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

12th IAFSS, Lund, Sweden, June 2017

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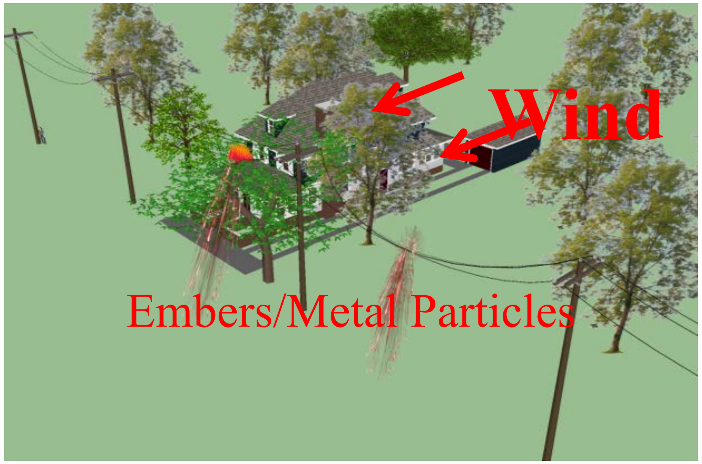
Wildland Fire Spotting

- 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

http://upload.wikimedia.org/wikipedia/commons/thumb/b/b9/Harris_fire_Mount_Miguel.jpg/1024px-Harris_fire_Mount_Miguel.jpg

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

http://www.blackberrybeads.com/wp-content/uploads/2011/09/wildfires-out-of-control-in-texas.jpg

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Other Hot Particle Sources of Ignition

Welding

Grinding

Fire works

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

Image source: http://wac.450f.edgecastcdn.net/80450F/newstalkkit.com/files/2012/08/120814_cleelum_fire_gal_1.jpg

Alleged Cause: Rebar Cutting or Welding on bridge

Damages: $59.8 million settlement, 61 homes destroyed, 36 square miles burned, hundreds of outbuildings

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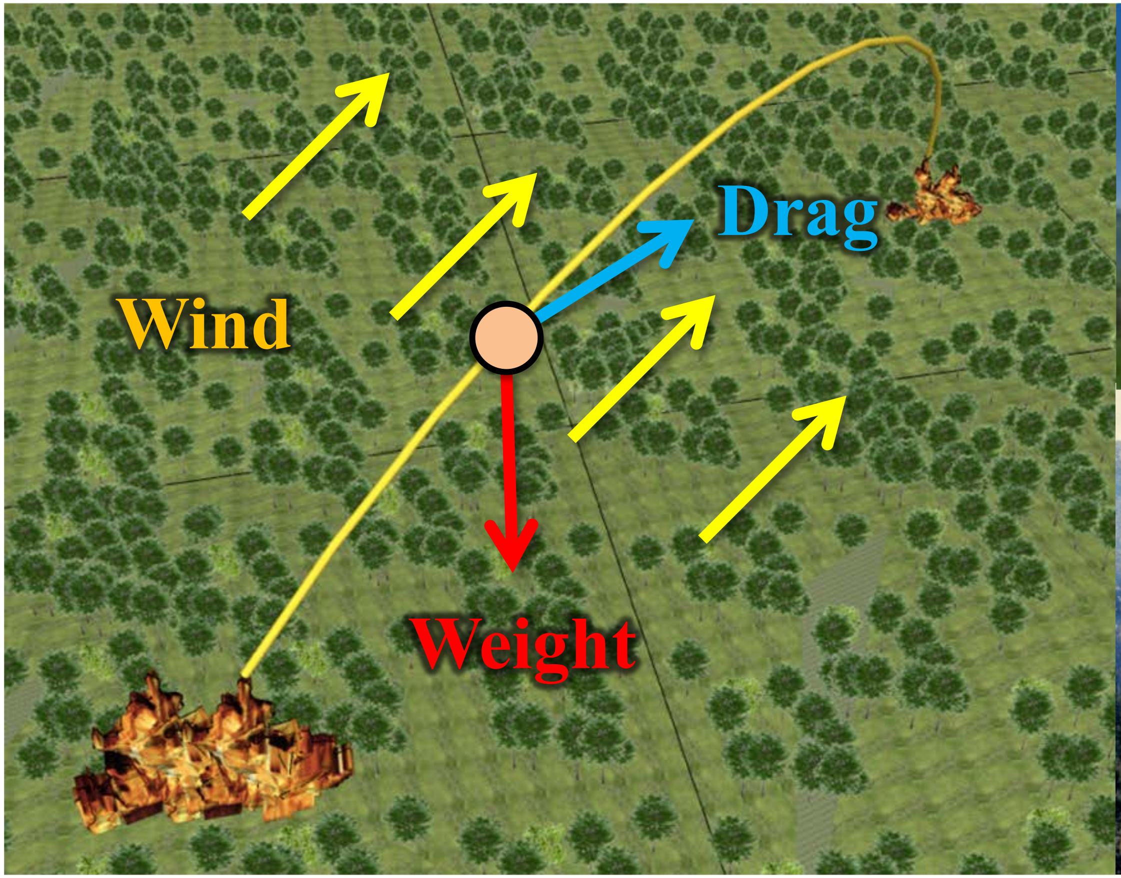
Firebrands Fire Spotting and Propagation



Firebrands Spotting (Witch fire, CA)

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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

Fire spotting at the urban/wild land interface

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Example of a Spot Fire Ignition

Images taken from a video produced by BCC , Texas

Is the Problem of Wildland Fire Spot Ignition Important?

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

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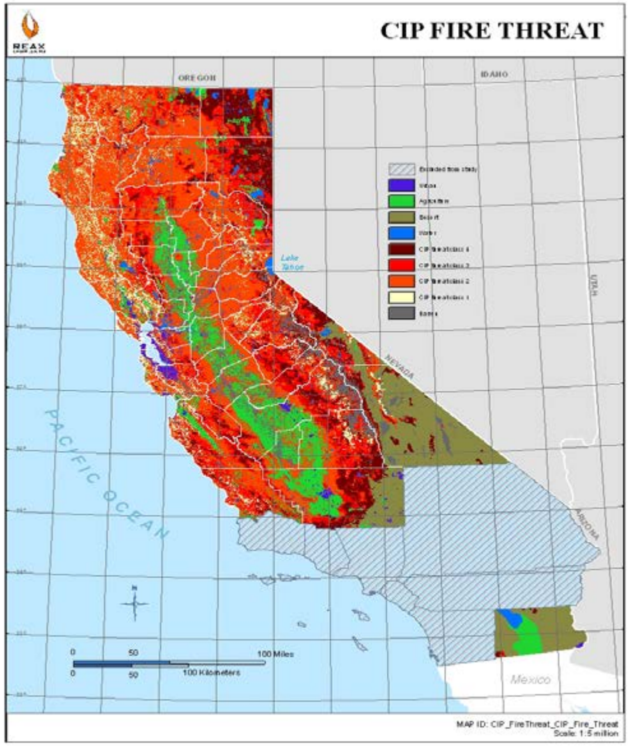
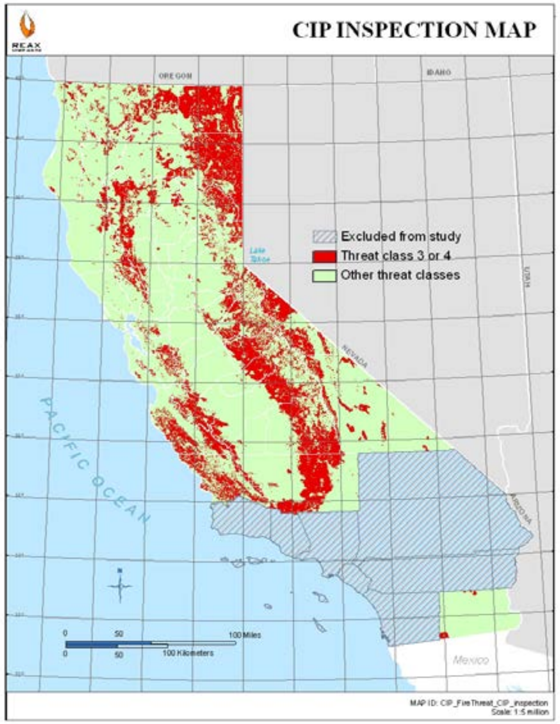
Example of the benefits of understanding the ignition of wildland fuels by hot or burning particles





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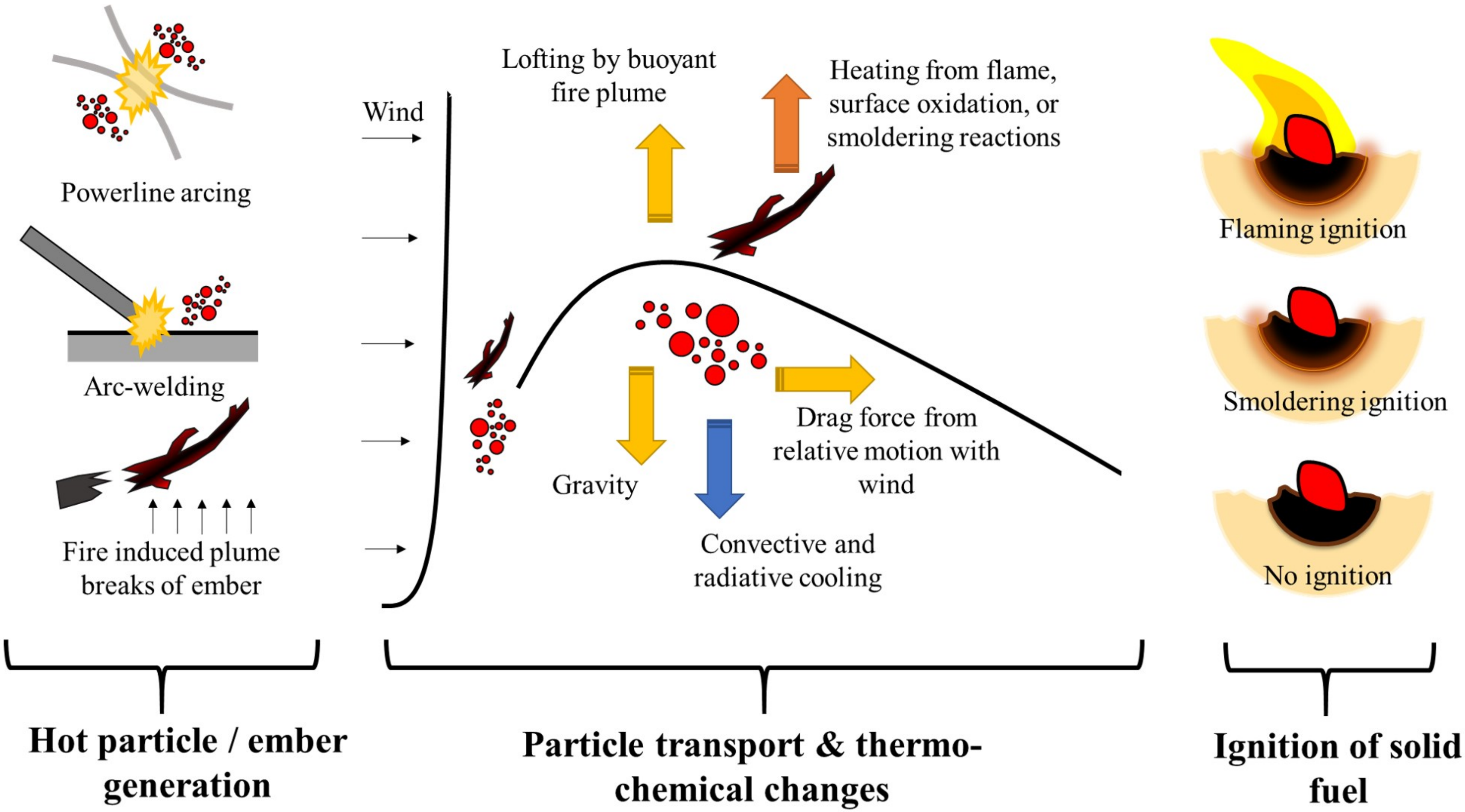
Steps in the development of spot wild fires

- Primary steps in the formation of spot fires are
  - Metal particle/spark generation (arcing, friction..)
  - Firebrand generation (vegetation fire/arcing)
  - 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



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Metal particle/spark generation (arcing, welding..) and evolution

Example of Power Lines Clashing & Arcing

Video produced by the Victoria power company, Australia


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Welding and Grinding are Sources of Hot Metal Particles and Sparks

Welding

Grinding

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Example of Sparks from Metal Grinding

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Particle size distribution: Al arcing

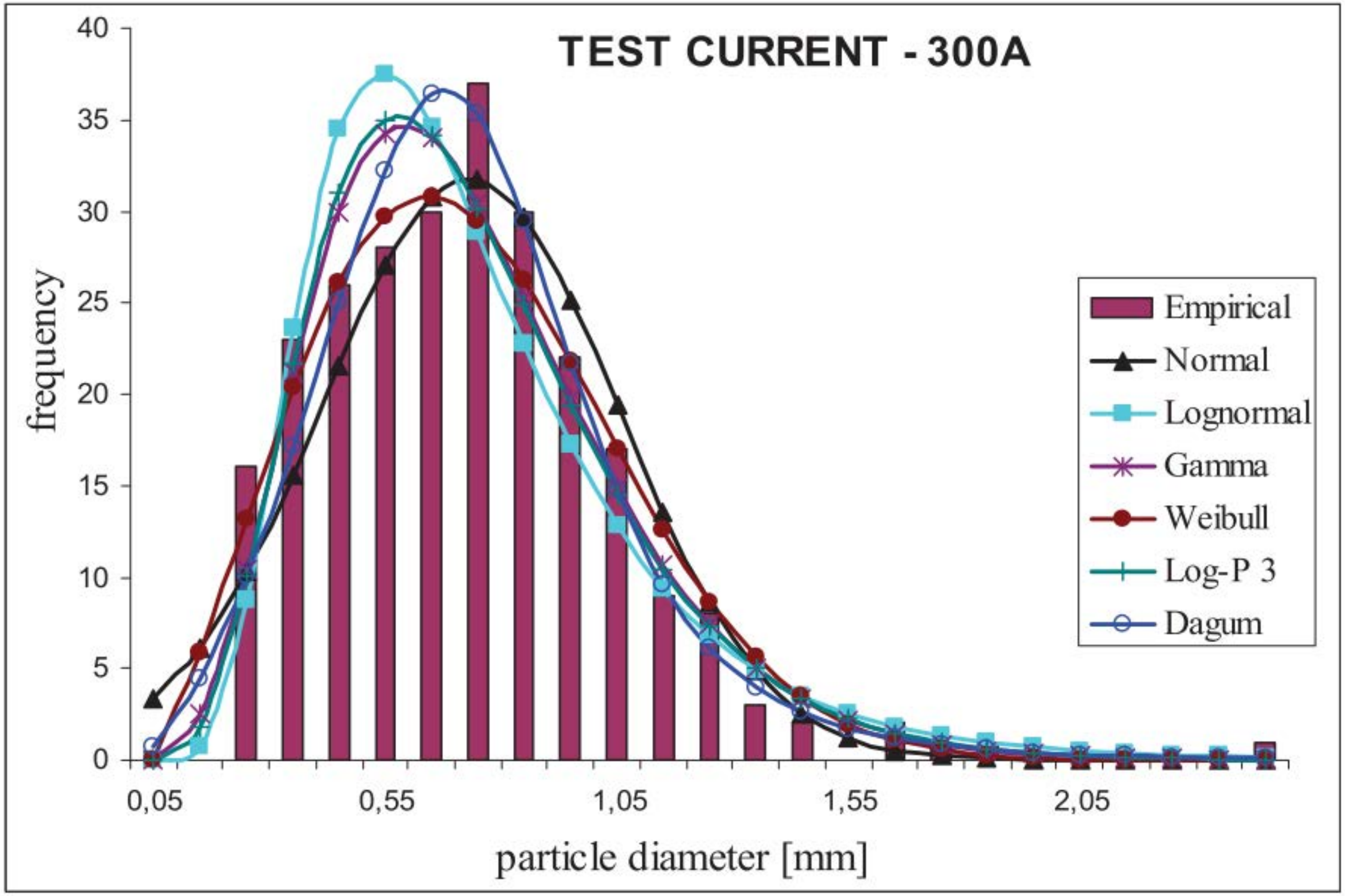

Fig. 8. Fitting probability density functions with test current of 300 A

Ramljak, I., 2014. Statistical analysis of particles of conductor clashing. … (ENERGYCON), 2014 IEEE …, pp.638–643.

