cutin which is common to the plant cuticle of many evergreen trees and shrubs.

Philpot (1970), using similar techniques as Susott (1982), found that mineral content also affected pyrolysis in several plants by affecting the temperature at which thermal decomposition occurred and the amount of material volatilized between 175 and 350 °C. The source of these conflicting results could be due to species, test method, or differences in sample preparation (pellets or ground material versus leaves and needles).

Forage analysis of common wildland shrubs provides estimates of structural carbohydrates (cellulose, hemicelluloses, and lignin). Neutral detergent fiber is composed of cellulose, hemicellulose, and lignin; acid detergent fiber is composed of cellulose and lignin. In 8 common chaparral species, cellulose and lignin content of leaves and small green branches ranged from 22 to 50%, and hemicellulose ranged from 10 to 22% (Narvaez *et al.* 2010). In big sagebrush (*Artemisia tridentata* Nutt.) hemicellulose was 13%, cellulose was 18%, and lignin was 13% (Nunez-Hernandez *et al.* 1989). The remainder of the dry mass (30 to 50%) is made up of non-structural carbohydrates which are often soluble in water or ethanol. In contrast, wood is composed of about 40-50% cellulose, 20-30% hemicelluloses, and 20-30% lignin (Sjöström 1993) and the nonstructural carbohydrates are a much smaller percentage, if present at all.

The objectives of the project were to 1) determine how heat fluxes produced by convection and thermal radiation, individually and together, influence mass loss in moist live fuels prior to ignition, 2) determine experimentally if thermal radiation alone is sufficient for ignition of live fuels or if an additional source of heat (coil, hot convection gases) is necessary to ignite the pyrolyzates, 3) determine through computer simulation of ignition if thermal radiation alone is sufficient or if an additional source of heat (hot convection gases from a flame) is necessary to ignite the pyrolyzates, 4) expand species tested in JFSP project 10-1-08-6 to include important shrub species, and 5) determine if results of the tests vary over the year as fuel moisture changes within living plants.

# Methods

Because live fuels are important in many fuel types across the U.S., 10 species of important live fuels were selected to be used in the testing work. We sampled lodgepole pine (*Pinus contorta* Douglas ex Loudon)[1], Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco), big sagebrush (*Artemisia tridentata* Nutt.), Gambel oak (*Quercus gambelii* Nutt.), chamise (*Adenostoma fasciculatum* Hook. & Arn.), hoaryleaf ceanothus (*Ceanothus crassifolius* Torr.), Eastwood's manzanita (*Arctostaphylos glandulosa*

[1] Botanical nomenclature source: USDA, NRCS. 2016. The PLANTS Database (http://plants.usda.gov, 28 January 2016). National Plant Data Team, Greensboro, NC 27401-4901 USA.

Eastw.*)*, fetterbush (*Lyonia lucida* (Lam.) K. Koch*)*, gallberry (*Ilex glabra* (L.) A. Gray*)*, and sand pine (*Pinus clausa* (Chapm. ex Engelm.) Vasey ex Sarg) (Table 1). Longleaf pine was originally proposed, but the needles were too long for the test apparatuses so sand pine was used instead. In order to test for the effects of seasonal differences in live fuel moisture on ignition success, samples were harvested monthly and shipped overnight to Missoula, MT and Provo, UT where they were stored in a refrigerator for up to 2 days to minimize moisture loss. Over the course of two years, the 10 species were tested monthly. The original intent was to test all evergreen plants over 12 months and Gambel oak (deciduous) when live foliage was present. Winter weather precluded access to the lodgepole pine sample site in Montana; the final collection schedule can be found in Table 2.

Two test apparatuses were used to examine the effects of radiation and convection on pyrolysis and ignition. At BYU in Provo, UT, a flat flame burner (FFB) coupled with a radiant panel was used to examine the individual and combined effects of the heating modes (Figure 1). This apparatus has been used extensively to examine combustion characteristics of live fuels (Engstrom *et al.* 2004; Pickett *et al.* 2010). At the USDA Forest Service Fire Laboratory in Missoula, MT, a Forced Ignition and Flame Spread Test (FIST) (McAllister *et al.* 2010, 2012) was used to examine effects of radiant heating on piloted ignition (Figure 2). The two devices provided different exposures to the samples. Radiant fluxes were comparable between the two devices: FIST panel irradiance = 50 kW $m^{-2}$, FFB measured radiant flux = 50 to 66 kW $m^{-2}$ for leaf and needle samples, respectively. Calculated convective fluxes for leaf and needle samples in the FFB = 75 and 137 kW $m^{-2}$ producing combined fluxes of 125 and 203 kW $m^{-2}$, respectively. While we originally had plans to coordinate this project with JFSP project 10-1-08-6 (Jolly and Butler 2013) by providing additional plant species to be analyzed chemically using forage analysis and heated in the Flame Quenching Apparatus, unforeseen difficulties precluded that from happening so only results for the FFB and FIST are presented here.

