WILDLAND FIRE SPOT IGNITION BY SPARKS AND FIREBRANDS

A. Carlos Fernandez-Pello

Department of Mechanical Engineering
University of California, Berkeley,
Berkeley, CA 94720-1740, USA
and
Reax Engineering
1921 University Ave,
Berkeley, CA 94704, USA

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Wildland Fire Spotting

- Wildland fire “spot ignition” refers to sparks/firebrands ejected from arcing power lines, hot work or by burning embers (firebrands) landing on vegetation and igniting it.
- Wildland fire “spotting propagation” is the ignition of vegetation by firebrands lofted by the plume of ground fires and transported by the wind ahead of the fire front.
- Under dry, hot, and windy conditions (such as Santa Ana winds in California) fire spotting is an important mechanism of wildland fire ignition and spread.
Power lines interaction fires

Sparks from conductors clashing or embers from conductors interacting with trees, when landing on thin fuel beds have the potential to ignite a wildfire.
Examples of spot fire ignition by power lines

**Witch Fire (California)**
- The Largest Fire of 2007 California Firestorm
- $1.8 Billion in losses

**Alleged Cause:**
- Hot particles from clashing power lines landing in dry grass

**Bastrop Fire (Texas)**
- Largest loss fire in USA in 2011
- Burned ~13,000 Hectacres

**Alleged Cause:**
- Hot particles from power lines interacting with trees and landing in dry grass
Other Hot Particle Sources of Ignition

Welding

Grinding

Fireworks
Taylor Bridge Fire - Cle Elum, Washington  (August 2012)

Alleged Cause: Rebar Cutting or Welding on bridge
Damages: $59.8 million settlement, 61 homes destroyed, 36 square miles burned, hundreds of outbuildings
Firebrands Fire Spotting and Propagation

- Wind
- Drag
- Weight
Firebrands Spotting (Witch fire, CA)
Wildland Urban Interface (WUI) Spot Fires

- Sparks or firebrands are transported downwind and ignite adjacent vegetation and/or structures
- Sparks/Firebrands ignite houses by:
  - Landing on roof or decks
  - Penetrating roof between ceramic tiles and wooden structure
  - Penetrating attic through vents
Example of a Spot Fire Ignition

Images taken from a video produced by BCC, Texas
Spot fire ignition of wildland fuels is an important pathway by which wildland fires are started and propagate

- Power lines, hot work and equipment cause approximately 28,000 wildland fires annually in the United States [NFPA & USFA]
- Spotting leads to very rapid fire spread because embers generated by burning vegetation are lofted and transported downwind to ignite secondary fires.
- Civilians and firefighters alike can become trapped between spot fires with no escape route
Research Impact

A better understanding of the ignition pathways could lead to improved:

• **Prediction**
  – Identify high-risk fuels
  – Assess particle source risk
  – Predict spot fire initiation

• **Prevention**
  – Prioritize fuel treatments
  – Set intelligent clearance distances
  – Set work site regulations
Example of the benefits of understanding the ignition of wildland fuels by hot or burning particles
Steps in the development of spot wild fires

- Primary steps in the formation of spot fires are
  - Metal particle/spark generation (arching, friction..)
  - Firebrand generation (vegetation fire/arching)
  - Metal Particles/embers lofted and transported by wind
  - Characteristics of the particles at landing
  - Ignition (smolder or flaming) of vegetation after the ember/particle lands
  - Potential growth of the fire
Steps in the development of spot wild fires

- **Powerline arcing**
- **Arc-welding**
- **Fire induced plume breaks of ember**

**Hot particle / ember generation**

**Particle transport & thermo-chemical changes**

- **Lofting by buoyant fire plume**
- **Heat from flame, surface oxidation, or smoldering reactions**
- **Drag force from relative motion with wind**
- **Convective and radiative cooling**

- **Ignition of solid fuel**
- **Flaming ignition**
- **Smoldering ignition**
- **No ignition**
Metal particle/spark generation (arching, welding..) and evolution
Example of Power Lines Clashing & Arcing

Video produced by the Victoria power company, Australia
Welding and Grinding are Sources of Hot Metal Particles and Sparks
Example of Sparks from Metal Grinding
Particle size distribution: Al arcing