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Particles ejected and transported by wind

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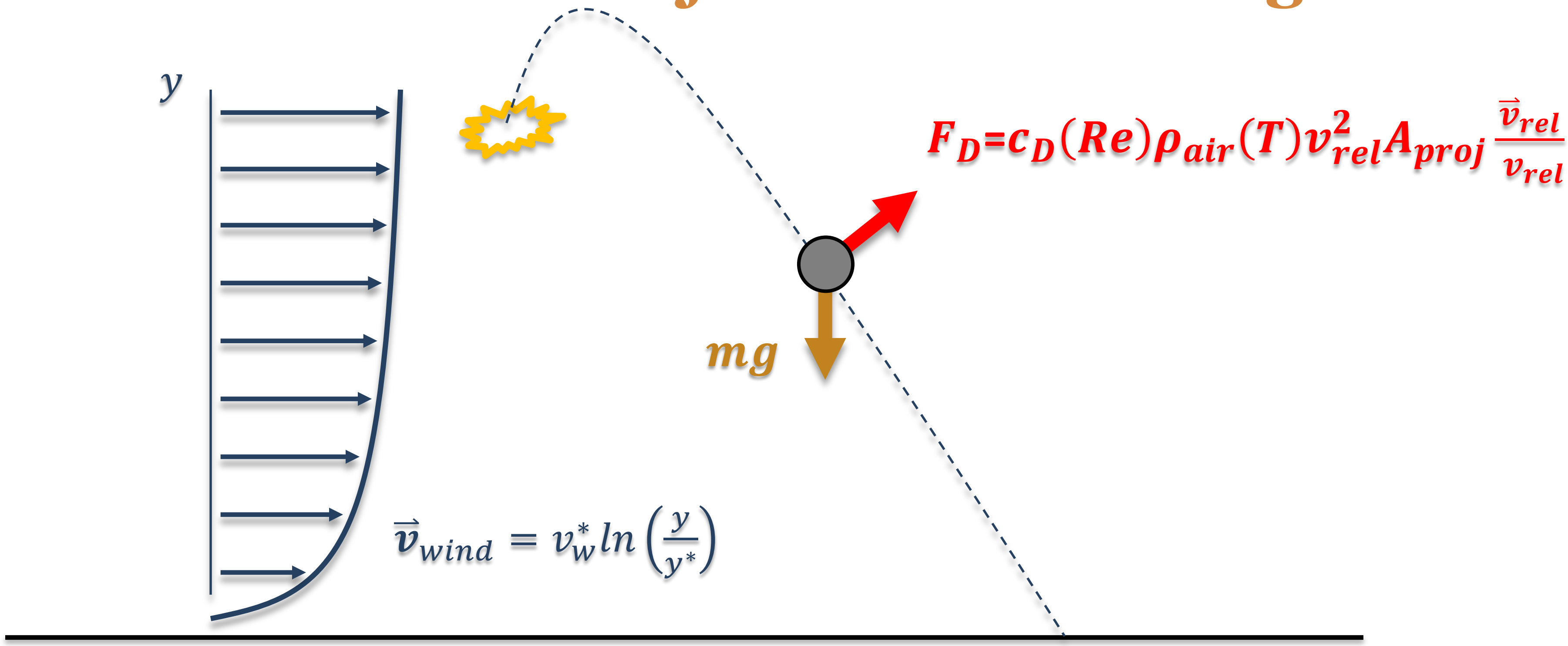
Particles Trajectories Modeling



Model Description – Equations of Motion

$$\ddot{\vec{x}} = F_D \frac{\vec{v}_p - \vec{v}_{wind}}{\|\vec{v}_p - \vec{v}_{wind}\|} + m\vec{g} \qquad \dot{\vec{x}} = \frac{d\vec{x}}{dt}$$

Particle Evolution Equations

$$\frac{\mathrm{d}\left(D_{eff}^{2}\right)}{\mathrm{d}t} = -\beta$$

$$\beta = \beta_0\left(1 + 0.276\,\mathrm{Re}_D^{\frac{1}{2}}\,\mathrm{Pr}^{\frac{1}{3}}\right)$$

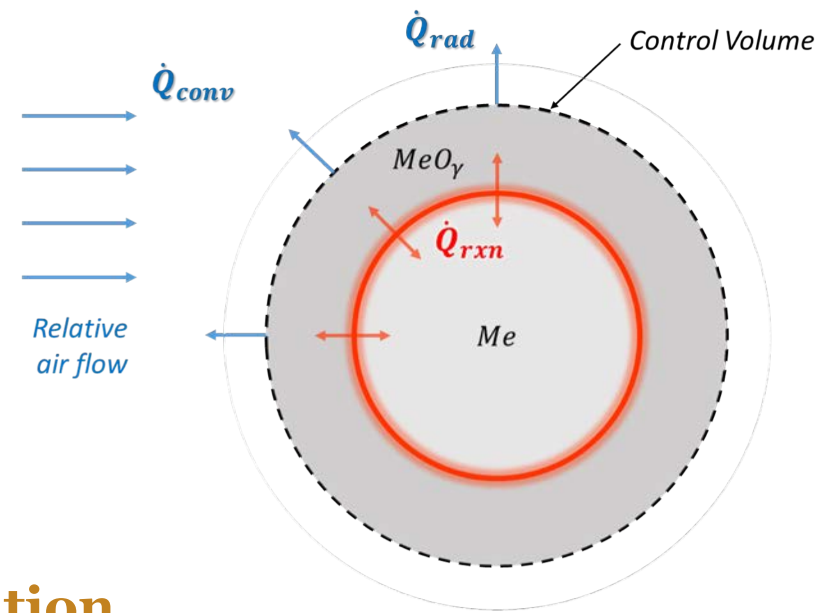
$$D_{eff} = \left(\frac{6\,m_P}{\rho_{P,0}\pi}\right)^{\frac{1}{3}}$$

$$\frac{dT_P}{dt} = -\frac{S_P}{(\rho c \mathcal{V})_P}(\dot{q}''_{rad} + \dot{q}''_C)$$

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

$$\dot{q}''_C = h(T_P - T_\infty)$$

Energy equation: particle combustion



Energy Conservation

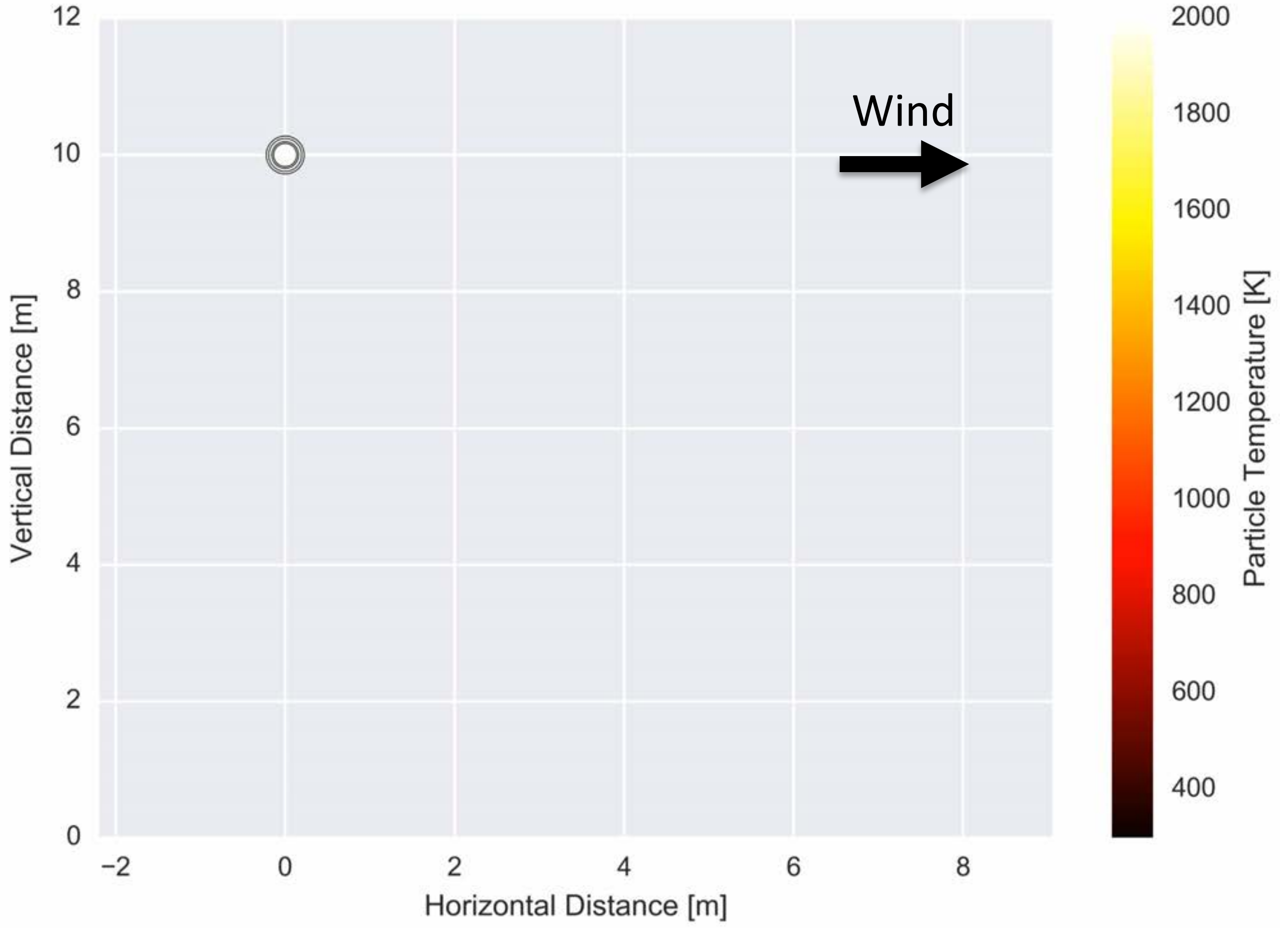
$$mC_p\frac{dT}{dt} = -[\dot{Q}_{Rad} + \dot{Q}_{Conv}] + \dot{Q}_{rxn}\left(\frac{\partial m_O}{\partial t}\right)$$

Energy variation

Convective & Radiative Losses

Heat Released from reaction

Particles Trajectories: Clashing Al Powerlines



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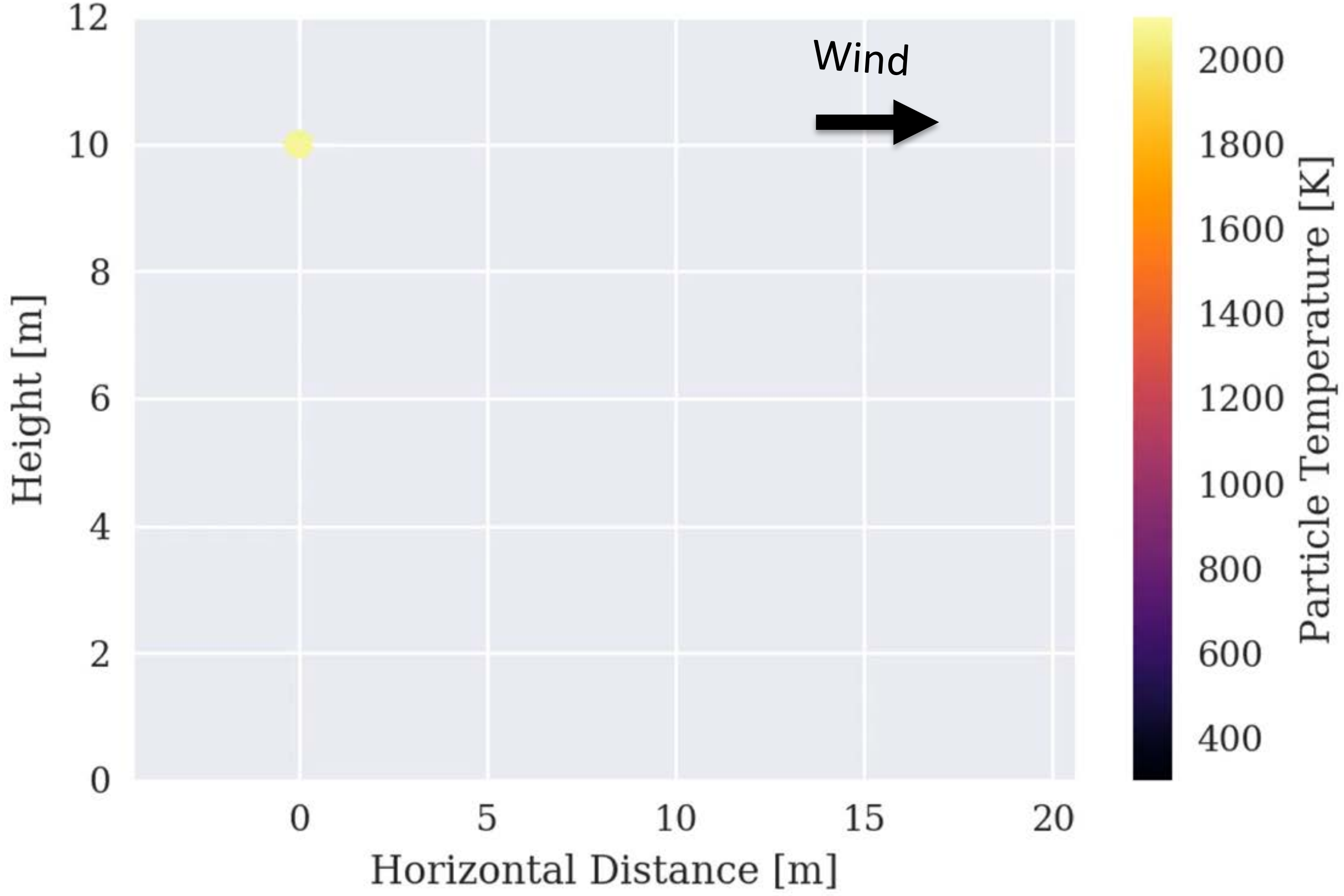
Particle Trajectories: Steel Welding



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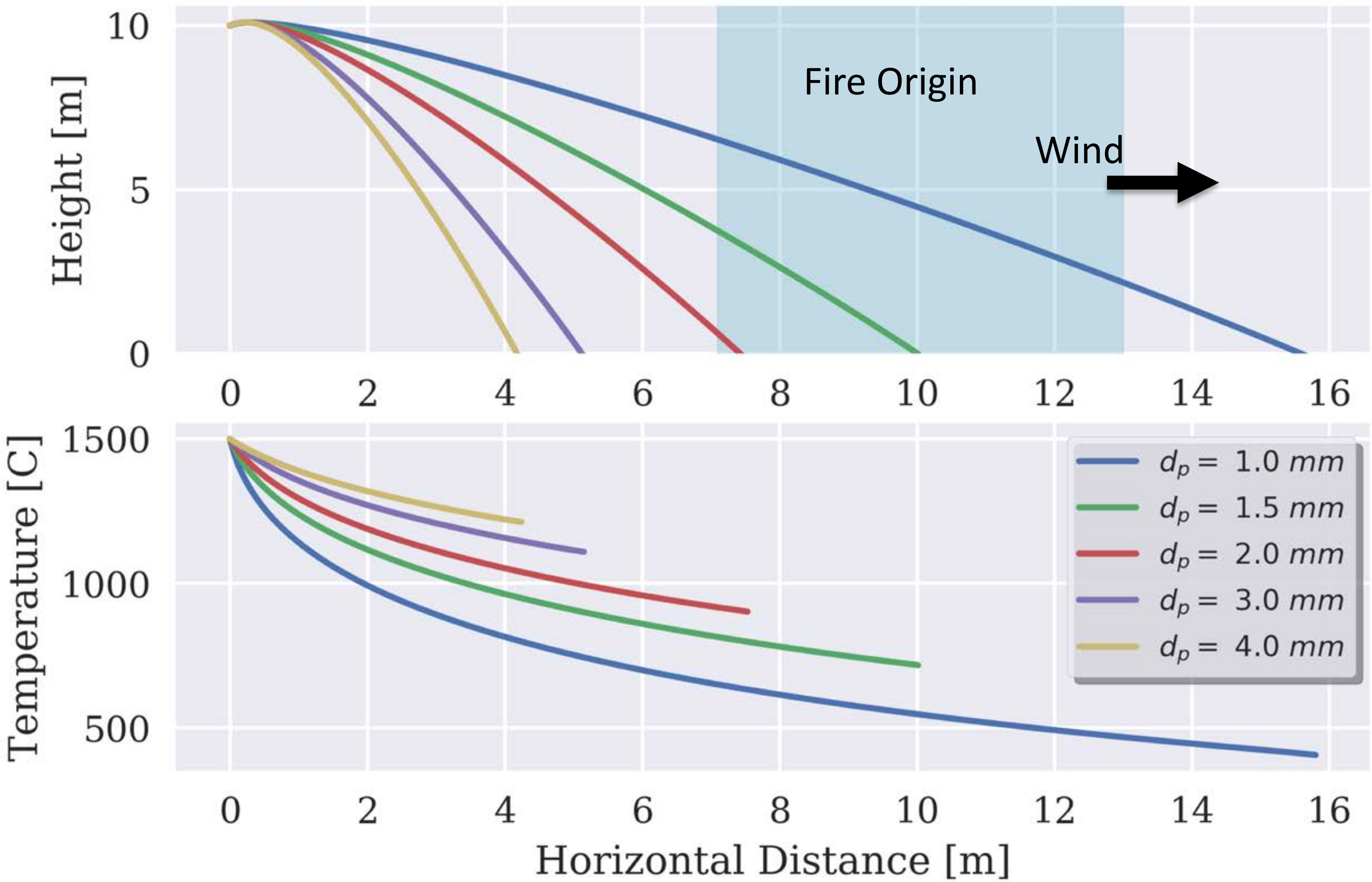
Trajectories Welding Steel Sparks