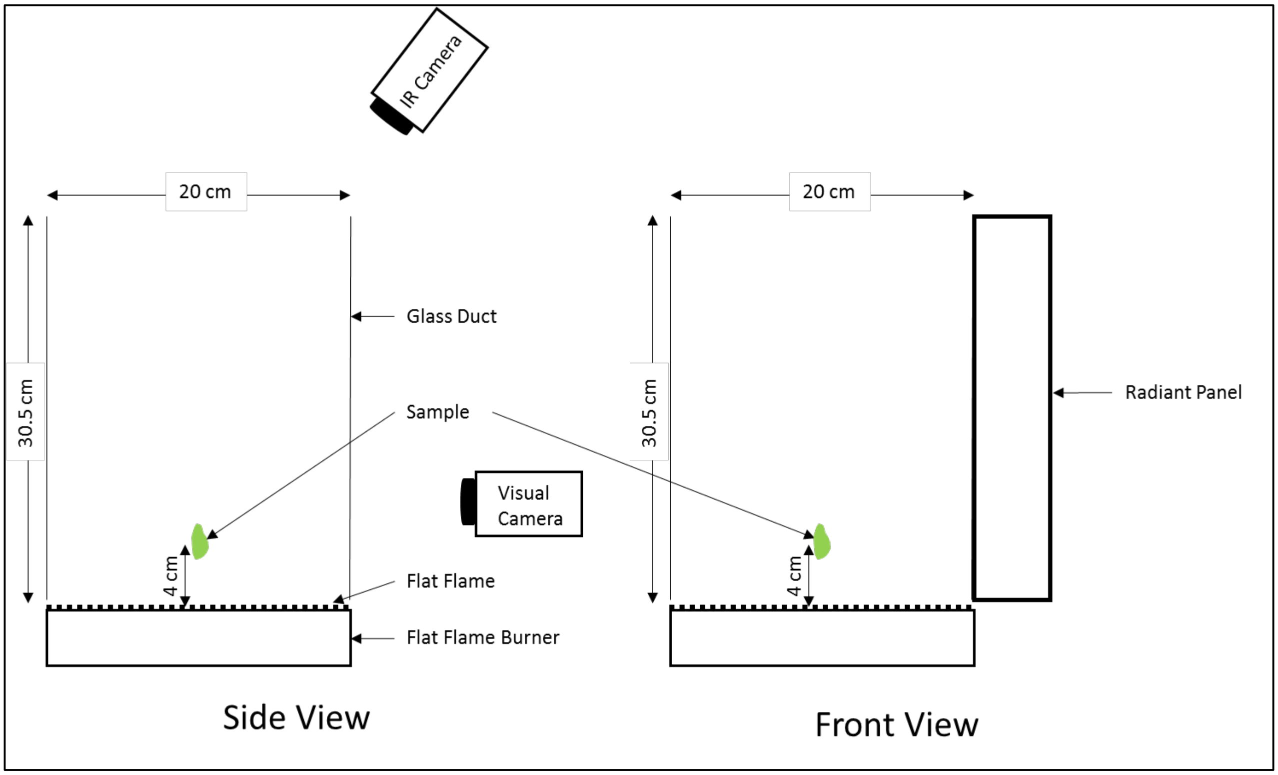



Figure 1. Experimental apparatus: flat flame burner, radiant panel, IR camera, video camera, glass cage to prevent ambient air entrainment, sample location, mass balance and sample holding rod. Post-flame gases are 1000 °C and 10 mol% $O_2$.

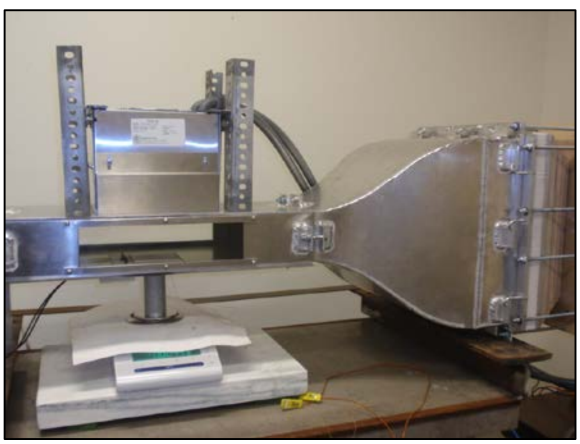
**1.** 

Figure 2. Forced Ignition and Flame Spread Test apparatus. All tests were performed with a fixed airflow velocity of 1 m $s^{-1}$ and an irradiance of 50 kW $m^{-2}$. Forced air flow from right to left and coil for piloted ignition of pyrolyzates to left of sample holder under radiant panel.

Table 1. Species, sampling location and fuel element description used in the FFB and FIST apparatuses.

| Species | Year | Locale[2] | Fuel Element Description | |
|---|---|---|---|---|
| | | | FFB | FIST |
| Chamise | 1 | R | 4 cm branch tip with needles attached (diameter < 2mm) | 4 cm branch tip with needles attached (diameter < 2mm, mass = 2 g) |
| Big sagebrush | 1 | P | 4 cm branch tip with leaves attached | 4 cm branch tip with leaves attached, mass = 2 g |
| Lodgepole pine | 1 | M | 2 cm branch tip with needles attached (diameter < 5mm) | Healthy needles, mass = 2 g |
| Manzanita | 2 | R | Single leaf | Healthy leaves, mass = 2 g |
| Ceanothus | 2 | R | Single leaf | Healthy leaves, mass = 2 g |
| Douglas-fir | 2 | M | 2 cm branch tip with needles attached (diameter < 3mm) | Healthy needles, mass = 2 g |
| Gambel oak | 2 | P | Single leaf | Healthy leaves, mass = 0.5 g |
| Gallberry | 2 | C | Single leaf | Healthy leaves, mass = 1 g |
| Fetterbush | 2 | C | Single leaf | Healthy leaves, mass = 0.8 g |
| Sand pine | 2 | C | 2 cm branch tip with needles attached (diameter < 3mm) | Healthy needles, mass = 2 g |

1. C=Crestview, FL; M = Missoula, MT; P=Provo, UT; R=Riverside, CA

Table 2. Species and sample harvest dates

| Species[1] | Year | Locale[2] | Collection Month |
|---|---|---|---|
| Chamise | 1 | R | Jun, Jul, Aug, Sep, Oct, Nov, Dec 2012, Jan, Feb, Mar, Apr, May 2013 |
| Big sagebrush | 1 | P | Same as chamise |
| Lodgepole pine | 1 | M | Same as chamise except no samples in Dec 2012, Jan 2013, Feb 2013 |
| Manzanita | 2 | R | Jun, Jul, Aug, Sep, Oct, Nov, Dec 2013, Jan, Feb, Mar, Apr, May 2014 |
| Ceanothus | 2 | R | Same as manzanita |
| Douglas-fir | 2 | M | Same as manzanita |
| Gambel oak | 2 | P | Jun, Jul, Aug, Sep, Oct, Nov 2013, Mar, Apr, May 2014 |
| Gallberry | 2 | C | Same as manzanita |
| Fetterbush | 2 | C | Same as manzanita |
| Sand pine | 2 | C | Same as manzanita |

In addition to gathering meteorological and site data, extensive measurements were performed on the samples to characterize them before testing (moisture content, leaf size). During testing, sample mass was recorded continuously and video imagery was collected. From these data, variables were extracted such as time to ignition, mass loss rate, flame length, etc. Each month, 25 replicates for each species were burned in the FFB apparatus and at Brigham Young University (BYU). Average moisture content for each species was measured by drying several fuel elements in a MAX1000 Computrac[2] Moisture

[2] The use of trade names is provided for reader information and does not imply endorsement by the U.S. Department of Agriculture of any product or service.