Fig. 8. Fitting probability density functions with test current of 300 A

Particles ejected and transported by wind
Particles Trajectories Modeling

Model Description – Equations of Motion

\[ \ddot{x} = F_D \frac{\vec{v}_p - \vec{v}_{wind}}{||\vec{v}_p - \vec{v}_{wind}||} + m\vec{g} \]

\[ \frac{d\vec{x}}{dt} = \ddot{\vec{x}} \]

\[ F_D = c_D(Re)\rho_{air}(T)v_{rel}^2A_{proj}\frac{\vec{v}_{rel}}{v_{rel}} \]

\[ \vec{v}_{wind} = v_w^*\ln \left( \frac{y}{y^*} \right) \]
Particle Evolution Equations

\[
\frac{d\left(D_{\text{eff}}^2\right)}{dt} = -\beta
\]

\[
D_{\text{eff}} = \left(\frac{6m_P}{\rho_{P,0}\pi}\right)^{\frac{1}{3}}
\]

\[
\frac{dT_P}{dt} = -\frac{S_P}{(\rho c_\nu)_P}\left(\dot{q}_{\text{rad}}'' + \dot{q}_C''\right)
\]

\[
\beta = \beta_0 \left(1 + 0.276 \text{Re}_D^{\frac{1}{2}} \text{Pr}^{\frac{1}{3}}\right)
\]

\[
\dot{q}_{\text{rad}}'' = \sigma \varepsilon (T_P^4 - T_\infty^4)
\]

\[
\dot{q}_C'' = h(T_P - T_\infty)
\]
Energy Conservation

\[ mC_p \frac{dT}{dt} = -[\dot{Q}_{Rad} + \dot{Q}_{Conv}] + \dot{Q}_{rxn} \left( \frac{\partial m_0}{\partial t} \right) \]

Energy variation
Convective & Radiative Losses
Heat Released from reaction
Particles Trajectories: Clashing Al Powerlines
Particle Trajectories: Steel Welding

Wind

Particle Temperature [K]

Height [m]

Horizontal Distance [m]
Trajectories Welding Steel Sparks

- Height [m]
- Temperature [°C]
- Horizontal Distance [m]

Fire Origin
Wind

- $d_p = 1.0 \text{ mm}$
- $d_p = 1.5 \text{ mm}$
- $d_p = 2.0 \text{ mm}$
- $d_p = 3.0 \text{ mm}$
- $d_p = 4.0 \text{ mm}$
Welding Sparks: landing locations
Firebrand/ember generation and evolution
Firebrand Generation (NIST)

Embers generated by burning trees

Embers from “Dragon” apparatus
Manzello et al
Firebrand characteristics evolution

Tarifa et al.

Manzello et al.
Ember burning size regression –

- Heterogeneous burning (smoldering) constant selected to match ember data from to “D^2–law” for mass loss
  - Cylinder geometry data fit by same burning constant as spheres

\[
\frac{d(D_{eff}^2)}{dt} = -\beta
\]

- Ember size found to regress as “D^4”
  - Cylinder geometry data can be fit if D^4 “law” scaled by aspect ratio of cylinders (AR=3)

\[
\frac{d(D_{P, cyl}^4)}{dt} = \frac{2\beta^2 t}{\sqrt{3}}
\]

- Charring and non–charring
- Various mass extinction ratios
- Burning constant for both cases & geometries modified by Re and Pr

\[
\beta = \beta_0 \left( 1 + 0.276 \text{Re} D^{\frac{1}{2}} \text{Pr}^{\frac{1}{3}} \right)
\]

\[
\beta_0 = 1.8 \times 10^{-7} m^2/s
\]
Ember Combustion Model

Pyrolysis of dry wood

\[
\text{virgin dry wood} \rightarrow v_c \text{Char} + (1 - v_c) \left[ (1 - v_s) \text{GPP} + v_s \text{Soot} \right]
\]

Char combustion

Endothermic global reaction in depth

Exothermic one-step char oxidation reaction

\[
C(s) + \frac{1}{2}O_2(g) \rightarrow CO(g)
\]
Fire Plume Modeling

C. Lautenberger, Reax Eng.
Embers lofted in fire plume and transported in wind.
Application of embers trajectories
Ignition of vegetation after the particle lands on the ground
After Landing, will the Particle Ignite the Vegetation?

• What determines the ignition of a wildland fuel by a hot metal particle or firebrand?
• Do different metals have the same propensity for ignition?
• Do the different wildland fuel beds have the same propensity for ignition?
• Do the fuel moisture and ambient conditions affect the potential of a particle to ignite a given fuel?
• Do live fuels behave the same as dead fuels?
Ignition Process

- Smoldering Ignition
- Flaming Ignition
- No Ignition
What are the controlling parameters?