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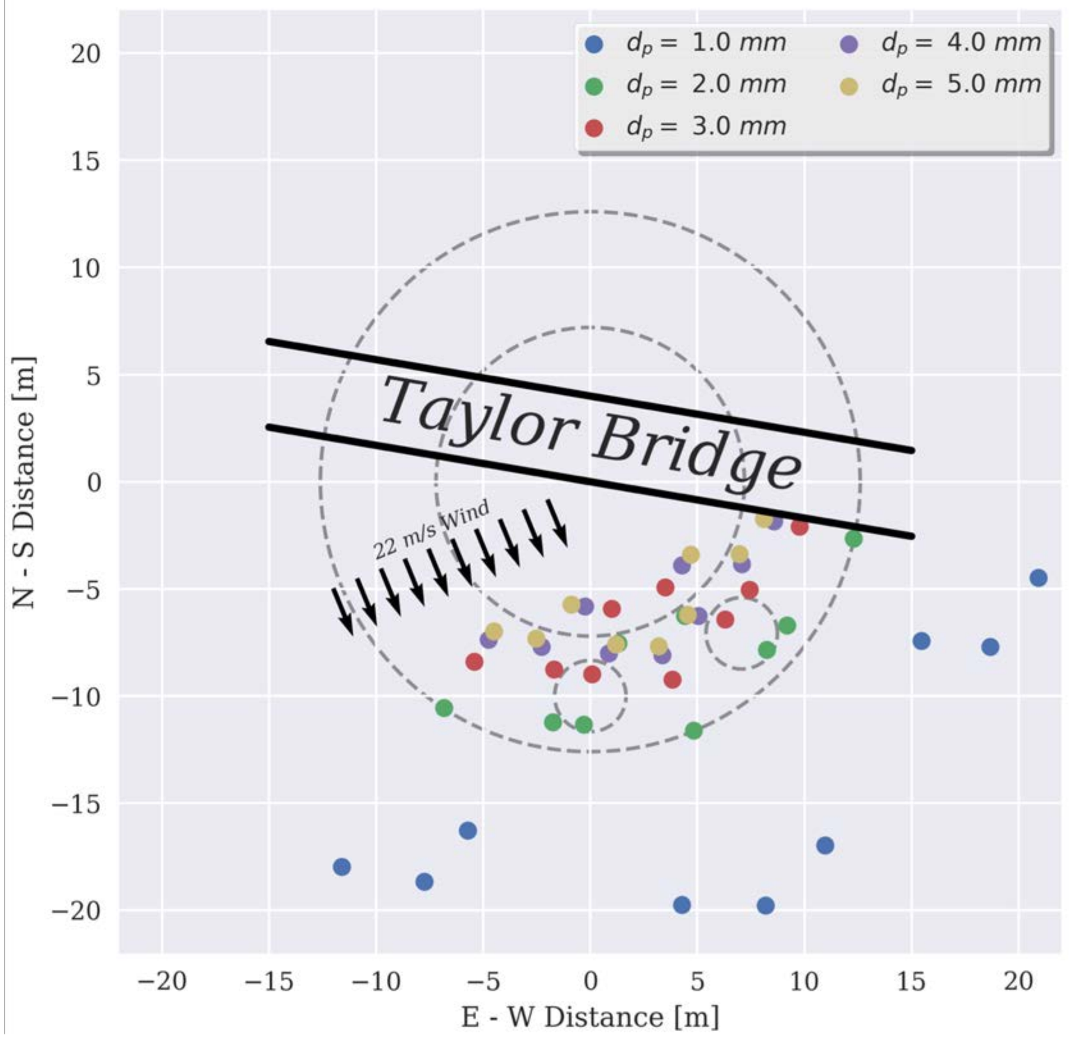
Welding Sparks: landing locations



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Firebrand/ember generation and evolution

Firebrand Generation (NIST)

Embers generated by burning trees

Embers from “Dragon” apparatus
Manzello et al

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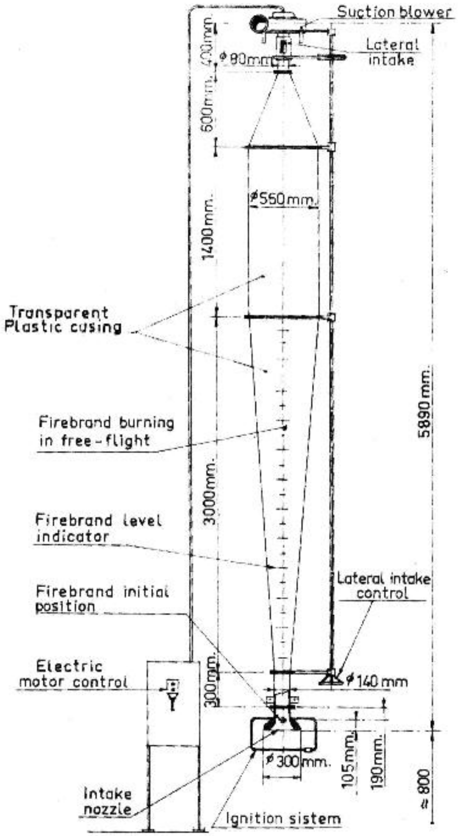
Firebrand characteristics evolution



Tarifa et.al

Manzello et al.

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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

$$\frac{\mathrm{d}\left(D_{eff}^2\right)}{\mathrm{d}t} = -\beta$$

- 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)

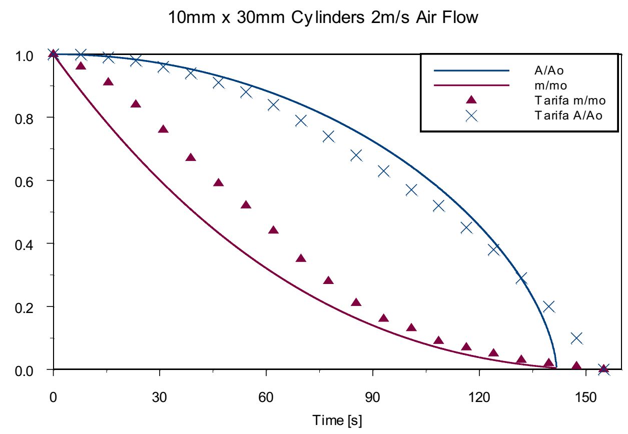
$$\frac{\mathrm{d}\left(D_{P,cyl}^4\right)}{\mathrm{d}t} = -\frac{2\beta^2 t}{\sqrt{3}}$$

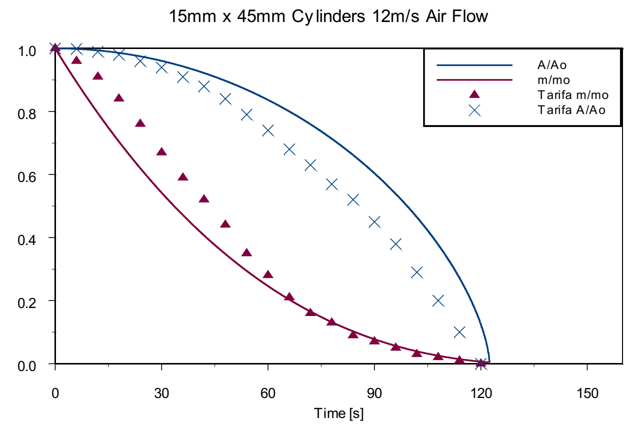
- Charring and non-charring
- Various mass extinction ratios
- Burning constant for both cases & geometries modified by Re and Pr

$$\beta = \beta_0\left(1 + 0.276\,\mathrm{Re}_D^{\frac{1}{2}}\,\mathrm{Pr}^{\frac{1}{3}}\right)$$

$\beta_0 = 1.8*10^{-7} m^2/s$

Fit to Tarifa for β_0 for cylinders





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Ember Combustion Model

Pyrolysis of dry wood

Endothermic global reaction in depth

$$virgin\ dry\ wood \rightarrow \nu_c Char + (1-\nu_c)\left[(1-\nu_s)GPP + \nu_s Soot\right]$$

Char combustion

Exothermic one-step char oxidation reaction

$$C_{(s)} + \frac{1}{2}O_{2(g)} \longrightarrow CO_{(g)}$$

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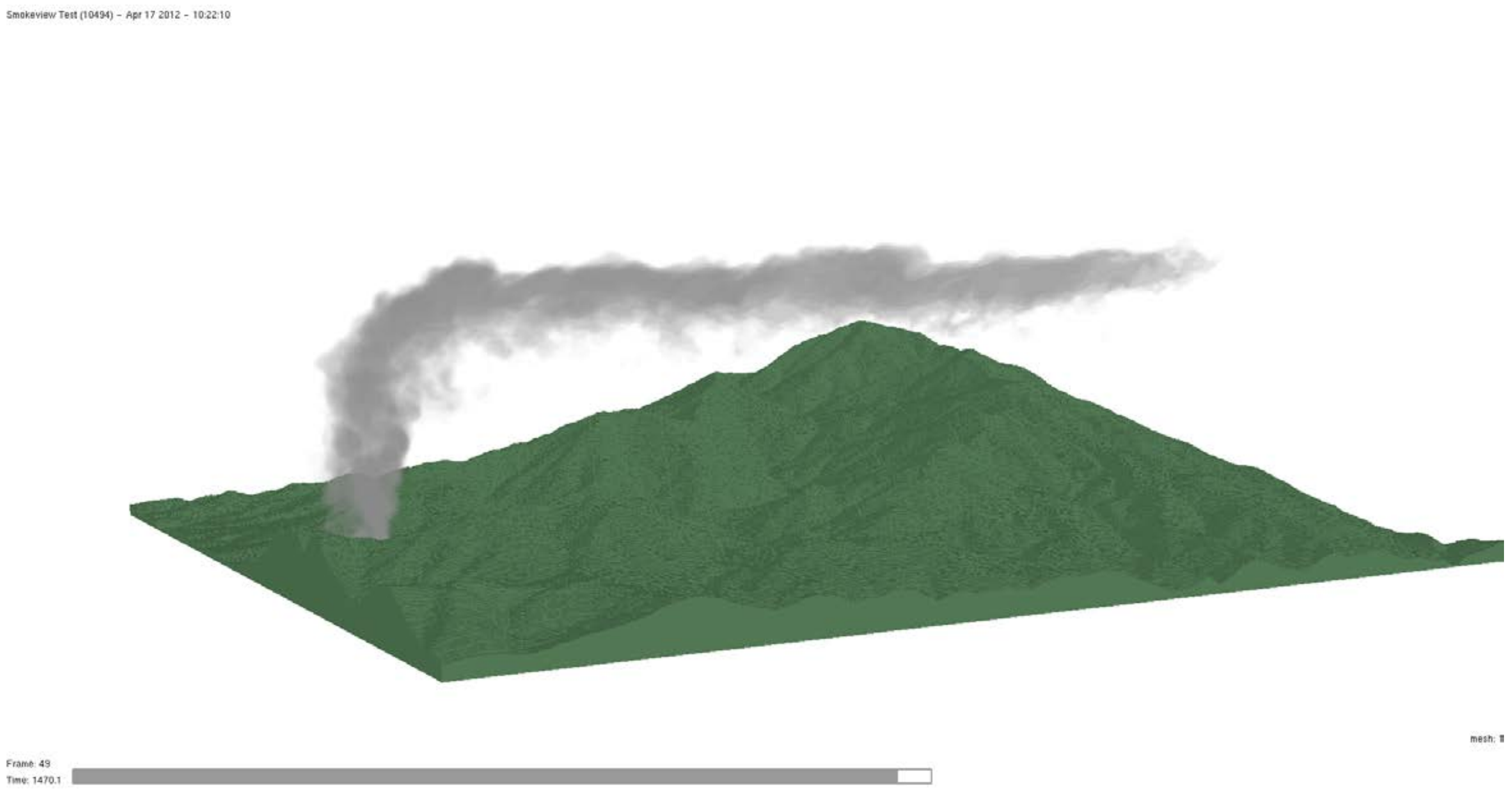
Fire Plume Modeling



C. Lautenberger, Reax Eng.

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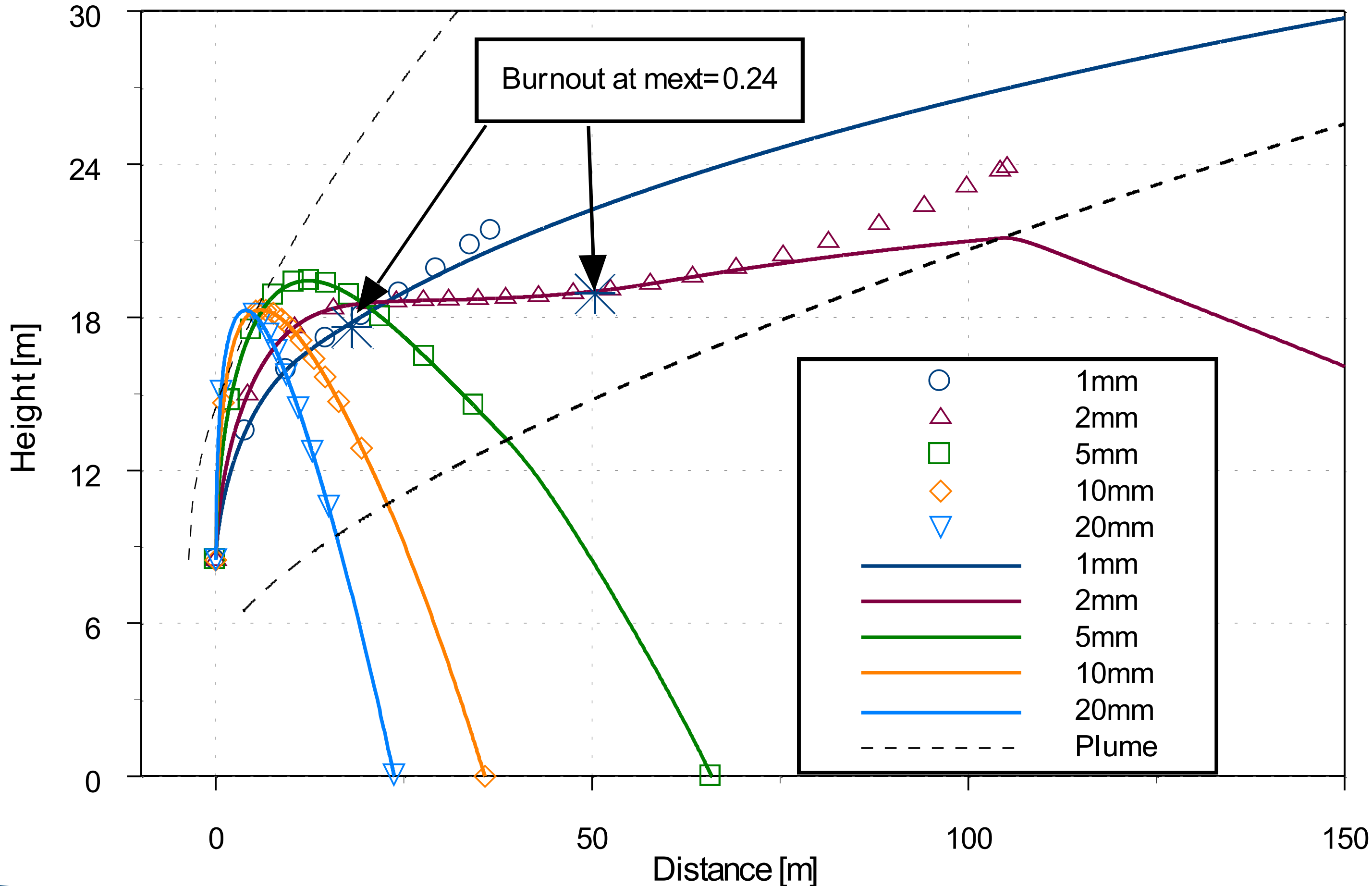
Embers lofted in fire plume and transported in wind