Analyzer at 95°C. Moisture content (MC) was reported on a dry mass basis (ASTM International 2007). Relative moisture content (RMC) was measured by comparing the water weight in a fresh sample to the water weight in the turgid sample (Jolly *et al.* 2014). Size, shape, and mass were recorded for each sample shortly before the burn experiments were conducted. Ether extractives were measured for manzanita, Douglas-fir, Gambel oak and fetterbush following the Crude Fat Extraction Method 4.5.05 (Horwitz and AOAC International 2011). Because of the time required to measure ether extractives, only two replicates were performed each month for the four species previously mentioned. Volatiles content and ash content were measured using ASTM procedures for volatiles content and ash; fixed carbon was calculated by difference. Three replicates were performed each month on each of the Year 2 species (Table 1). To avoid fuel-bed and particle shape effects (D. Prince and A. Lewis, 2013 personal communications), needle species samples were cut to nominally 5 mm lengths while broad leaf species samples were hole-punched. Approximately 0.35 g of sample was used for each replicate.

Video images, mass and temperature data were collected using the FFB apparatus shown earlier in Figure 1. Samples were individually weighed and placed within the apparatus. The water-cooled FFB produced exhaust gases at 1000°C and 10 mol% oxygen that flowed past the sample suspended on a holding rod using an alligator clip. The holding rod was connected to a Mettler Toledo XS204 Cantilever mass balance. Mass data were continuously measured using National Instruments Labview 8.6 Software. Mass data were post-processed to account for the buoyant force exerted on the sample and holding rod by the FFB exhaust gases. A glass cage surrounding the sample prevented ambient air from being entrained in the FFB exhaust gases. An Omega K-type thermocouple (0.013 mm diameter, 0.05 s response time) was used to measure the gas temperature. Smith (2005) corrected these temperature measurements for thermocouple radiation losses and found the losses to be small at these temperatures. Video data were captured using a Panasonic SDR S50 Camcorder and were post-processed to extract the flame characteristics listed in Table 3.

In the FIST apparatus, the sample holder, measuring 9 cm by 9 cm with a depth of 2.5 cm, is a thin, lightweight aluminum box lined with Cotronics-brand ceramic paper and a 1.27 cm thick Cotronics-brand ceramic board on the bottom. The sample holder sits on top of the mass balance with the upper surface of the sample flush with the bottom of the tunnel. The sample was heated from above using an infrared heater capable of producing a uniform heat flux of 0 to 50 kW/m$^2$ over the sample surface. Ignition was by means of a coiled Kanthal wire kept above 1000°C, located a fixed distance downstream that was chosen to remove the igniter location as a potential variable in the experiments. The time to ignition was recorded visually as the time from the initiation of heating until a flame was sustained over the surface of the sample. The mass of the sample was recorded at 5 Hz. To obtain the mass loss rate at ignition, a locally weighted scatterplot smoothing (LOESS) regression was performed. The slope of the regression at the moment of ignition was taken as the mass loss rate at ignition. No attempt was made to calculate the exposed surface area to find the mass flux. All tests were repeated three times to provide an estimate of the experimental variability. To mimic the wind and high heat fluxes associated with a wildfire, all tests were performed with a fixed airflow velocity of 1 m/s and an irradiance of 50 kW/m$^2$. Though wildfires typically produce radiant heat fluxes in the range of 50 to 250 kW/m$^2$ (Butler *et al.* 2004; Silvani *et al.* 2009), an irradiance of 50 kW/m$^2$ was chosen for these tests because it is the maximum attainable with this apparatus.

Table 3. Flame characteristics derived from video and IR data.

| Variable | Description |
|---|---|
| Ignition Time (s) | Time when a visible, sustained flame appears |
| Burnout Time (s) | Time when the flame disappears |
| Maximum Flame Height (cm) | Height of tallest flame during a run |
| Time to Max Flame Height (s) | Time when tallest flame occurs |
| Ignition Temperature (°C) | Average surface temperature at the time of ignition |
| Maximum Ignition Temperature (°C) | Maximum surface temperature at the time of ignition |

In the FIST apparatus, lodgepole pine, Douglas-fir, and sand pine were tested using needles pulled from the branch, only taking healthy-looking needles. For both sagebrush and chamise, 4 cm-long branch tips were used. Gambel oak, manzanita, ceanothus, fetterbush, and gallberry were tested using only healthy-looking leaves pulled from the branch. Because of the length of the needles and leaves, no cutting was necessary to fit them into the sample holder. For lodgepole pine, Douglas-fir, and manzanita, the new growth was easily identifiable so the old and new growth for these species was tested separately until no difference was seen either in the ignition time or moisture content. Sample size was 2g for most species tested and was weighed within 0.05 g. Due to the size of the leaves, the sample sizes of the Gambel oak, fetterbush, and gallberry leaves differed and were 0.5 g, 0.8 g, and 1 g, respectively. The sample size was chosen so that all species of fuel could lie in the sample holder as a single layer thus eliminating the potential problem of shading of portions of the sample from the heat flux (Weise *et al.* 2005). All samples were coated in a thin layer of graphite powder to increase the sample absorptivity. It has been shown that vegetation shows spectral absorptivity, particularly for wavelengths below 2.8μm (Monod *et al.* 2009; Boulet *et al.* 2011), and the wavelength of the radiant energy from the quartz lamps is 0.955 μm at 50 kW $m^{-2}$. When placed into the sample holder, sheets of ceramic paper (also darkened) were used to support the fuels such that they were flush with the surface of the holder and all samples were arranged to cover as much surface area as possible (Figure 3).

Figure 3. Lodgepole pine needles (left) and fetterbush leaves (right) in sample holder.