Particle Properties
- Temperature
- Size
- Material

Fuel Bed Properties
- Chemical Composition
- Morphology
- Moisture Content

Smoldering Ignition
Flaming Ignition
No Ignition
How spot ignition can be tested?

- **Particle Properties**
  - Temperature
  - Size
  - Material

- **Fuel Properties**
  - Chemical Composition
  - Morphology
  - Moisture Content

- **Uniform Air Flow**

- **Tube Furnace**

- **Fuel bed**
  - Sand

- **Smoldering Ignition**
- **Flaming Ignition**
- **No Ignition**
Experimental Apparatus: UC Berkeley

- Crucible with Thermocouple
- Tube Furnace
- High Speed Cameras
- Fuel Bed
Experimental Procedure

1. Particle equilibrates with T-controlled furnace in ceramic crucible (Temp. measured by crucible TC)

Tube Furnace

Fuel bed

Sand

Uniform Air Flow
Experimental Procedure

1. Particle equilibrates with T-controlled furnace in ceramic crucible (Temp. measured by crucible TC)

Uniform Air Flow

 Tube Furnace

$g$

Fuel bed

Sand
Experimental Procedure

1. Particle equilibrates with T-controlled furnace in ceramic crucible (Temp. measured by crucible TC).
2. Crucible is removed/rotated, particle drops onto fuel bed.

Uniform Air Flow
Experimental Procedure

1. Particle equilibrates with T-controlled furnace in ceramic crucible (Temp. measured by crucible TC)
2. Crucible is removed/rotated, particle drops onto fuel bed

Uniform Air Flow
Experimental Procedure

- Sand
- Fuel bed
- Uniform Air Flow

Flaming Ignition does or doesn’t occur
Video of a test

(steel particle landing in pine needles)
The Effect of particle material and type of fuel bed on Flaming Ignition: Objective

- Establish ignition boundaries for four particle materials: aluminum, brass, steel, copper and of several fuels beds: cellulose, grass, pine needles.
- The ignition boundaries separate flaming or smoldering and no-ignition cases as a function of diameter and temperature for a given material and fuel bed.
Metal Particles Characteristics

- Heated using tube furnace: max temp 1100°C
  - Aluminum: solid & molten
  - Steel, Brass & Copper: only solid

- Diameter range: ~2-11mm (Steel & Aluminum)
  - ~3-11mm (Copper & Brass)
Effect of Metal type: Cellulose Fuel Bed

- Surrogate Fuel: Powdered $\alpha$-cellulose
  - Largest component of woody biomass
  - Chemically homogeneous
  - Physically uniform
- Lab conditioned
- (Moisture Content $\sim 6.0\%$)
- Density: $338 \text{ kg/m}^3$
Cellulose Flaming Ignition by Steel Particles

Particles from mechanical devices (e.g. brake pieces, bearings etc.)
Schlieren Videos: Ignition by large and small particles

Test Condition: 15.9 mm, 625 °C

Test Condition: 3.18 mm, 1075 °C

Time: 0 ms

Schlieren Video Captured at 1200 fps
Schlieren Videos: Observations

• Flaming ignition by large particles appear to be a pilot type ignition with the particle providing the energy for fuel pyrolysis and ignition
• Flaming ignition by small particles appears to be a hot spot spontaneous type of ignition with the particle providing the energy for fuel pyrolysis
• Powdered material may facilitate the ignition process by reducing the energy necessary to produce a flammable mixture in the gas
Flaming Ignition Propensity: Al

![Flaming Ignition Graph]

The graph illustrates the relationship between temperature (in degrees Celsius) and diameter (in millimeters) for flaming ignition propensity. The shaded areas indicate regions of flaming ignition and no ignition, with temperature and diameter thresholds defining these regions. The color gradient on the right side represents the observed ignition probability, ranging from 0 to 100%. The data points and curves show how ignition propensity changes with temperature and diameter, highlighting critical thresholds for flaming ignition.
Effect of Particle Material

Tests were performed on powdered cellulose fuel bed.

- Copper
- Brass
- Stainless Steel
- Aluminum

Flaming Ignition

No Ignition

Temperature (°C) vs. Diameter (mm)
Flaming Ignition: Temperature and Energy

Ignition propensity is very sensitive to diameter.