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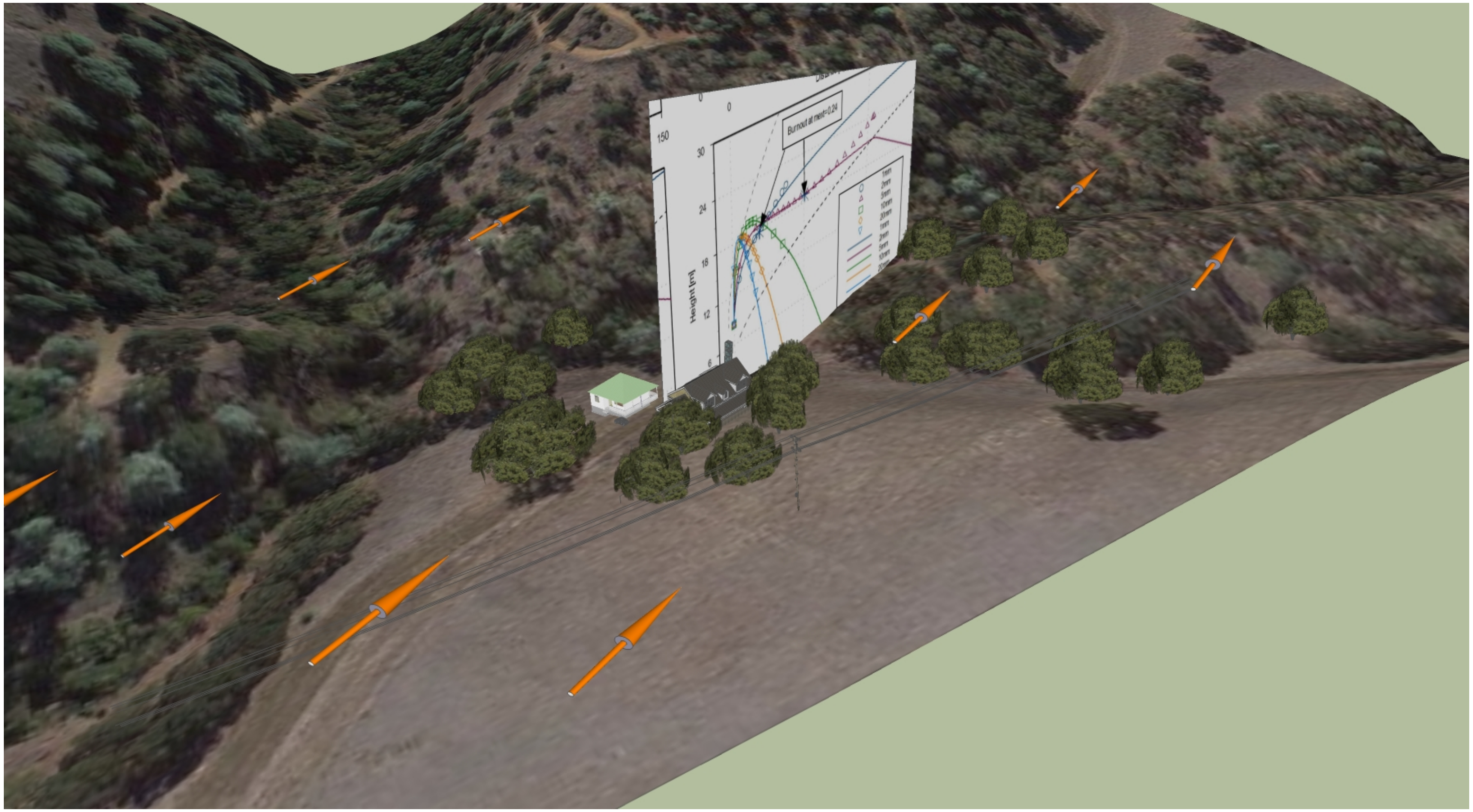
Application of embers trajectories



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?

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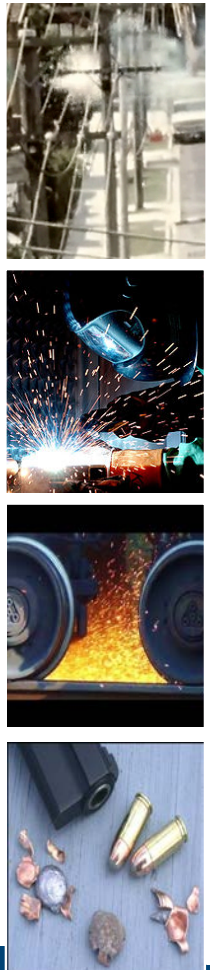
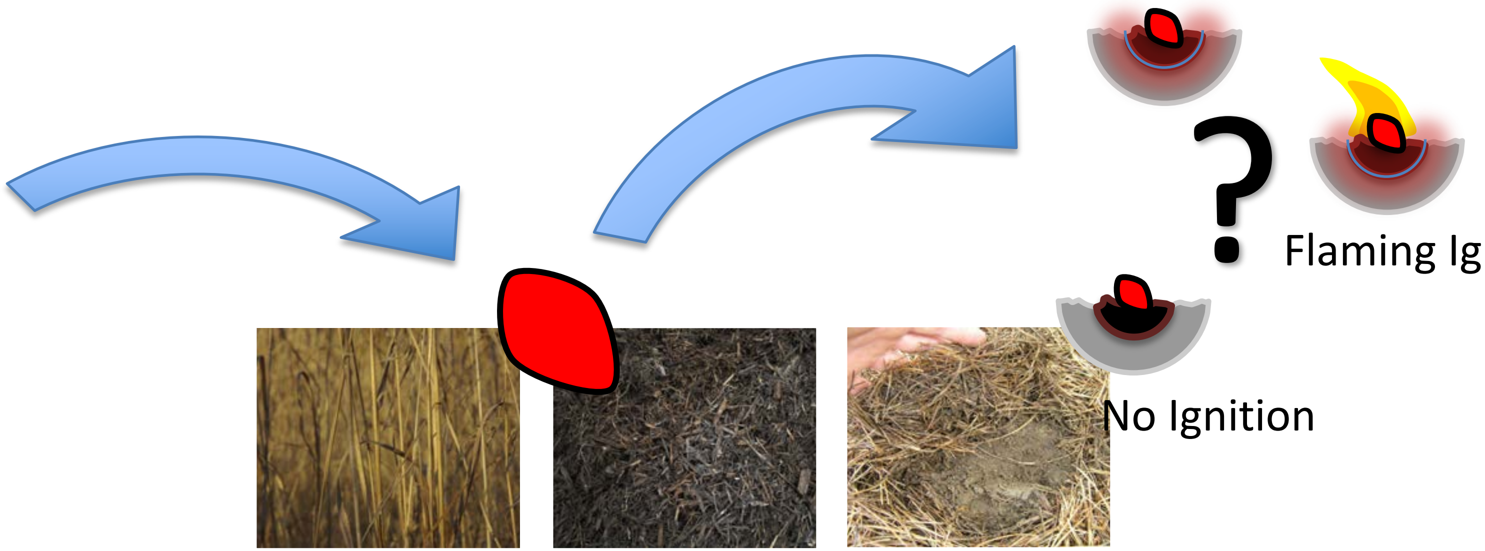
Ignition Process

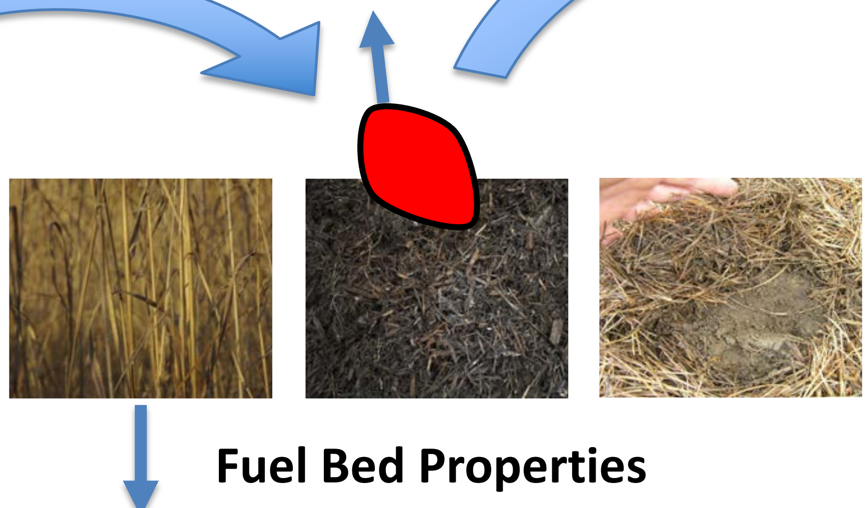




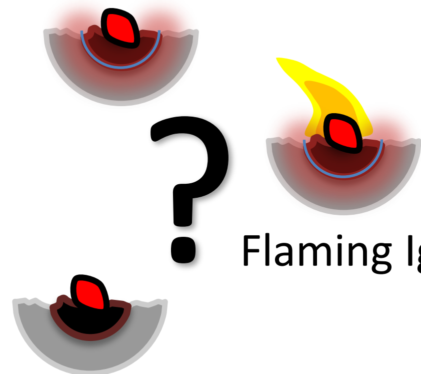
What are the controlling parameters?




Particle Properties
- Temperature
- Size
- Material



Fuel Bed Properties
- Chemical Composition
- Morphology
- Moisture Content



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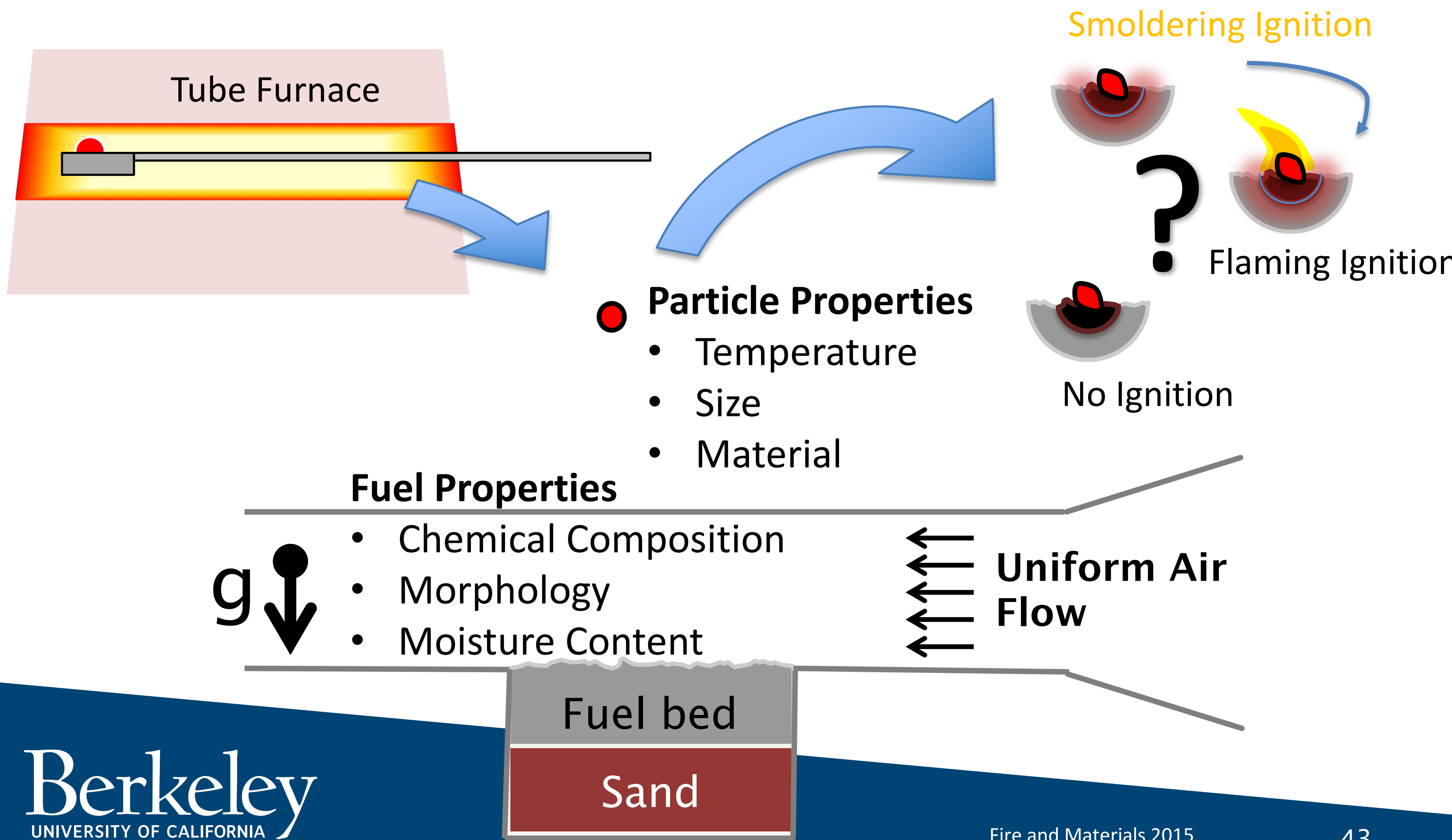
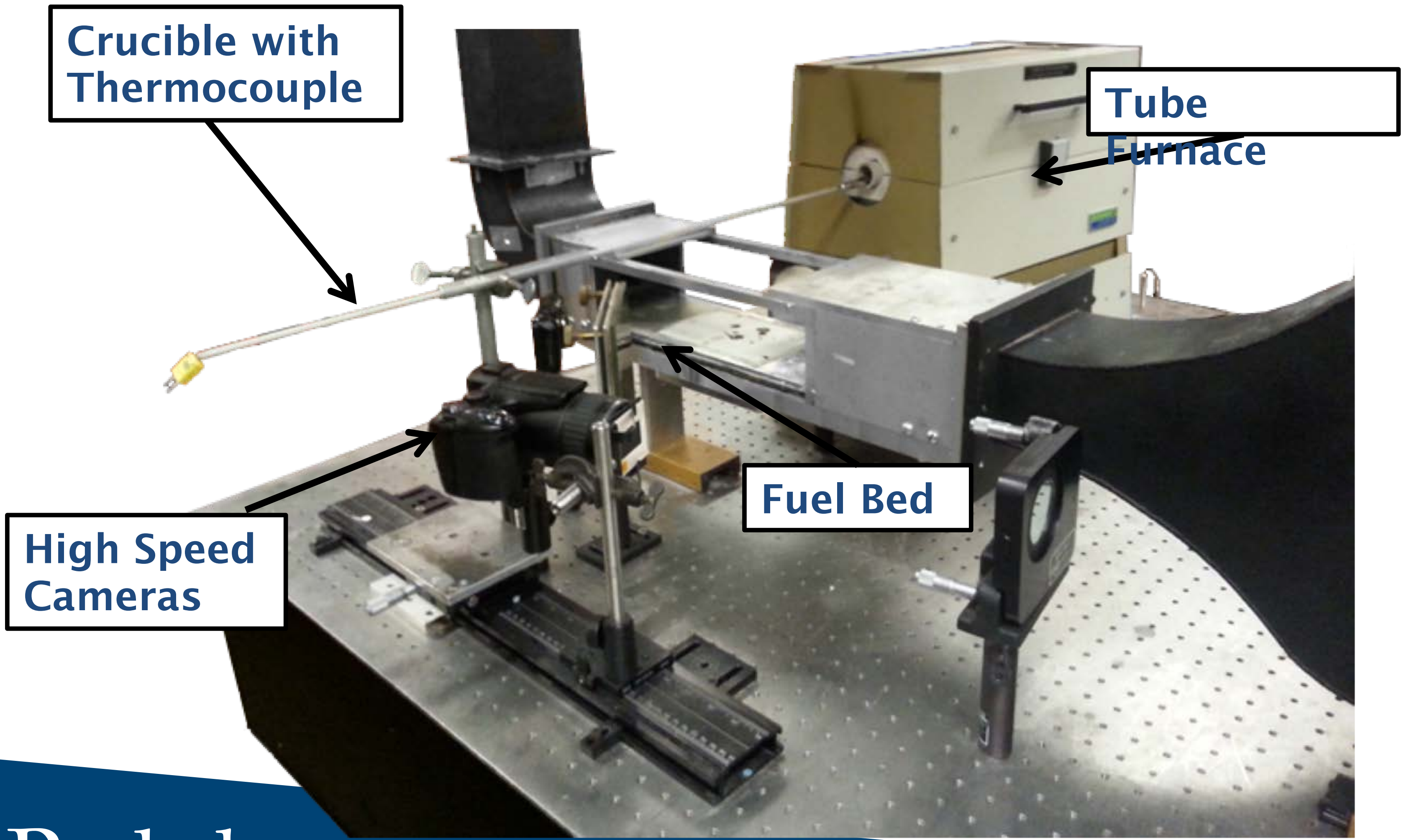
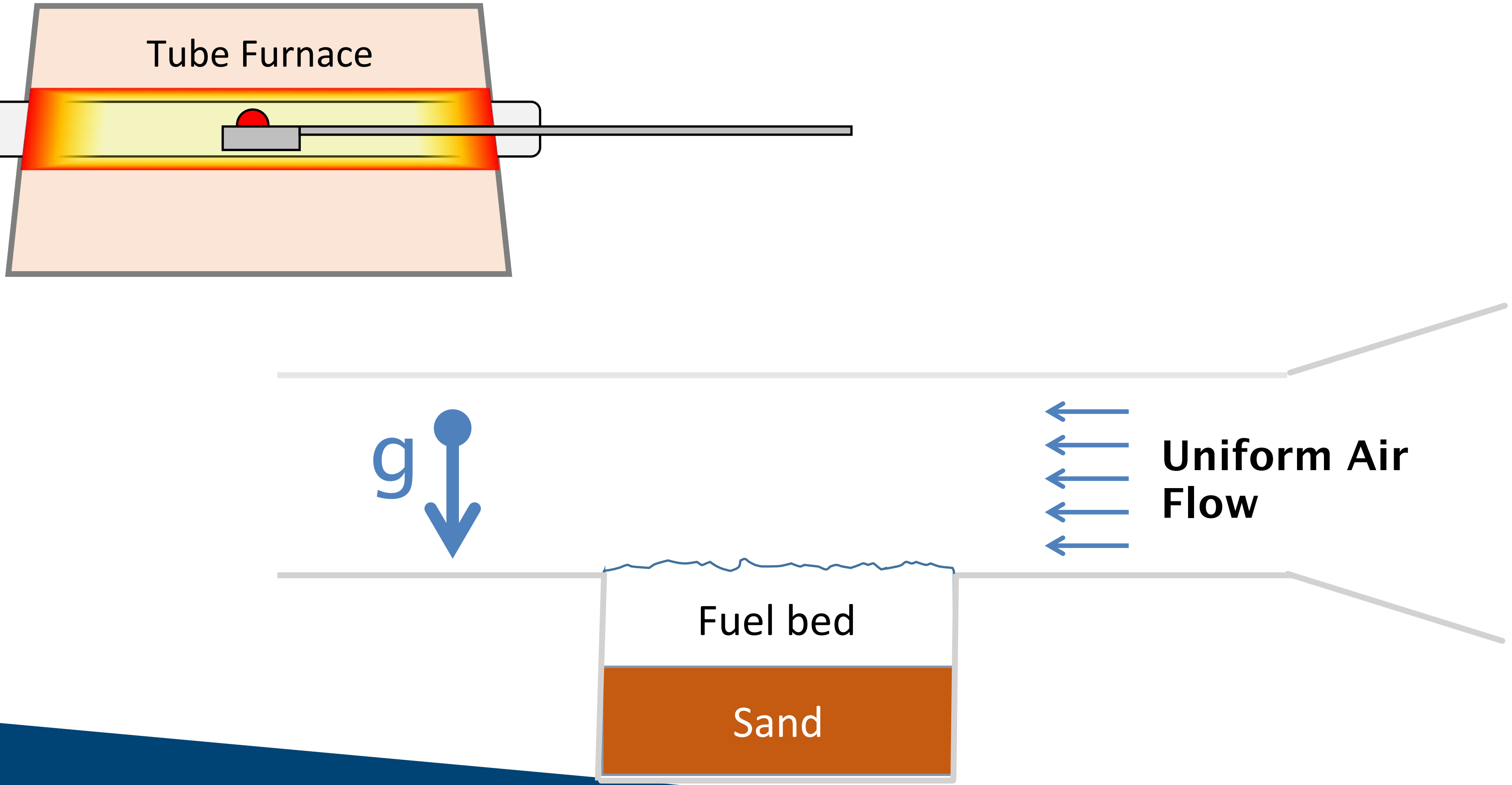
How spot ignition can be tested?