## 2. Modeling of Experiments

The burning of an isolated leaf-like element was modeled in a series of studies and the model results were validated against previous experimental results including burning experiments performed on manzanita leaves at BYU. The relative importance of heating modes and the effect of fuel moisture content on pyrolysis and combustion of live fuels were explored in several stages. Four different configurations of a single fuel element and the heating modes were modelled. In the initial study (Yashwanth *et al.* 2015) a simplified configuration (Figure 4a), a one-dimensional slab, was subjected to various modes of heating, using a general pyrolysis model, Gpyro (Lautenberger 2007). The heating mode was varied by applying different convective and/or radiative, time-dependent heat flux boundary conditions on one side of the slab while keeping the other side insulated. Initially, the fuel was treated as chemically inactive and following this it was presumed to decompose via a single-stage kinetic model involving two solid phase species coupled with one gas phase species. Dry wood properties were used for the fuel. This single-step model approximation for wood degradation was validated with experimental results (Ohlemiller *et al.* 1987). Critical time was defined as the time when the temperature of the heated side reached a critical value at which the ignition was assumed to take place.

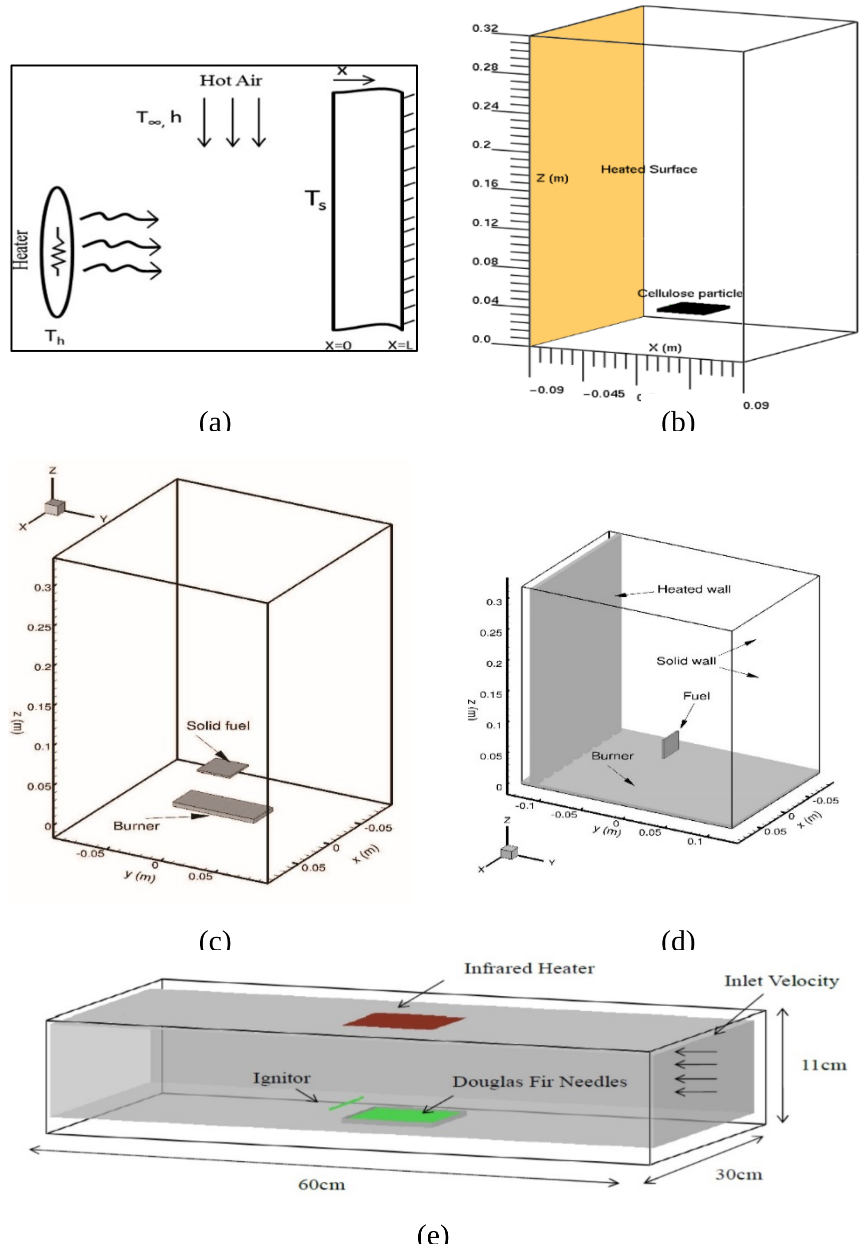



Figure 4. Configuration of experiments used to determine effects of convection and radiation on ignition of live fuels. Configuration for BYU flat flame burner: (a) 1D Gpyro-FDS configuration for radiant and convective heating, Gpyro3D-FDS configurations for radiant (b), convective (c), and radiant with convective (d) heat fluxes. (e) WFDS configuration for FS FIST apparatus for radiant flux in cross-flow with piloted ignition.

We conducted three modeling studies in full three dimensional configurations via Gpyro3D-FDS, while making improvements in the coupling of these two models. First, we investigated the effects of thermal radiation and moisture content (Figure 4b) on the pyrolysis and gas-phase ignition of a solid fuel element containing high moisture content (Yashwanth *et al.* 2016). The solid fuel had dimensions of a typical manzanita leaf, modeled as thin cellulose, subjected to radiative heating on one side. We incorporated a five-step extended Broido-Shafizadeh reaction model for thermal degradation, moisture evaporation, and pyrolysis of cellulose in Gpyro3D. The solid-phase model was successfully validated against published data. Ignition of the fuel element at three initial moisture contents (5%, 40%, or 80%) exposed to a 1500 K radiant source was simulated. We next employed an improved chemistry model that included hemicellulose and lignin along with cellulose and moisture in the solid fuel, and a 12-step kinetic mechanism to account for the multi-component decomposition process in detail. The solid fuel was oriented horizontally (Figure 4c) to resemble the individual manzanita leaf experiments using convective heating (Pickett *et al.* 2010). In the final study of the BYU experiments, the effect of both convection and radiation (Figure 4d) was investigated with the fuel element oriented vertically (Yashwanth 2015).