Ignition Propensity very Sensitive to Temperature

Berkeley UNIVERSITY OF CALIFORNIA
Natural Fuel Beds Tested

(a) Cellulose Powder

(b) Grass Powder

(c) Cellulose Strips

(e) Pine Needles

(d) Grass Blend
Flaming Ignition Boundaries: Aluminum Particles
Smoldering vs. Flaming Ignition
Smoldering Ignition-Powdered Grass

Ignition by 1.59 mm Diam. Steel Particle
33.3x Speed

Temp: 850 C
Temp: 1000 C

Direction of cross-flow
Experimental Ignition Boundaries

(a) Stainless Steel

(b) Aluminum

Temperature [°C]

Observed Ignition Propensity

Diameter [mm]

Flaming Ignition

Smoldering Ignition

No Ignition
Observations

• Thermal properties (with exception of heat of melting) do not significantly affect ignition boundaries
• Increased energy correlates with increased likelihood of ignition, but energy alone does not determine ignition.
• The combination of particle energy and temperature determines ignition
• Powdered fuels are more easily ignited than their natural state.
• The effects of fuel bed composition and morphology appear to be more important for larger particles than for smaller particles
• Smolder ignition occurs at lower particle temperature and size that for flaming ignition
Effect of Moisture: Firebrand Ignition

**Fuel Bed:** Redwood sawdust

**Fuel Moisture Content** \( MC = \frac{m_{\text{water}}}{m_{\text{dry}}} \) 0–50%

**Ember Size:** 1.5–11 mm in diameter (cylinders with aspect ratio of 1)

**Cross Flow velocity:** 0.5 m/s

**Ember State:** Glowing Combustion
Smolder Ignition: Effect of Moisture

\[ d_p = 3.17 \text{mm} \quad d_p = 4.80 \text{mm} \quad d_p = 6.35 \text{mm} \quad d_p = 9.50 \text{mm} \quad d_p = 11.00 \text{mm} \]
Smolder Ignition Boundary

- 50% Ignition Boundary (curve-fit)
- 50% Ignition Likelihood (exp.) $\pm 2\sigma$

Moisture Content [%]

Ember Diameter [mm]

No Ignition

Smoldering Ignition
Moisture content

• Many plants (like conifers and chaparral species) have distinct growing seasons
  – Use carbohydrates from previous and current year to put on new leaves and needles

• For live fuels, the dry mass can change during the growing season as carbohydrates are generated, stored, transported to form new growth
  – Sugars also help keep the needles from freezing in the winter
  – As new needles mature, sink of carbohydrates → source

• Moisture content of live fuel can change without any change in the amount of water contained in the fuel
Effect of Live Fuels

Communication from S. McAllister (USFS)

- Investigate the effect of moisture and live fuels on the different fuel bed materials ignition
Effect of moisture: Observations

- The maximum moisture content resulting in ignition increased with ember size
- Glowing embers 1.5mm in diameter were unable to ignite smolder in dry sawdust
- Incipient smoldering spread was primarily radial while it was lobed when ignited by hot metal particles
  - Ember produces heat from glowing combustion while metal particles acts as a heat sink to the incipient smolder
R² = 0.0316

R² = 0.8156

R² = 0.2831

R² = 0.0913

Ignition time (s)

Moisture content (%)

- Chamise
- Sagebrush
- Lodgepole pine
- Gambel oak

http://www.usu.edu/weeds/plant_species/nativespecies/nativespeciesimages/sagebrush/sagebrush_basin_leaves2.jpg
http://www.ljnc.com/pages/plants/GambelOak.html
Video of the effect of heating a live fuel (Grand Fir)
High-speed video: Grand fir
Theoretical Modeling of the Ignition of Fuel Beds by Metal Particles and Embers
Analytical Modeling

- Hot Spot Spontaneous Ignition theory gives a critical diameter for ignition of the form

\[
d_{cr} = C_1 T_p \sqrt{\exp\left(\frac{C_2}{T_p}\right)}
\]

- Parameters \(C_1\) and \(C_2\) determined by fitting to data
Data Correlation with Hot Spot Model

- Hot Spot Spontaneous Ignition theory correlates the experiments qualitatively
Smolder Ignition: Simplified model

1-D Finite Volume Scheme with implicit time stepping

Hot Particle

0

Fuel Bed

1

i-1

i

1 - D Finite Volume Scheme with implicit time stepping

Oxidative Pyrolysis

Oxidative Ashing

Virgin &rarr; Char &rarr; Ash

Thermal Pyrolysis
Numerical Model: Firebrand Ignition

- 2D schematic of experimental wind tunnel and its computer model representation:
Solid-phase Governing Equations (1)

Conservation of solid mass:
\[ \frac{\partial \rho}{\partial t} = -\dot{\omega}_{fg} \]