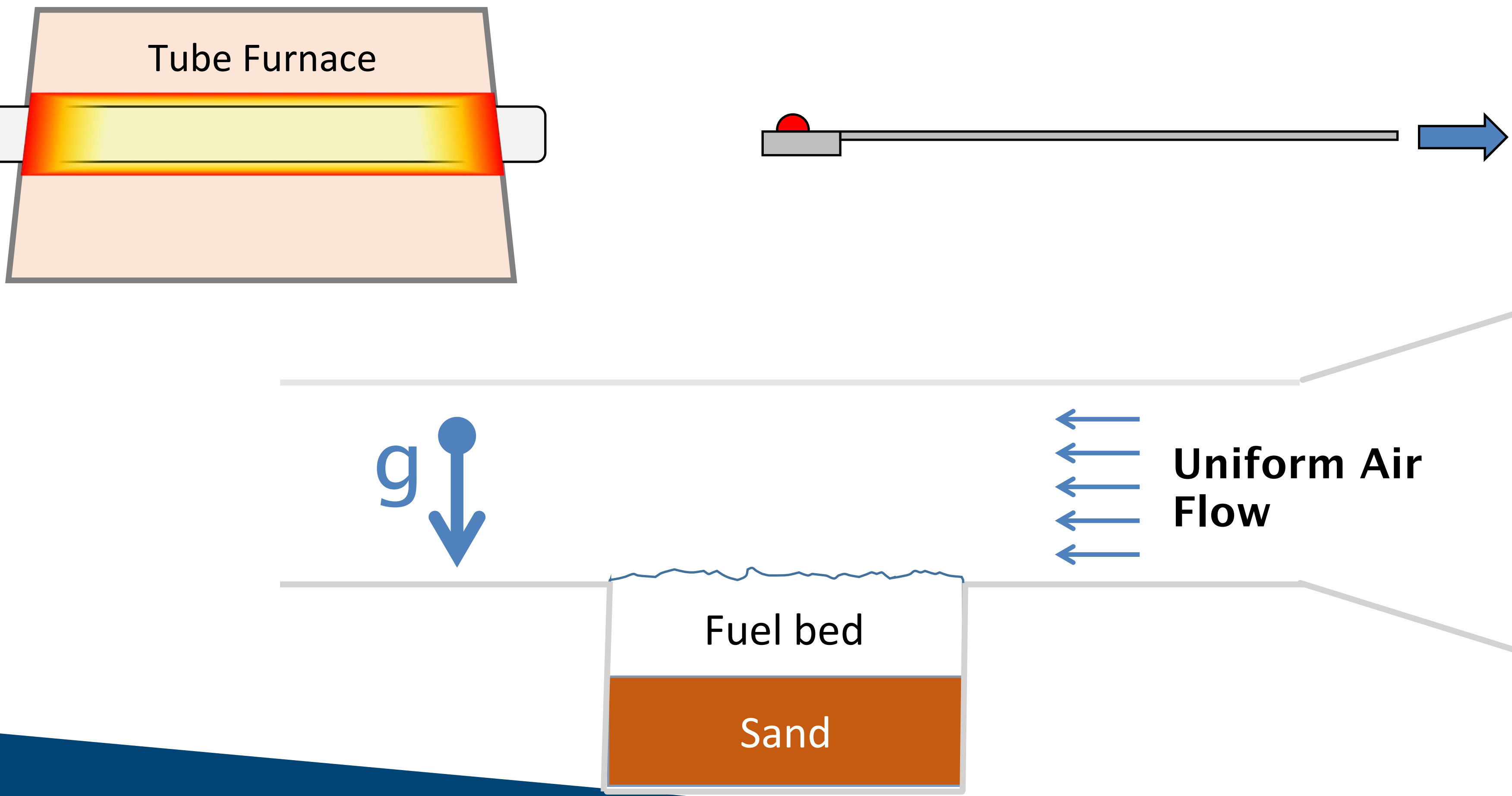
Experimental Apparatus :UC Berkeley



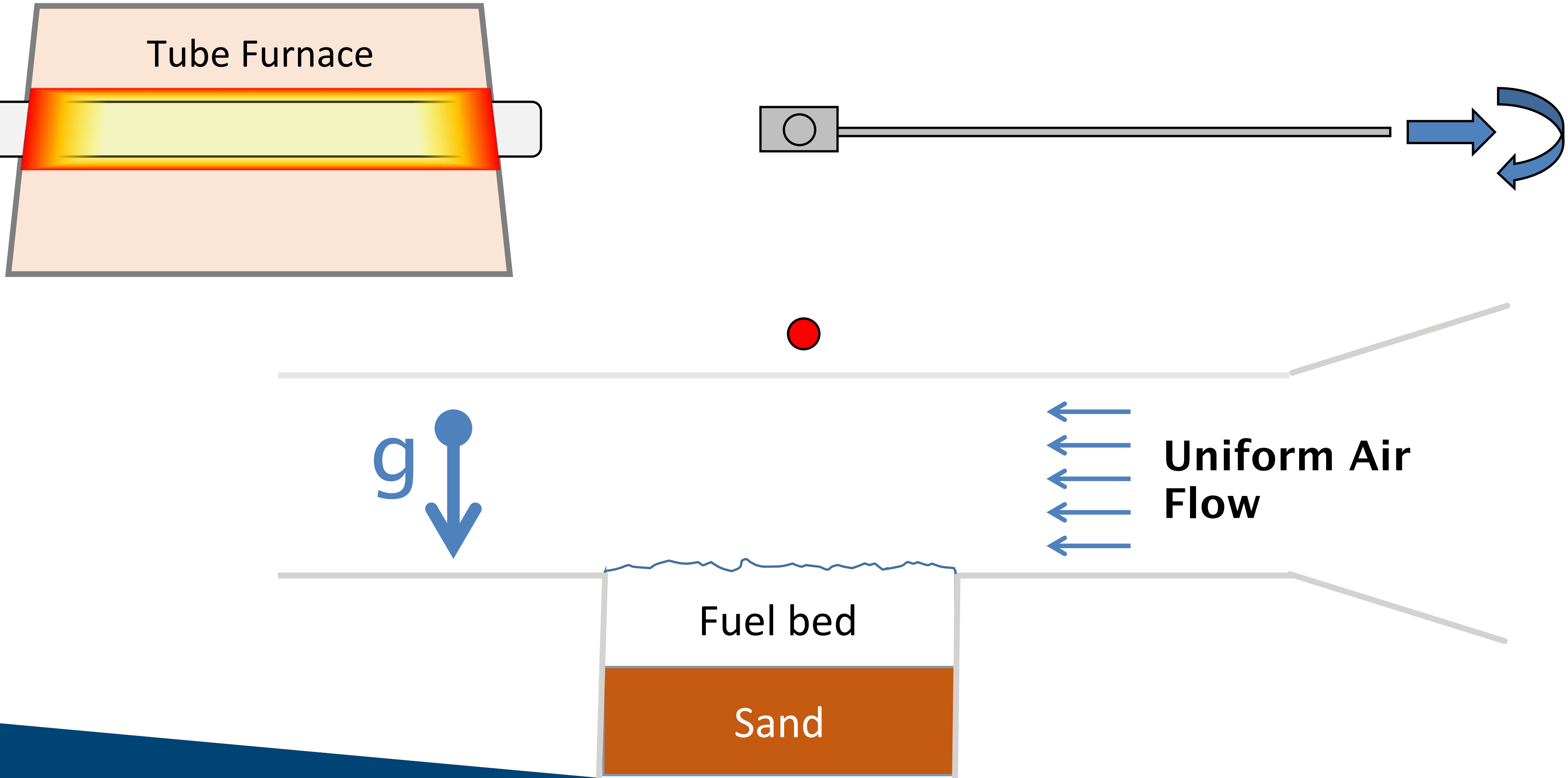
Experimental Procedure



Experimental Procedure



Experimental Procedure



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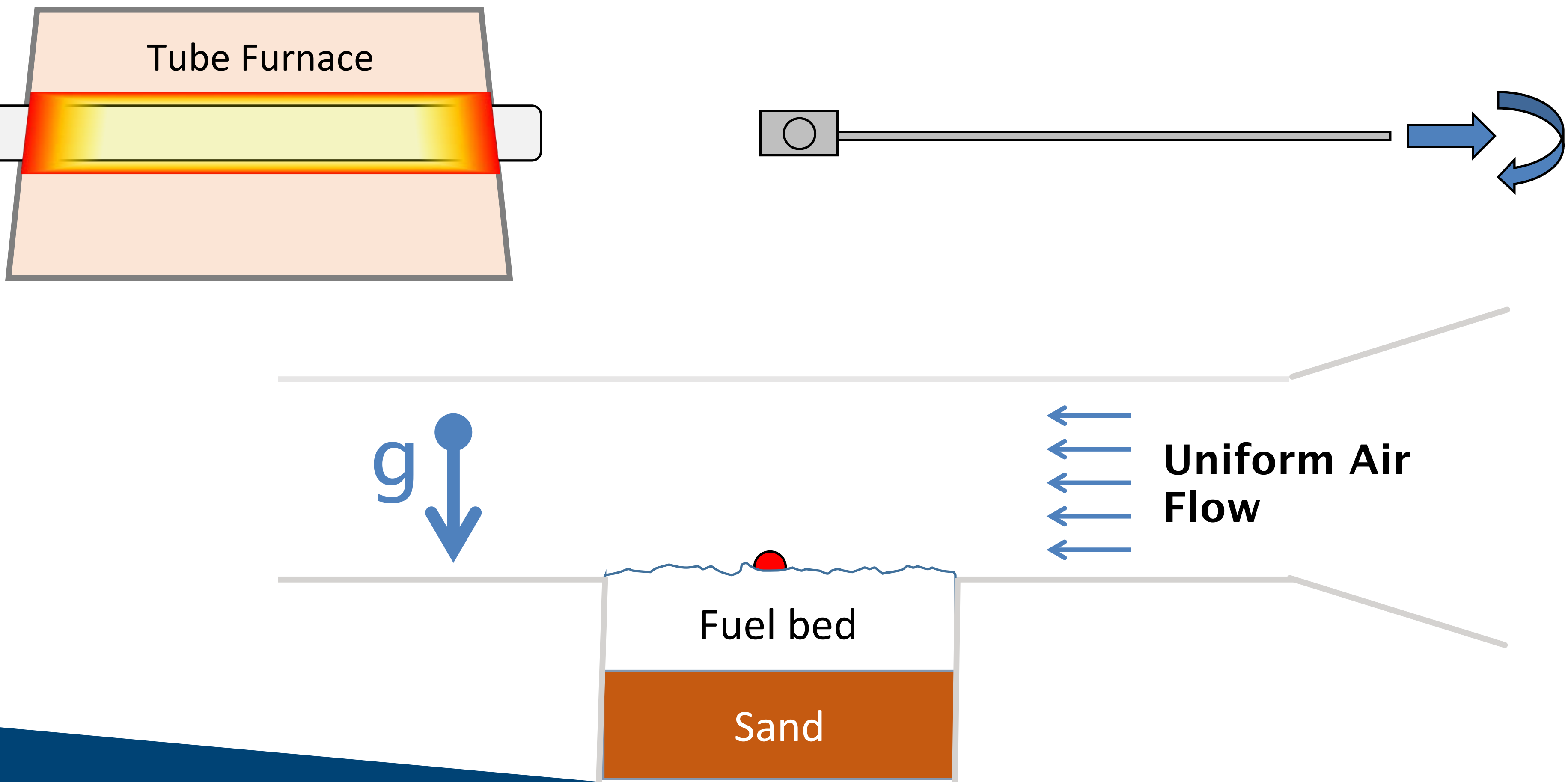
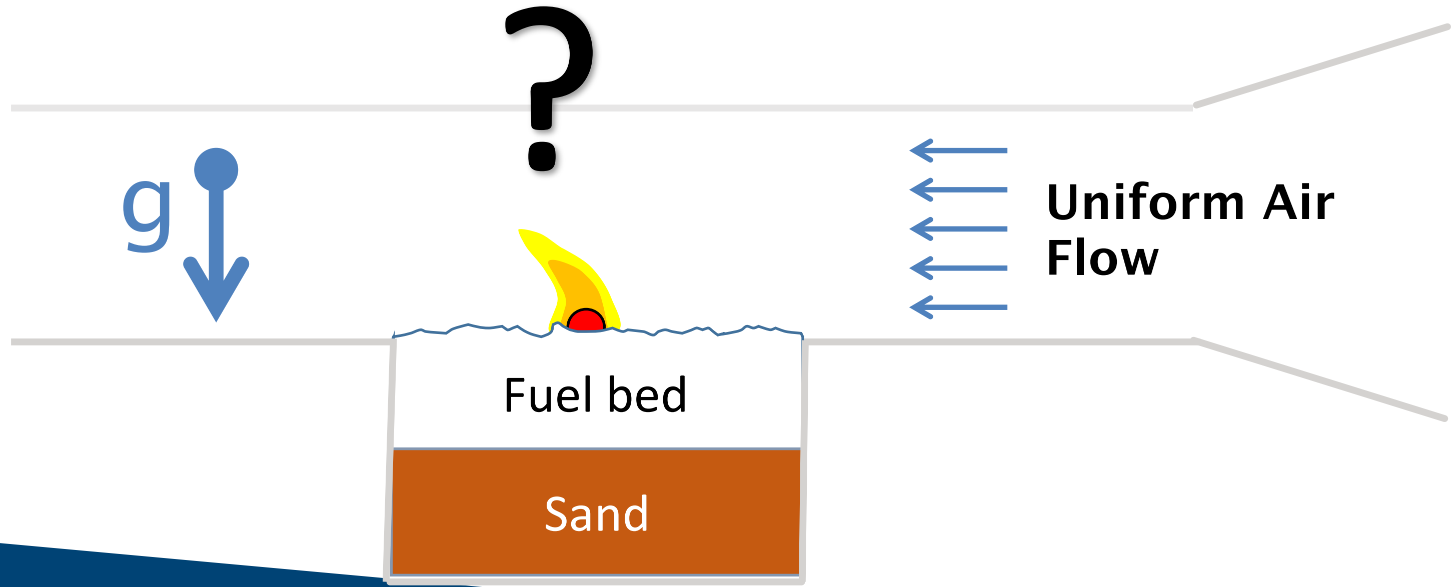
Experimental Procedure