A study using WFDS to model experimental results from the FIST apparatus examined radiant heating in cross flow (Figure 4e) with piloted ignition (McAllister *et al.* 2012). The walls of the wind tunnel were computationally modeled as inert walls maintained at an ambient temperature of 293 K. Velocity inlet boundary condition was applied to the right entrance of the wind tunnel establishing a laminar airflow with a velocity of 1m/s through the wind tunnel. The fuel, Douglas-fir needles, was approximated as fixed, thermally thin fuel elements uniformly distributed within the sample holder. The infrared heater located above the fuel was modeled as a 9cm x 9cm surface maintained at a temperature of 1050 K. The ignitor was represented by non-reacting fuel particles held at a constant temperature of 1000 K throughout the simulation. The fuel elements underwent degradation based on Arrhenius-type laws. The pyrolyzate gases were assumed $CH_4$. Fuel moisture content was varied from 90 to 130% and ignition times, mass loss and heat release rates were calculated.

## 3. Key Findings (Not all have been subjected to peer review)

Radiant fluxes of 50 to 70 kW m$^{-2}$ alone were not sufficient to ignite the single leaves or clusters of leaves. This was demonstrated in both experiments and modeling. An additional source of energy (such as the coil in the FIST or the hot convective gases in the FFB) was necessary for successful ignition of live fuel samples. These results confirm earlier assumptions and observations of fire spread in wildland fuels (Fons 1946; Batchelder and Hirt 1966 p. 19) and the more recent work in deep fuel beds and single particles (Finney *et al.* 2010; Cohen 2015).

In the modeling experiments, lower moisture content resulted in earlier onset of pyrolysis and ignition, resulting in higher solid and gas phase temperatures. Local moisture evaporation and temperature rise were observed and a significant amount of moisture remained in the samples during ignition for both the horizontally and vertically-oriented leaves (Figure 4 b, c, d). Evaporation occurred at a higher rate near the leading, lateral and trailing edge of the solid fuel compared to the region located at the center. These results agree with the experimental results first reported by Fletcher et al (2007) and further confirmed by the experimental work in this study. The numerical results suggest that moisture content not only affected the process of pyrolysis, but also influenced the ignition and gas phase combustion of the solid fuel by acting as a diluent as has been suggested previously (Fons 1946; Albini 1980; Catchpole and Catchpole 1991) and demonstrated recently in a modeling study (Ferguson *et al.* 2013). One implication of this result is that the thermally-thin assumption (temperature is uniform) does not apply to living fine fuel particles contrary to what is often assumed (Albini 1980; Catchpole and Catchpole 1991) which will require a different approach to modeling in comparison to dead fine fuel particles.

The measured radiant fluxes (50 to 70 kW $m^{-2}$) were generally smaller than the estimated convective fluxes in the BYU apparatus for leaf species (75 kW $m^{-2}$ for manzanita) and much lower for needle species (~140 kW $m^{-2}$ for a Douglas-fir needle). This makes comparison of the effects of radiation versus convection in this experiment not possible. From the perspective of the solid fuel, the heating mode does not appear to matter—it is only the amount of energy absorbed and the resulting solid temperature that matters. This is what influences pyrolysis.

Live fuels cannot be considered as simply wet dead fuels. Ignition and burning behavior cannot be described using single-parameter correlations similar to those used for dead fuels. While time to ignition typically increases in dead fuels as moisture content increases, this was not observed in the majority of the live fuels in this study. However, moisture content, sample mass, apparent density (broad-leaf species), surface area (broad-leaf), sample width (needle species) and stem diameter (needle) were identified as the most important predictors of ignition behavior. Due to the potential physical and chemical changes that live fuels undergo, moisture content alone is not a particularly useful descriptor of live fuels when discussing ignition behavior.

Modeling results indicate that it is important to include chemical reactions for pyrolysis and ignition or significant prediction errors will result. Inclusion of water in the reaction scheme, both in liquid and vapor form, improves model predictions and increases complexity of calculations.

The ignition time calculated by the WFDS modeling of the FIST experiments increased almost linearly with an increase in moisture content. The ignition times calculated by modeling were in good agreement with the ignition times measured in experiments for moisture content between 100 to 120%. However, the modeling ignition times differ from measured ignition times by about 2-4 s for the lower moisture cases. For moisture content of 130%, an appreciable difference was seen between numerical and experimental ignition times. The cause for this is currently unknown.

Leaf species experienced a significant increase in burning rate when convection and radiation were used together in comparison to convection alone. Needle species showed no significant difference between convection-only and convection combined with radiation reaffirming the importance leaf shape on heat transfer and ignition. Because of the differences in heat flux due to leaf shape, there is likely no practical difference between heating modes from the perspective of the solid— only the amount of energy absorbed and the resulting solid temperature that matter. This remains to be verified.

## 4. Management Implications

In the operational fire behavior systems in the U.S. based on the Rothermel model (Rothermel 1972), ignition is assumed to be a function of moisture content only. This research has demonstrated that the assumption is invalid for live fuels. All operational fuel models used for fire behavior prediction contain a dead fuel component which is necessary in order for the implementations of the Rothermel model to predict a non-zero rate of spread. While the model can be made to predict rate of spread in live fuels by increasing the moisture of extinction (Weise *et al.* 2015), this is not something that will be typically done by a field user of the model. The management implications of the present work are that the Rothermel model may not work particularly well in fuel types dominated by live vegetation and that improvement will not be made until significant changes are made to the model's formulation.

In the 1978 and 1988 versions of the National Fire Danger Rating System, ignition is recognized in the calculation of the Ignition Component (IC) (Bradshaw *et al.* 1984). Schroeder (Schroeder 1969) calculated the probability that an ember would start a fire after landing on receptive fuels. This calculation is made for a fine fuel particle which is typically defined to be a dead fuel particle. The results of the present research provide information that could be used to reformulate these calculations for those situations where an ember may land on a live fuel particle such as in prostrate vegetation. As highlighted in the IMRT Task Force report on monitoring live fuel moisture following the South Canyon Fire (Cohen *et al.* 1995; Weise and Saveland 1996), while appropriate use of live fuel moisture in fire danger and fire behavior prediction was not possible because of a lack of knowledge on the role of live fuel moisture, there was still value in tracking live fuel moisture over the year because it did provide a relative measure of fire danger in systems dominated by live fuels. While fuel moisture content has been shown to not be a reliable predictor of ignition in live fuels in the present study, monitoring the annual trends in live fuel moisture can still provide a relative measure of fire danger in these ecosystems until the details of how live fuels ignite and burn is well-understood.