Conservation of solid species:
\[ \frac{\partial (\rho Y_i)}{\partial t} = \dot{\omega}_{fi} - \dot{\omega}_{di} \]

Conservation of gas mass:
\[ \frac{\partial (\rho_g \bar{\psi})}{\partial t} + \frac{\partial \dot{m}_x^\prime}{\partial x} + \frac{\partial \dot{m}_z^\prime}{\partial z} = \dot{\omega}_{fg} \]

Conservation of gas species:
\[ \frac{\partial (\rho_g \bar{\psi} Y_j)}{\partial t} + \frac{\partial (\dot{m}_x^\prime Y_j)}{\partial x} + \frac{\partial (\dot{m}_z^\prime Y_j)}{\partial z} = -\frac{\partial j_{j,x}^\prime}{\partial x} - \frac{\partial j_{j,z}^\prime}{\partial z} + \dot{\omega}_{fj} - \dot{\omega}_{dj} \]
Solid-phase Governing Equations (2)

Conservation of solid energy:

\[
\frac{\partial (\bar{\rho} \bar{h})}{\partial t} + \frac{\partial (m_x h_g)}{\partial x} + \frac{\partial (m_z h_g)}{\partial z} = -\frac{\partial q_x}{\partial x} - \frac{\partial q_z}{\partial z} + \dot{Q}_s + \sum_{i=1}^{M} (\dot{\omega}_f^m - \dot{\omega}_d^m) h_i
\]

Conservation of gas energy (thermal equilibrium):

\[T_g = T\]

Pressure evolution equation (from Darcy’s law):

\[
\frac{\partial}{\partial t} \left( \frac{P\bar{M}\bar{\psi}}{RT_g} \right) = \frac{\partial}{\partial x} \left( \frac{\bar{K}}{\nu} \frac{\partial P}{\partial x} \right) + \frac{\partial}{\partial z} \left( \frac{\bar{K}}{\nu} \frac{\partial P}{\partial z} \right) + \dot{\omega}_f^m
\]
Reaction Source Terms

Stoichiometry:

\[ 1 \text{ kg } A_k + \sum_{j=1}^{N} \nu'_{j,k} \text{ kg gas } j \rightarrow \nu_{B,k} \text{ kg } B_k + \sum_{j=1}^{N} \nu''_{j,k} \text{ kg gas } j \]

Thermal pyrolysis reaction rate:

\[
\dot{\omega}_{dA_k} = \left( \frac{\rho Y_{A_k}}{(\bar{\rho} Y_{A_k})_{\Sigma}} \right)^{n_k} \left( \bar{\rho} Y_{A_k} \right)_{\Sigma} Z_k \exp \left( -\frac{E_k}{RT} \right)
\]

Oxidative pyrolysis reaction rate:

\[
\dot{\omega}_{dA_k} = \left( \frac{\rho Y_{A_k}}{(\bar{\rho} Y_{A_k})_{\Sigma}} \right)^{n_k} \left( \bar{\rho} Y_{A_k} \right)_{\Sigma} \left[ 1 + Y_{O_2} \right]^{n_{O_2,k}} Z_k \exp \left( -\frac{E_k}{RT} \right)
\]
Computer Code – Gas Phase

• Fire Dynamics Simulator (FDS)
  – CFD–based fire model developed by NIST and VTT
  – 2D implementation applied here
  – Single step finite rate combustion reaction
  – Ember modeled as volumetric heat source
Computer Code – Solid Phase

- **Gpyro** – [http://reaxengineering.com/trac/gpyro](http://reaxengineering.com/trac/gpyro)
  - Open source – funded by NSF as part of larger project
  - Conjugate heat transfer in reacting porous media (2D)
  - Solves for pressure and gas/solid species in porous fuel bed
  - Coupled to FDS where it is applied as boundary condition
Flaming Ignition – Gas Temperature

Smokeview 5.2.2 – Jul 18 2008

Frame: 253
Time: 253.0

Berkeley
UNIVERSITY OF CALIFORNIA
Flaming Ignition – Gaseous Reaction Rate
Flaming Ignition – Solid Temperature
The problem of wildfire spotting ignition and propagation is complex with multiple physical-chemical mechanism controlling it, which make it difficult to study.