Experimental Procedure



Video of a test

(steel particle landing in pine needles)

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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)

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Effect of Metal type: Cellulose Fuel Bed

- Surrogate Fuel: Powdered α-cellulose
  - Largest component of woody biomass
  - Chemically homogeneous
  - Physically uniform
- Lab conditioned
- (Moisture Content ~6.0%)
- Density: 338 kg/m^3

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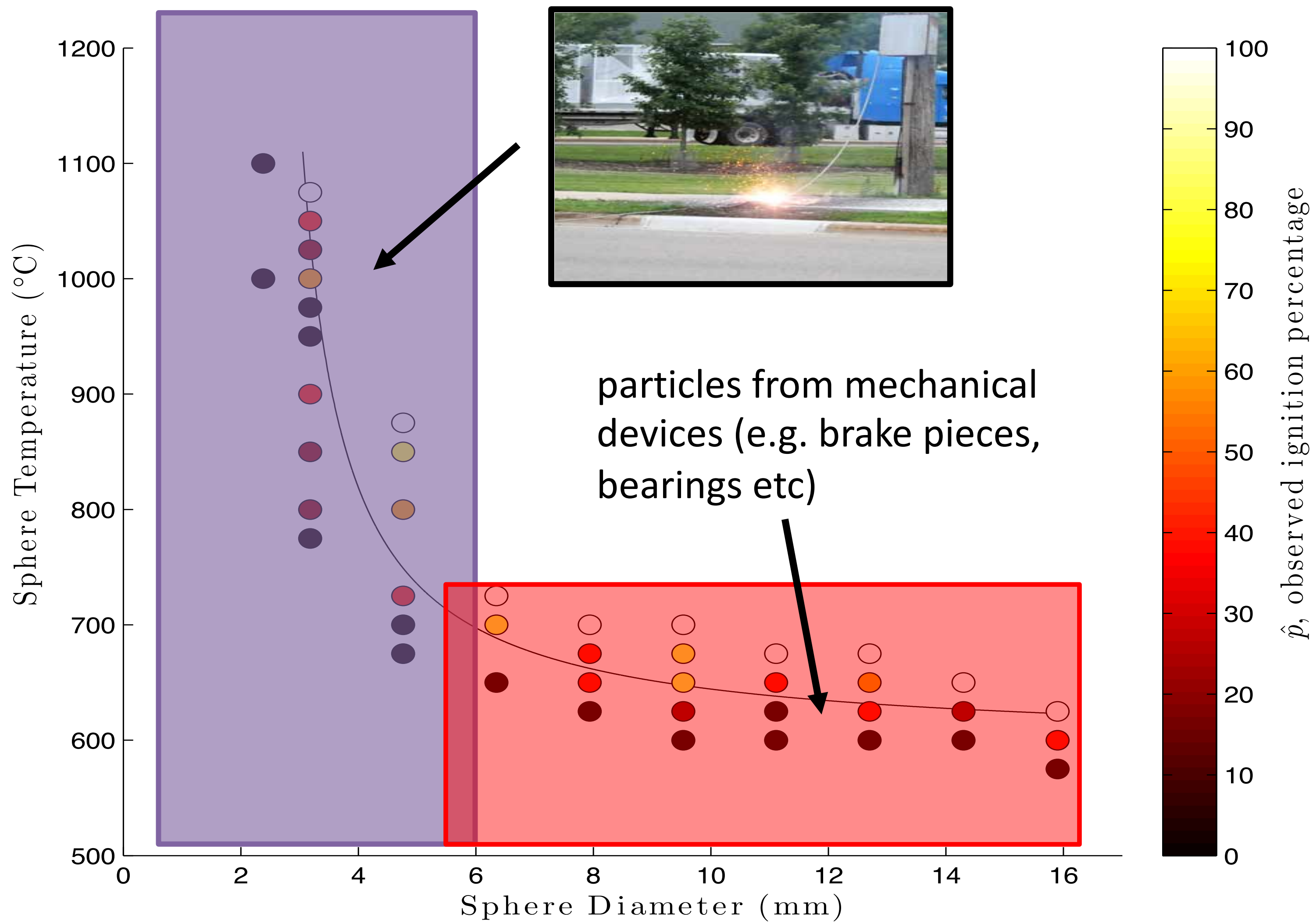
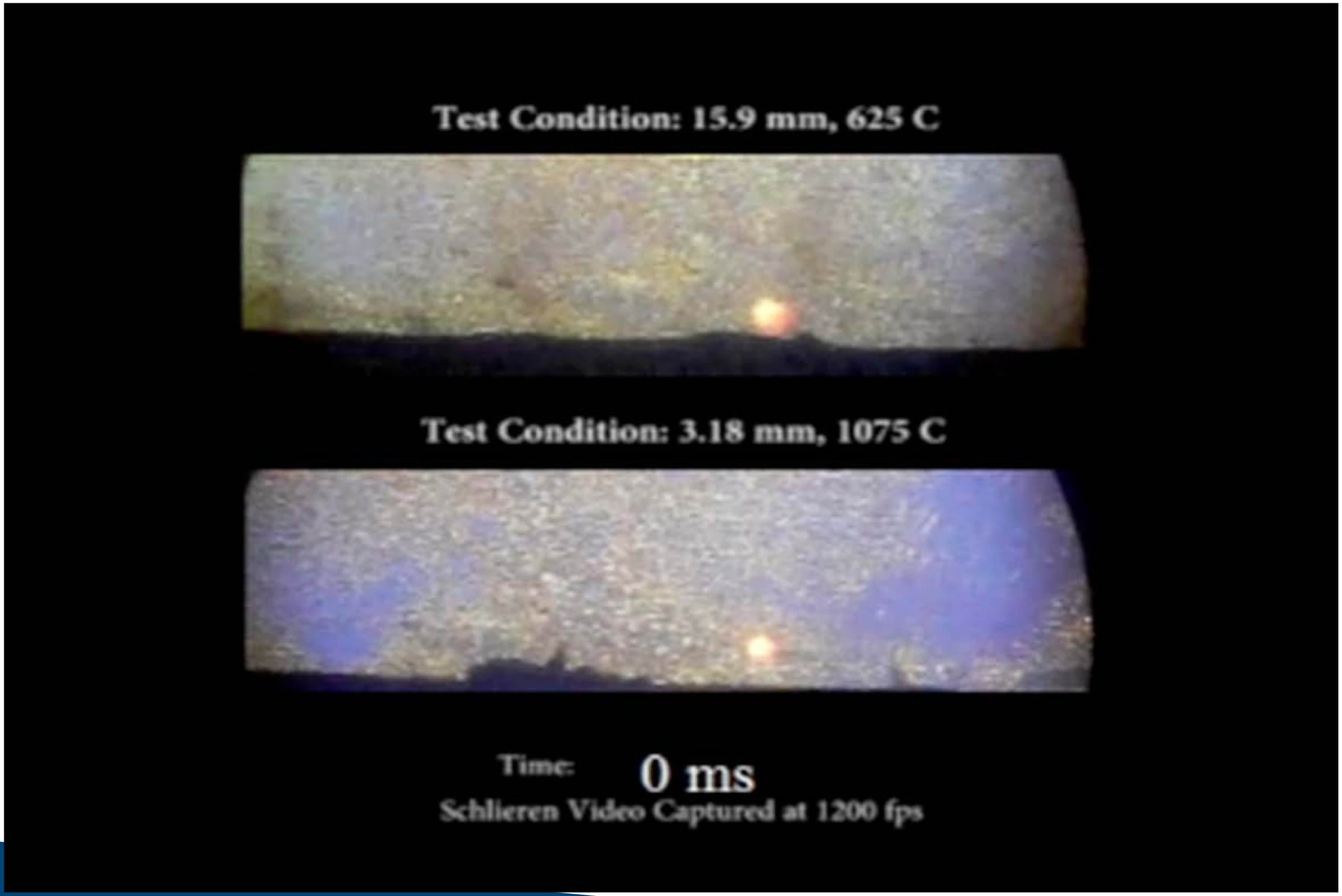
Cellulose Flaming Ignition by Steel Particles



Schlieren Videos: Ignition by large and small particles



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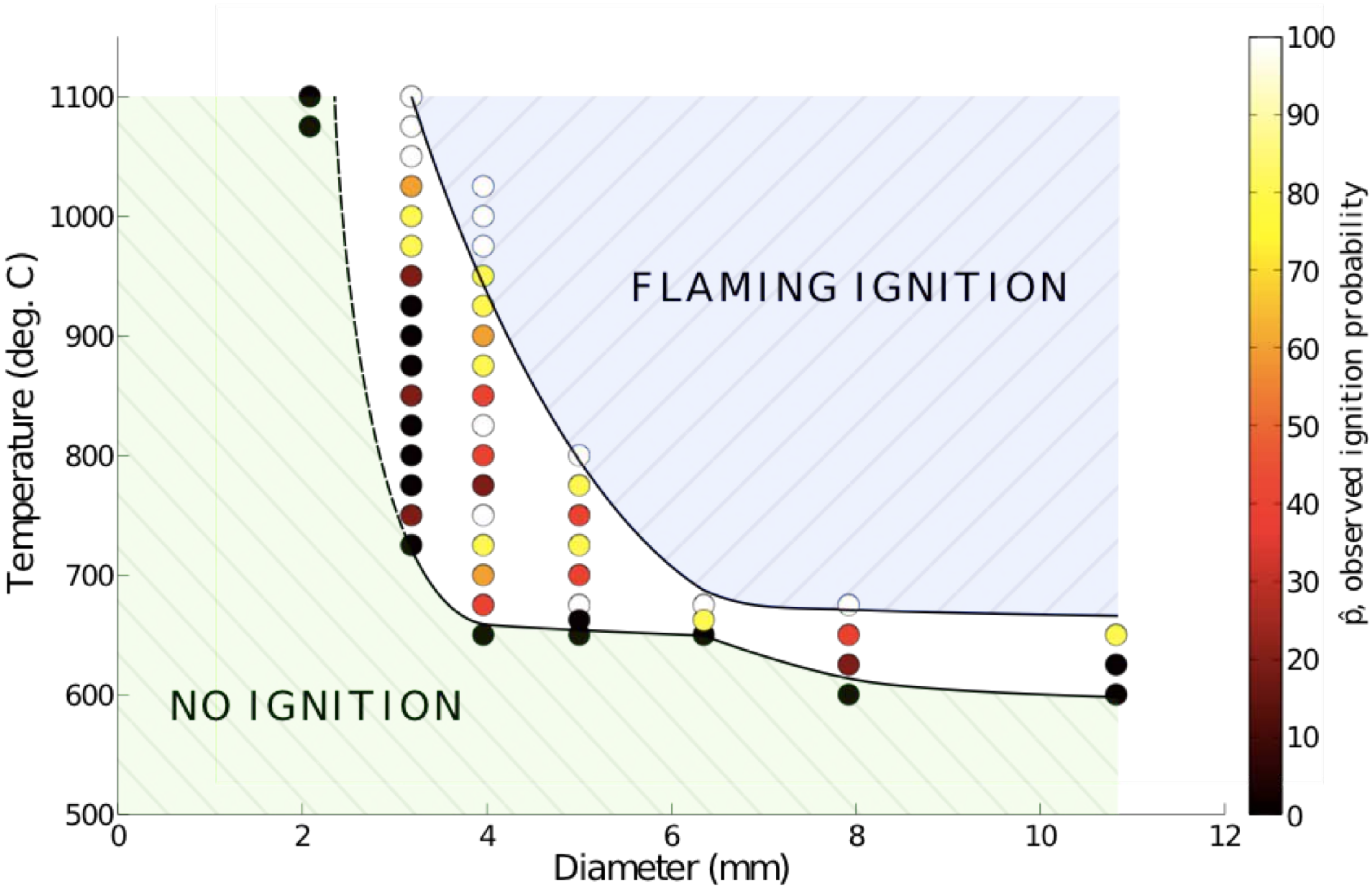
Schlieren Videos: Observations

- 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



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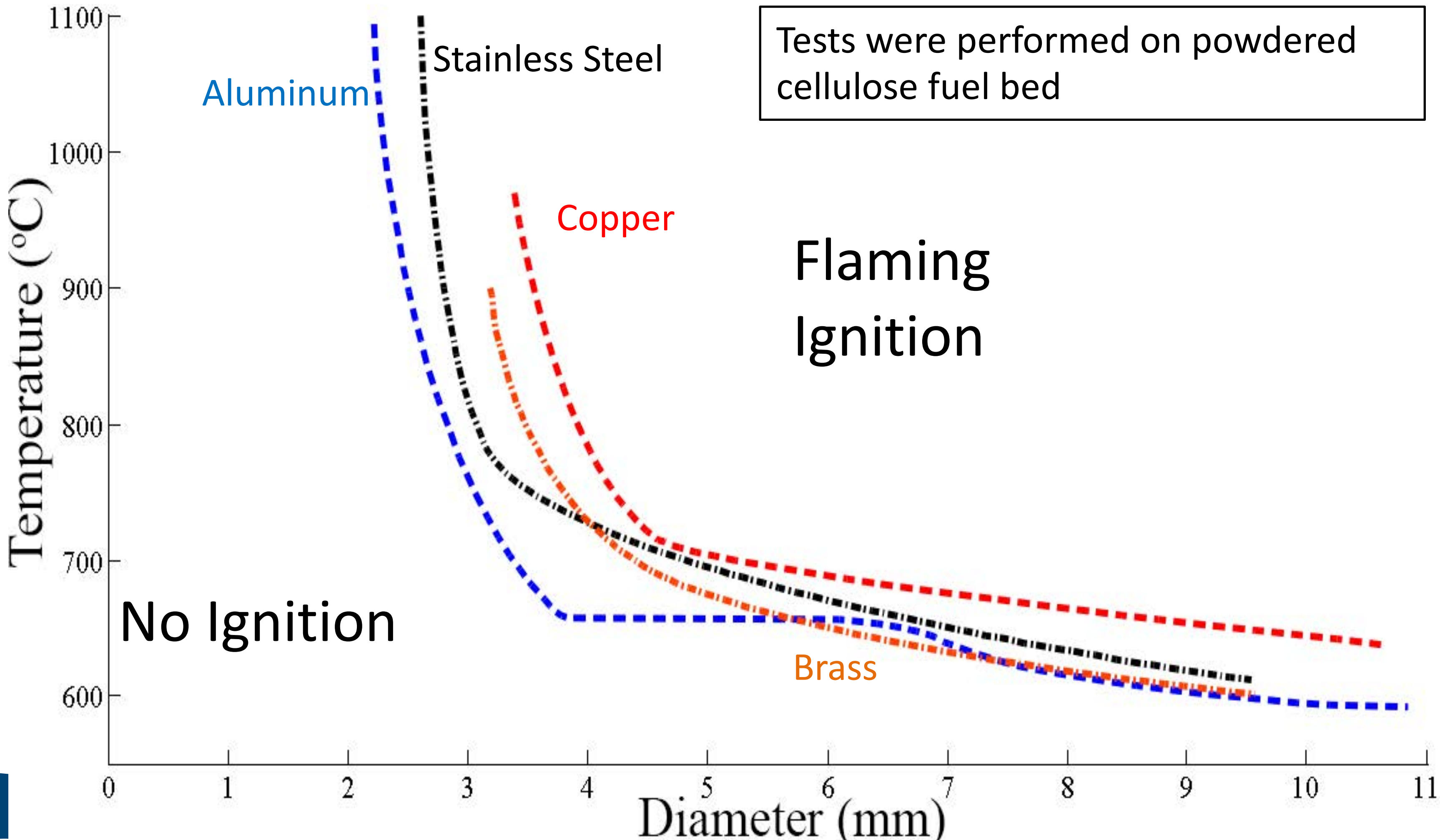
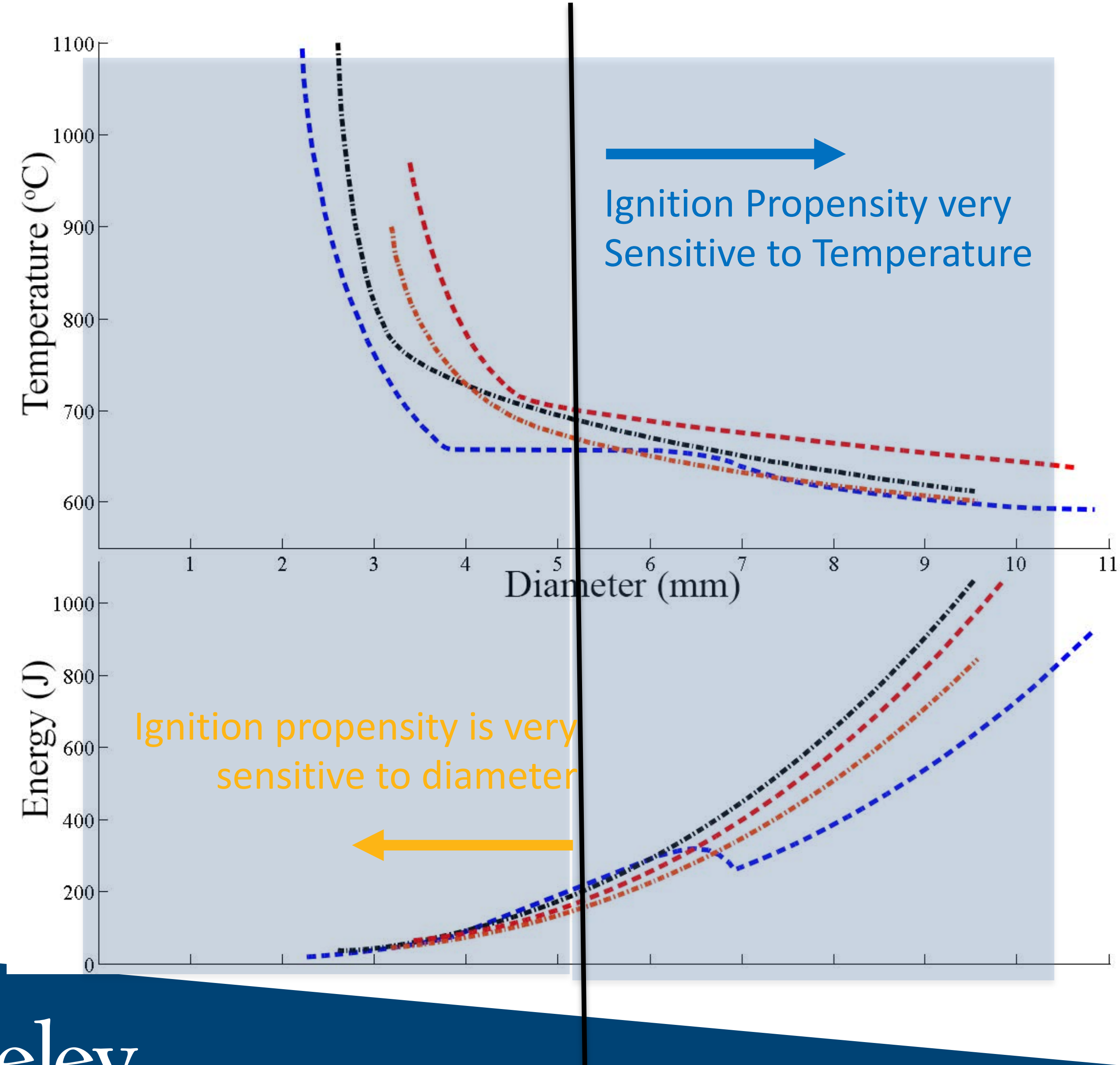
Effect of Particle Material