## 5. Relationship to other recent findings

This study expanded the amount of information available on live fuel ignition that complements ignition work being performed at the FS Missoula Fire Sciences Lab and the Forest Products Lab. Other scientists are examining ignition and burning characteristics of live vegetation using the cone calorimeter and the FM Global Fire Propagation Apparatus as well as other devices. These data will contribute to an increased understanding worldwide of how live fuels ignite and the data will be available for use by other scientists through the Forest Service's Research Data Archive by 2017.

## 6. Future work

The team who has worked on this project, with additional members, has successfully secured $2M in funding from the DOD SERDP program to measure and model pyrolysis in live southern fuels at the bench, wind tunnel, and field-scale from 2016-2020. The knowledge gained, experience developed, and numerical models formulated during this project were instrumental in securing this grant and will be used and modified as needed in the course of this future work.

## 7. Deliverables

| Deliverable Type | Citation | Orig./Add. (O/A) | Delivery Dates |
|---|---|---|---|
| Poster presentation | Lansinger, V., J. R. Gallacher, T. H. Fletcher. 2013. Seasonal Effects on the Ignition Characteristics of Live Fuels in Wildfires. American Institute of Chemical Engineers (AIChE) Annual Meeting, November 3-8, 2013, San Francisco, CA. | O | Nov 2013 |
| Oral presentation | Gallacher, J. R., Lansinger, V., Hansen, S., Jack, D., Weise, D.R., Fletcher, T.H. 2014. Effects of season and heating mode on ignition and burning behavior of three species of live fuel measured in a flat flame burner system. Paper 14S-45, Spring Technical Meeting, Western States Section, Combustion Institute, Mar. 25-26, 2014, California Institute of Technology, Pasadena, CA. 14 p. | O | Mar 2014 |
| Oral presentation | S. McAllister and D.R. Weise. 2014. Effects of season on ignition of three species of live wildland fuels using the FIST apparatus. Spring Technical Meeting, Western States | O | Mar 2014 |

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| | Section, Combustion Institute, Mar. 25-26, 2014, California Institute of Technology, Pasadena, CA. | | |
| Oral presentation | B. L. Yashwanth, B. Shotorban, S. Mahalingam, D. R. Weise. 2014. A numerical investigation of the effect of moisture content on pyrolysis and combustion of live fuels. Spring Technical Meeting, Central States Section, Combustion Institute, Mar. 16-18, 2014, Tulsa, OK. | O | Mar 2014 |
| Ph.D. dissertation | Gallacher, Jonathan. In process. Application of measured seasonal variations of the ignition behavior of live fuels and a fundamental 3-D shrub generation method to a semi-empirical fire spread model. Brigham Young University, College of Engineering, Department of Chemical Engineering. | O | Anticipated Mar 2016 |
| Ph.D. dissertation | Yashwanth, Bangalore. 2015. Effects of heating modes and moisture content on ignition and pyrolysis of live fuels. University of Alabama in Huntsville, College of Engineering, Department of Aerospace and Mechanical Engineering. 157 p. | O | Aug 2015 |
| Refereed publication | Yashwanth B.L., Shotorban B., Mahalingam S., Weise D.R. 2015. An investigation of the influence of heating modes on ignition and pyrolysis of woody wildland fuel. Combustion Science and Technology, 187, 780-796. doi: 10.1080/00102202.2014.973948 | O | Mar 2015 |
| Refereed publication | Gallacher, J. R., Lansinger, V., Smith, S., Doll, A., Weise, D.R., Fletcher, T.H. (in review). The ignition and burning of live fuels studied using natural variation in fuel characteristics. Submitted to Combustion Science and Technology | O | Anticipated 2016 |
| Poster presentation | Thomas H. Fletcher, Jonathan R. Gallacher, Victoria Lansinger, Sydney Hansen, David R. Weise. 2014. Effects of Season and Heating Model on Ignition and Burning Behavior of Ten Live Fuel Species Measured in a Flat-flame Burner System. 35th Symposium (International) on Combustion, 4-8 August 2014, San Francisco, CA. Poster presentation W4P070. | A | Aug 2014 |
| Poster presentation | Sara McAllister, David Weise. 2014. Effects of Season on Ignition of Live Wildland Fuels Using the FIST Apparatus. 35th Symposium (International) on Combustion, 4-8 August 2014, San Francisco, CA. Poster presentation W4P071. | A | Aug 2014 |
| Oral presentation | Yashwanth, B. L., Gallacher, J. R., Shotorban, B., Mahalingam, S., Fletcher, T. H., Weise, D. R. 2015. Experimental and numerical investigation of the effect of heating modes and moisture content on pyrolysis and ignition of live fuels. 9th US National Meeting, May 17-20, 2015, Cincinnati, Ohio. Pittsburgh, PA: Central States Section of the Combustion Institute. Oral presentation 1D06. | A | May 2015 |
| Oral presentation | McAllister, S., Weise, D. 2015. Effects of season on ignition of live wildland fuels using the FIST apparatus. 9th US National Meeting, May 17-20, 2015, Cincinnati, Ohio. | A | May 2015 |