As experimental and theoretical progress is made on the problem, models predicting sparks/embers generation, trajectories, spot ignition and fire propagation, could be used in conjunction with topographical and vegetation maps, and weather patterns to:

- Determine the potential fire spotting, spread and damage of a particular fire as it develops
- Provide information to fire commanders about the danger of spotting ignition and subsequent fire propagation characteristics (speed, direction, intensity)
- Develop fire threat maps to be to schedule inspection and maintenance of power lines, and manage fire prevention

Concluding Remarks
Acknowledgements

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## Particle Material Properties

<table>
<thead>
<tr>
<th></th>
<th>Stainless Steel</th>
<th>Brass</th>
<th>Aluminum (solid)</th>
<th>Aluminum (molten)</th>
<th>Copper</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k$ (W/mK)</td>
<td>21.5</td>
<td>120</td>
<td>237</td>
<td>90</td>
<td>390</td>
</tr>
<tr>
<td>$\alpha$ (mm^2/s)</td>
<td>5.1</td>
<td>38</td>
<td>90</td>
<td>33</td>
<td>114</td>
</tr>
<tr>
<td>$\rho c_p$ (MJ/m^3K)</td>
<td>3.2</td>
<td>3.3</td>
<td>2.4</td>
<td>2.71</td>
<td>3.43</td>
</tr>
<tr>
<td>$\Delta T_m$ (°C)</td>
<td>1400 - 1420</td>
<td>915 - 955</td>
<td>650</td>
<td>n/a</td>
<td>1015</td>
</tr>
<tr>
<td>$\Delta h_m$ (MJ/kg)</td>
<td>n/a</td>
<td>n/a</td>
<td>390</td>
<td>n/a</td>
<td>n/a</td>
</tr>
</tbody>
</table>
# Fuel Bed Properties

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Density [kg/m³]</th>
<th>MC [%]</th>
<th>Chemical Composition</th>
<th>d_char [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cellulose Powder</td>
<td>363 ± 34.4</td>
<td>6.5 ± 2</td>
<td>100% α – Cell.</td>
<td>0.4</td>
</tr>
<tr>
<td>Cellulose Strips</td>
<td>45 ± .2</td>
<td>7.3 ± 2</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Pine Needles</td>
<td>59 ± 1.0</td>
<td>8.5 ± 2</td>
<td>38-42% Cellulose 13-21% Lignin 6-8% Ash [33]</td>
<td>2</td>
</tr>
<tr>
<td>Grass Blend Powder</td>
<td>299 ± 2.4</td>
<td>6.9 ± 2</td>
<td>33-45% α – Cell. 22-27% Hemi-Cell.</td>
<td>0.5</td>
</tr>
<tr>
<td>Grass Blend</td>
<td>79 ± 1.0</td>
<td>7.6 ± 2</td>
<td>6-15% Lignin 5-7% Protein 8-10% Ash</td>
<td>7.5</td>
</tr>
</tbody>
</table>
Schlieren Videos: Large Particles

Bottom screen

Top screen

Schlieren Artifact
Schlieren Videos: small particles

Test Condition: 3.18 mm, 775 C

Test Condition: 3.18 mm, 1075 C

Time: 0 ms
Schlieren Video Captured at 1200 fps
Structural differences

• Not all leaves and needles built the same
  – Plants that keep their leaves (evergreen) can afford to build “tougher” epidermis layers to keep water in
    • Especially important where water can be scarce
    • Costs more to make leaf water tight → not worth it if deciduous
    • Made tougher by adding layer of sclerenchyma below epidermis and around vascular tissue AND/OR developing thick and waxy cuticle on epidermis
  – Plants called “sclerophyllous”
  – Occurs in conifers and chaparral species

http://www.deanza.fhda.edu/faculty/mccauley/6a-labs-plants-04.htm
Schematic of Fire Propagation

Wind and flat terrain

No wind

Wind and sloped terrain
FARSITE

• Calculates spread of wildland surface fire based on topography, fuels, and weather
• Takes elevation data (e.g., from USGS) as input
• Fire spread rate calculated from empirical Rothermel spread equation

\[
V_s = \frac{\ell_{pre}}{t_{ig}} = \frac{\ell_{pre}}{Q_{ig}/\dot{Q}''} = \frac{\ell_{pre}}{\varepsilon \rho_b Q_{ig}} \frac{\xi \dot{q}_{HRR}}{\ell_{pre}} = \frac{\xi \dot{q}_{HRR}}{\varepsilon \rho_b Q_{ig}}
\]

• Can be generalized to include wind and slope effects:

\[
V_f = \frac{\dot{q}_{HRR} \xi (1 + \Phi_w + \Phi_s)}{\rho_b \varepsilon Q_{ig}}
\]