Flaming Ignition: Temperature and Energy



Natural Fuel Beds Tested

(a) Cellulose Powder

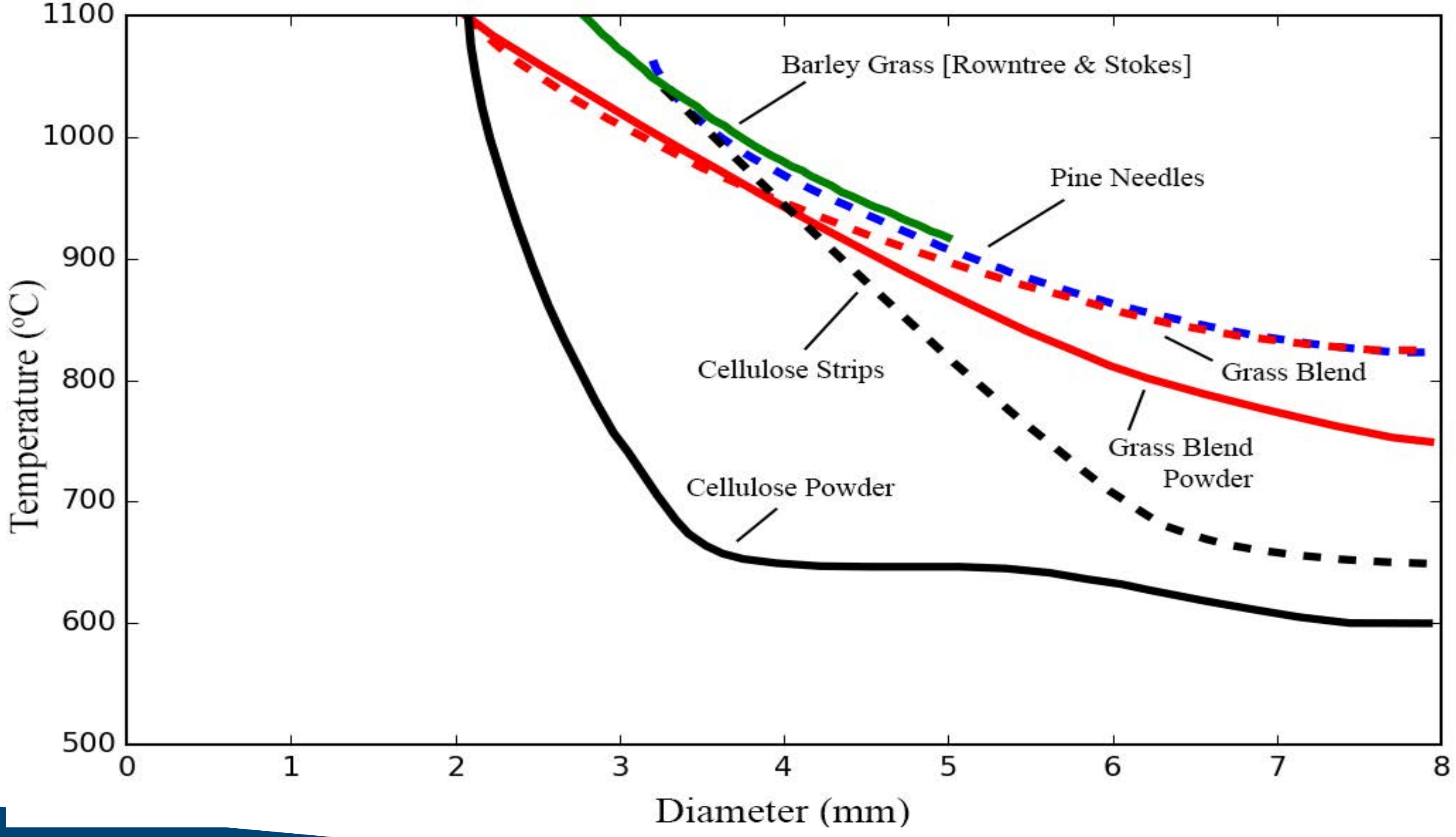
(b) Grass Powder

(e) Pine Needles

(c) Cellulose Strips

(d) Grass Blend

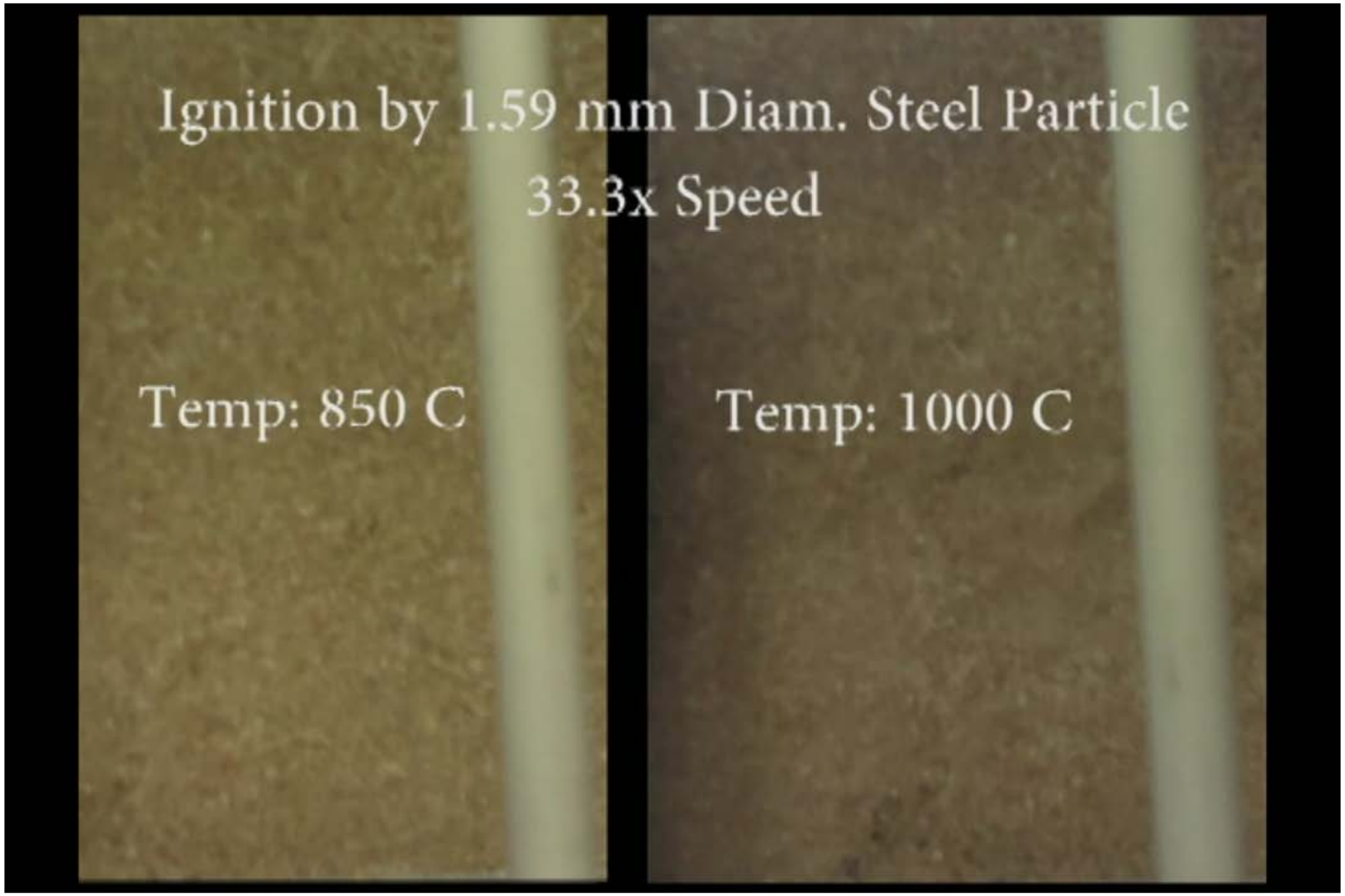
Flaming Ignition Boundaries: Aluminum Particles



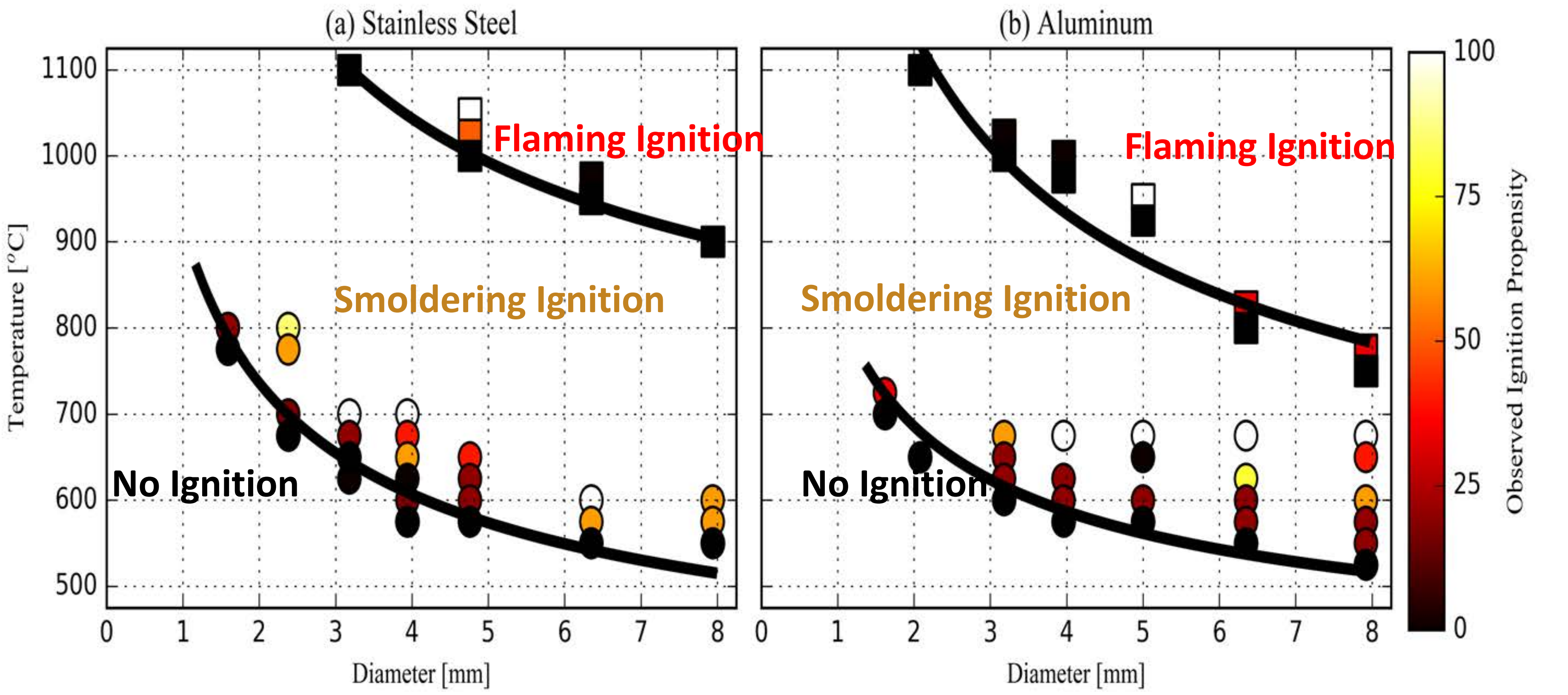
Smoldering vs. Flaming Ignition

Smoldering Ignition-Powdered Grass

Direction of cross-flow



Experimental Ignition Boundaries



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

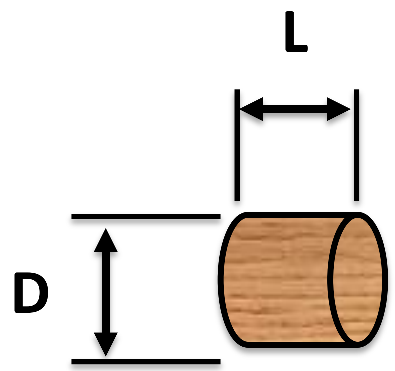
Fuel Bed: Redwood sawdust

Fuel Moisture Content (MC = m_{water}/m_{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