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| | Pittsburgh, PA: Central States Section of the Combustion Institute. Oral presentation 1D08. | | |
| Oral presentation | Shen, C., Gallacher, J.R., Prince, D.R., Fletcher, T.H., Weise, D.R. 2015. Experiments and modeling of fire spread in shrubs in a wind tunnel. 9th US National Meeting, May 17-20, 2015, Cincinnati, Ohio. Pittsburgh, PA: Central States Section of the Combustion Institute. Oral presentation 1D11. | A | May 2015 |
| Oral presentation | Gallacher, J. R., Lansinger, V., Hansen, S., Weise, D.R., Fletcher, T.H. 2015. Effects of season and heating model on ignition and burning behavior of ten species of live fuel measured in a flat-flame burner system. 9th US National Meeting, May17-20, 2015, Cincinnati, Ohio. Pittsburgh, PA: Central States Section of the Combustion Institute. Oral presentation 1D15. | A | May 2015 |
| Oral presentation | B.L. Yashwanth, B. Shotorban, S. Mahalingam. 2015. Understanding the role of moisture in live fuels subject to pyrolysis and ignition through radiation heat transfer. 9th US National Meeting, May 17-20, 2015, Cincinnati, Ohio. Pittsburgh, PA: Central States Section of the Combustion Institute. Oral presentation 1D05. | A | May 2015 |
| Oral presentation | B.L. Yashwanth, B. Shotorban, S. Mahalingam. 2015. A computational investigation of the role of moisture in live fuels subject to pyrolysis and ignition through convective heat transfer. 9th US National Meeting, May 17-20, 2015, Cincinnati, Ohio. Pittsburgh, PA: Central States Section of the Combustion Institute. Oral presentation 1D18. | A | May 2015 |
| Oral presentation | McAllister, S., Weise, D. 2015. Effects of season on ignition of live wildland fuels using the FIST apparatus. 9th US National Meeting, May 17-20, 2015, Cincinnati, Ohio. Pittsburgh, PA: Central States Section of the Combustion Institute. Oral presentation 1D08. | A | May 2015 |
| Oral presentation | Shen, C., Gallacher, J.R., Prince, D.R., Fletcher, T.H., Weise, D.R. 2015. Experiments and modeling of fire spread in shrubs in a wind tunnel. 9th US National Meeting, May 17-20, 2015, Cincinnati, Ohio. Pittsburgh, PA: Central States Section of the Combustion Institute. Oral presentation 1D11. | A | May 2015 |
| Oral presentation | Gallacher, J. R., Lansinger, V., Hansen, S., Weise, D.R., Fletcher, T.H. 2015. Effects of season and heating model on ignition and burning behavior of ten species of live fuel measured in a flat-flame burner system. 9th US National Meeting, May17-20, 2015, Cincinnati, Ohio. Pittsburgh, PA: Central States Section of the Combustion Institute. Oral presentation 1D15. | A | May 2015 |
| Oral presentation | B.L. Yashwanth, B. Shotorban, S. Mahalingam. 2015. Understanding the role of moisture in live fuels subject to pyrolysis and ignition through radiation heat transfer. 9th US National Meeting, May 17-20, 2015, Cincinnati, Ohio. Pittsburgh, PA: Central States Section of the Combustion Institute | A | May 2015 |

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| | Institute. Oral presentation 1D05. | | |
| Oral presentation | B.L. Yashwanth, B. Shotorban, S. Mahalingam. 2015. A computational investigation of the role of moisture in live fuels subject to pyrolysis and ignition through convective heat transfer. 9th US National Meeting, May 17-20, 2015, Cincinnati, Ohio. Pittsburgh, PA: Central States Section of the Combustion Institute. Oral presentation 1D18. | A | May 2015 |
| Oral presentation | McAllister, S., Weise, D. 2015. Effects of season on ignition of live wildland fuels using the FIST apparatus. 9th Mediterranean Combustion Symposium, June 7-11, 2015, Rhodes, Greece. | A | June 2015 |
| Oral presentation | Gallacher, J. R., V. Lansinger, S. Smith, A. Doll, D. R. Weise and T. H. Fletcher. 2015. The Ignition and Burning of Live Fuels Studied Using Natural Variation in Fuel Characteristics, Western States Section of the Combustion Institute, Brigham Young University, Provo, UT (October 5-6, 2015). | A | Oct 2015 |
| Oral presentation | Gallacher, J. R., V. Lansinger, S. Hansen, S. Smith, D. R. Weise and T. H. Fletcher. 2015. The Effect of Heating Mode on the Ignition and Burning Behavior of 10 Live Shrub Fuels, Western States Section of the Combustion Institute, Brigham Young University, Provo, UT (October 5-6, 2015). | A | Oct 2015 |
| Oral presentation | Smith, S. A., J. R. Gallacher, and T. H. Fletcher. Effects of Season and Heating Mode on Ignition and Burning Behavior of Ten Species of Live Fuel Measured in a Flat-flame Burner System, Undergraduate research session of the Annual AIChE Meeting, Salt Lake City, UT (November 9, 2015). | A | Nov 2015 |
| Oral presentation | S. Mahalingam, B.L. Yashwanth, B. Shotorban. 2015. A full-physics computational study of pyrolysis and ignition of a leaf-like fuel element exposed to convective heating. 6th International Fire Ecology and Management Congress, San Antonio, TX (Nov 16-20, 2015). | A | Nov 2015 |
| Oral presentation | Gallacher, J. R., V. Lansinger, S. Smith, A. Doll, D. R. Weise, and T. H. Fletcher. 2015. The Ignition and Burning of Live Fuels Studied Using Natural Variation in Fuel Characteristics. 6th International Fire Ecology and Management Congress, San Antonio, TX (Nov 16-20, 2015). | A | Nov 2015 |
| Oral presentation | Gallacher, J. R., V. Lansinger, S. Hansen, S. Smith, D. R. Weise, and T. H. Fletcher. 2015. The Effect of Heating Mode on the Ignition and Burning Behavior of 10 Live Shrub Fuels, 6th International Fire Ecology and Management Congress, San Antonio, TX (Nov 16-20, 2015). | A | Nov 2015 |
| Refereed publication | Yashwanth B.L., Shotorban B., Mahalingam S., Lautenberger, C.W., Weise D.R. 2015. A numerical investigation of the effect of radiation and moisture content on pyrolysis and combustion of live fuels. Combustion and | A | 2016 |

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| | Flame, 163, 301-316, doi:10.1016/j.combustflame.2015.10.006. | | |
| Refereed publication | Gallacher, J.R., Lansinger, V., Hansen, S., Ellsworth, T., Weise, D.R., Fletcher, T.H. (in review). Physical properties and dimensions of 10 live shrub and conifer fuels to predict fire behavior. | A | Approved for journal submittal or FS pub. |
| Refereed publication | Gallacher, J. R. Lansinger, V., Hansen, S., Smith, S., Weise, D.R., Fletcher, T.H. (in review). The effect of heating mode on the ignition and burning behavior of 10 live shrub fuels. Submitted to Combustion Science and Technology. | A | Anticipated 2016 |
| Refereed publication | Yashwanth, B.L., Shotorban, B., and Mahalingam, S. (in review). Pyrolysis and combustion characteristics of leaf-like fuel under convection and radiation heating. Proceedings of the Combustion Institute | A | Submitted to conference. |
| Refereed publication | Yashwanth, B.L., Shotorban, B., and Mahalingam, S. (in preparation). A computational study of convective heating of a leaf-like fuel element. | A | Target journal is Combustion and Flame |
| Refereed publication | McAllister, S., Weise, D.R. (in review). Effects of season on ignition of live wildland fuels using the FIST apparatus. | A | Combustion Science and Technology is a potential outlet |
| Conference paper | Gallacher, J. R., Lansinger, V., Hansen, S., Jack, D., Weise, D.R., Fletcher, T.H. 2014. Effects of season and heating mode on ignition and burning behavior of three species of live fuel measured in a flat flame burner system. Paper 14S-45, Spring Technical Meeting, Western States Section, Combustion Institute, Mar. 25-26, 2014, California Institute of Technology, Pasadena, CA. 14 p. | A | Mar 2014, distributed to conference attendees only |
| Conference paper | S. McAllister and D.R. Weise. 2014. Effects of season on ignition of three species of live wildland fuels using the FIST apparatus. Spring Technical Meeting, Western States Section, Combustion Institute, Mar. 25-26, 2014, California Institute of Technology, Pasadena, CA. | A | Mar 2014, distributed to conference attendees only |
| Conference paper | Yashwanth, B.L. Shotorban, B. Mahalingam, S. Weise, D.R. 2014. A numerical investigation of the effect of moisture content on pyrolysis and combustion of live fuels. Spring Technical Meeting, Central States Section, Combustion Institute, Mar. 16-18, 2014, Tulsa, OK. | A | Mar 2014, distributed to conference attendees only |
| Conference paper | Yashwanth, B.L., Gallacher, J. R., Shotorban, B., Mahalingam, S., Fletcher, T. H., Weise, D. R. 2015. Experimental and numerical investigation of the effect of heating modes and moisture content on pyrolysis and ignition of live fuels. 9th US National Meeting, May 17-20, 2015, Cincinnati, Ohio. Pittsburgh, PA: Central States Section of the Combustion Institute. | A | May 2015, distributed to conference attendees only |

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| Conference paper | Yashwanth, B.L., Shotorban, B., Mahalingam. S. 2015. Understanding the role of moisture in live fuels subject to pyrolysis and ignition through radiation heat transfer. 9th US National Meeting, May 17-20, 2015, Cincinnati, Ohio. Pittsburgh, PA: Central States Section of the Combustion Institute. | A | May 2015, distributed to conference attendees only |
| Conference paper | Yashwanth, B.L. Shotorban, B. Mahalingam, S. 2015. A computational investigation of the role of moisture in live fuels subject to pyrolysis and ignition through convective heat transfer. 9th US National Meeting, May 17-20, 2015, Cincinnati, Ohio. Pittsburgh, PA: Central States Section of the Combustion Institute. | A | May 2015, distributed to conference attendees only |
| Conference paper | McAllister, S., Weise, D. 2015. Effects of season on ignition of live wildland fuels using the FIST apparatus. 9th US National Meeting, May 17-20, 2015, Cincinnati, Ohio. Pittsburgh, PA: Central States Section of the Combustion Institute. | A | May 2015, distributed to conference attendees only |
| Conference paper | Shen, C., Gallacher, J.R., Prince, D.R., Fletcher, T.H., Weise, D.R. 2015. Experiments and modeling of fire spread in shrubs in a wind tunnel. 9th US National Meeting, May 17-20, 2015, Cincinnati, Ohio. Pittsburgh, PA: Central States Section of the Combustion Institute. | A | May 2015, distributed to conference attendees only |
| Conference paper | Gallacher, J.R., Lansinger, V., Hansen, S., Weise, D.R., Fletcher, T.H. 2015. Effects of season and heating model on ignition and burning behavior of ten species of live fuel measured in a flat-flame burner system. 9th US National Meeting, May17-20, 2015, Cincinnati, Ohio. Pittsburgh, PA: Central States Section of the Combustion Institute. | A | May 2015, distributed to conference attendees only |
| Conference paper | McAllister, S., Weise, D. 2015. Effects of season on ignition of live wildland fuels using the FIST apparatus. 9th US National Meeting, May 17-20, 2015, Cincinnati, Ohio. Pittsburgh, PA: Central States Section of the Combustion Institute. | A | May 2015, distributed to conference attendees only |
| Conference paper | McAllister, S., Weise, D. 2015. Effects of season on ignition of live wildland fuels using the FIST apparatus. 9th Mediterranean Combustion Symposium, June 7-11, 2015, Rhodes, Greece. | A | June 2015, distributed to conference attendees only |
| Conference paper | Gallacher, J.R., Lansinger, V., Smith, S., Doll, A., Weise D.R., Fletcher, T.H. 2015. The Ignition and Burning of Live Fuels Studied Using Natural Variation in Fuel Characteristics, Western States Section of the Combustion Institute, Brigham Young University, Provo, UT (October 5-6, 2015). | A | Oct 2015, distributed to conference attendees only |
| Conference paper | Gallacher, J.R., Lansinger, V., Hansen, S., Smith, S., Weise, D.R. Fletcher, T.H. 2015. The Effect of Heating Mode on | A | Oct 2015, distributed |

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| | the Ignition and Burning Behavior of 10 Live Shrub Fuels, Western States Section of the Combustion Institute, Brigham Young University, Provo, UT (October 5-6, 2015). | | to conference attendees only |
| Conference paper | Anand, C., McAllister, S., Shotorban, B., Mahalingam, S., and Weise, D.R. Physics-based Modeling of Piloted Ignition of Live Forest Fuels, Central States Section of the Combustion Institute Spring Technical Meeting, Knoxville, TN (May 15-17, 2016) | A | May 2016, distributed to conference attendees only |

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