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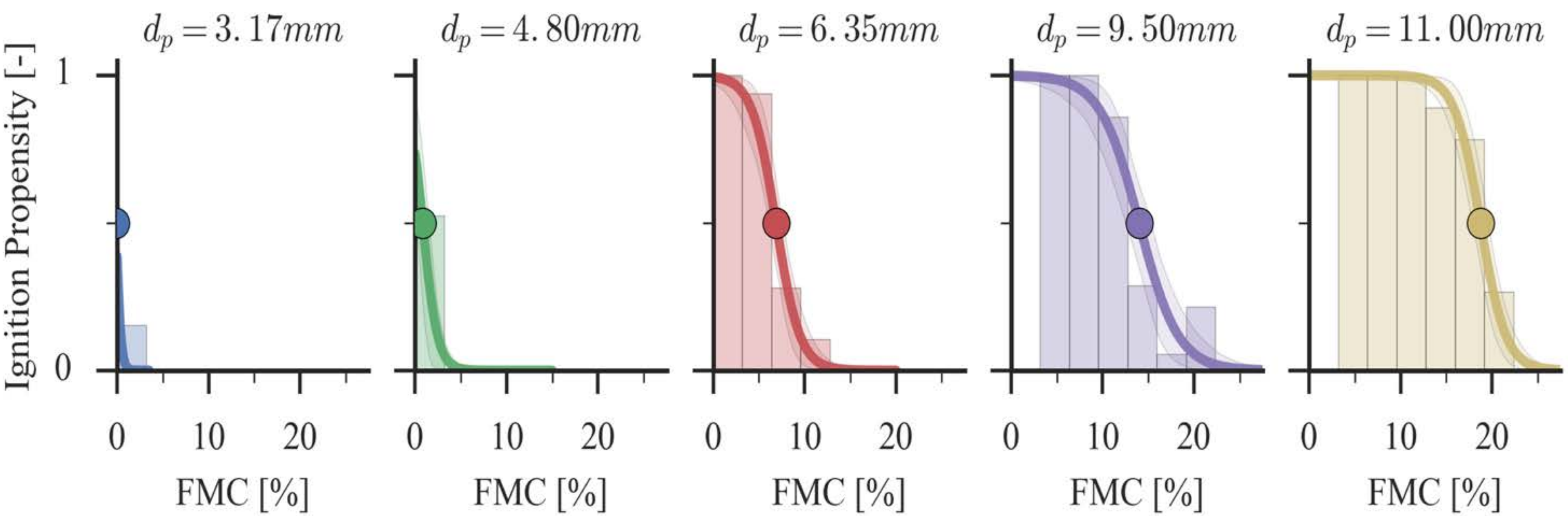
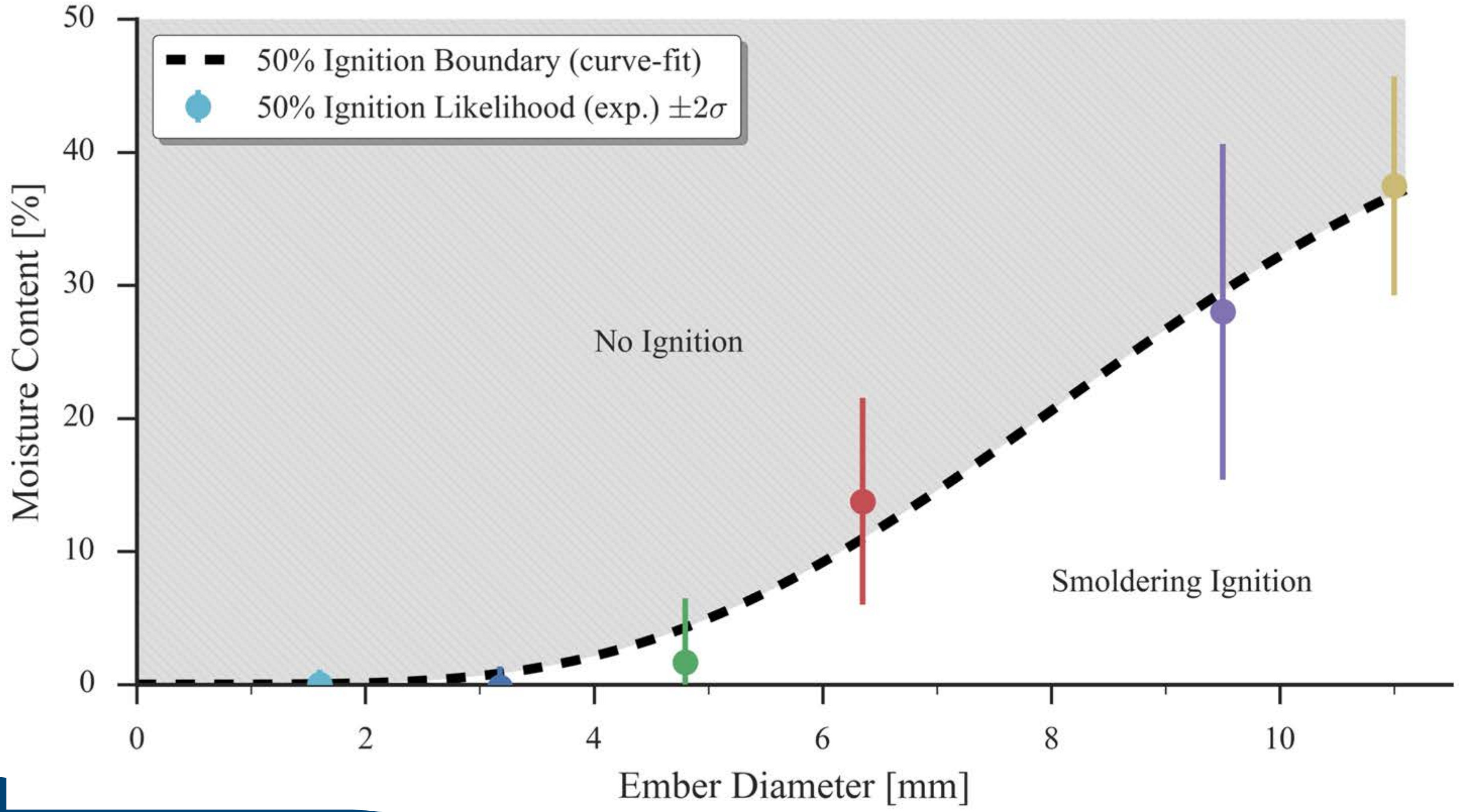
Smolder Ignition: Effect of Moisture



Smolder Ignition Boundary



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

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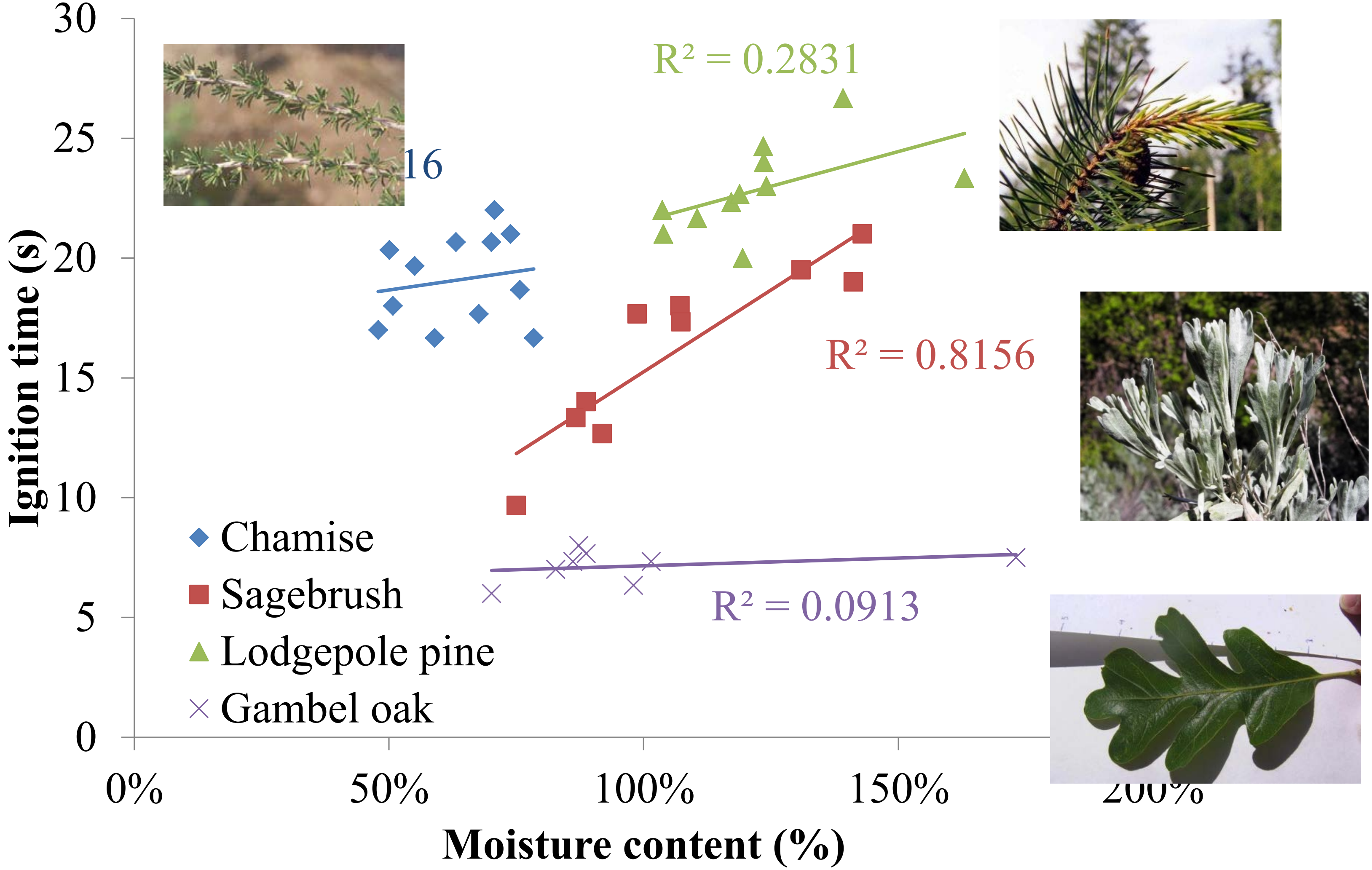
Effect of Live Fuels

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



http://www.botgard.ucla.edu/html/botanytextbooks/generalbotany/typesofshoots/longshootshortshoot/a1329tx.html
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

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Theoretical Modeling of the Ignition of Fuel Beds by Metal Particles and Embers

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Analytical Modeling

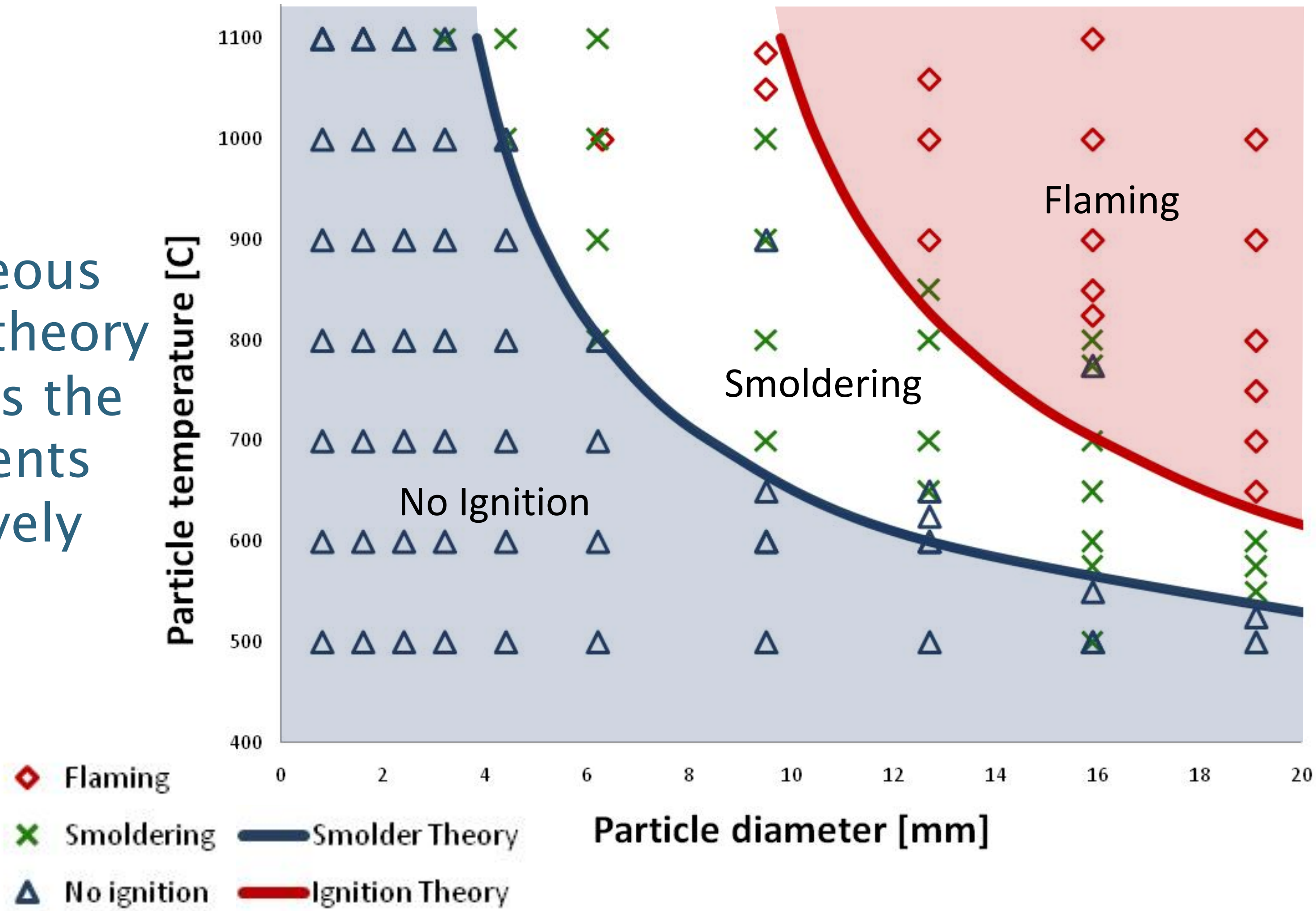
- Hot Spot Spontaneous Ignition theory gives a critical diameter for ignition of the form

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

- 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



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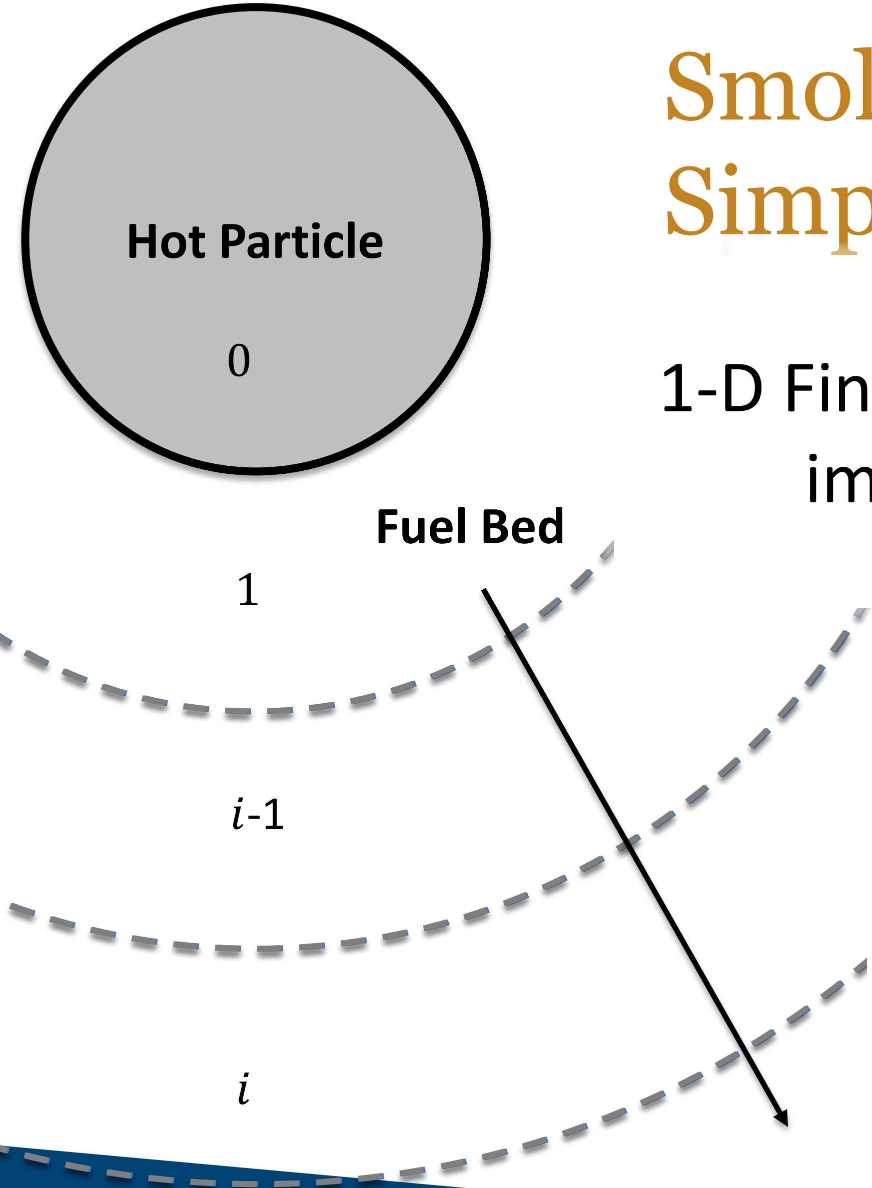
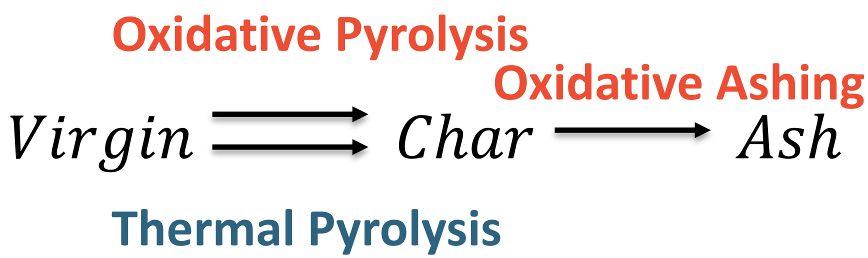
Smolder Ignition: Simplified model

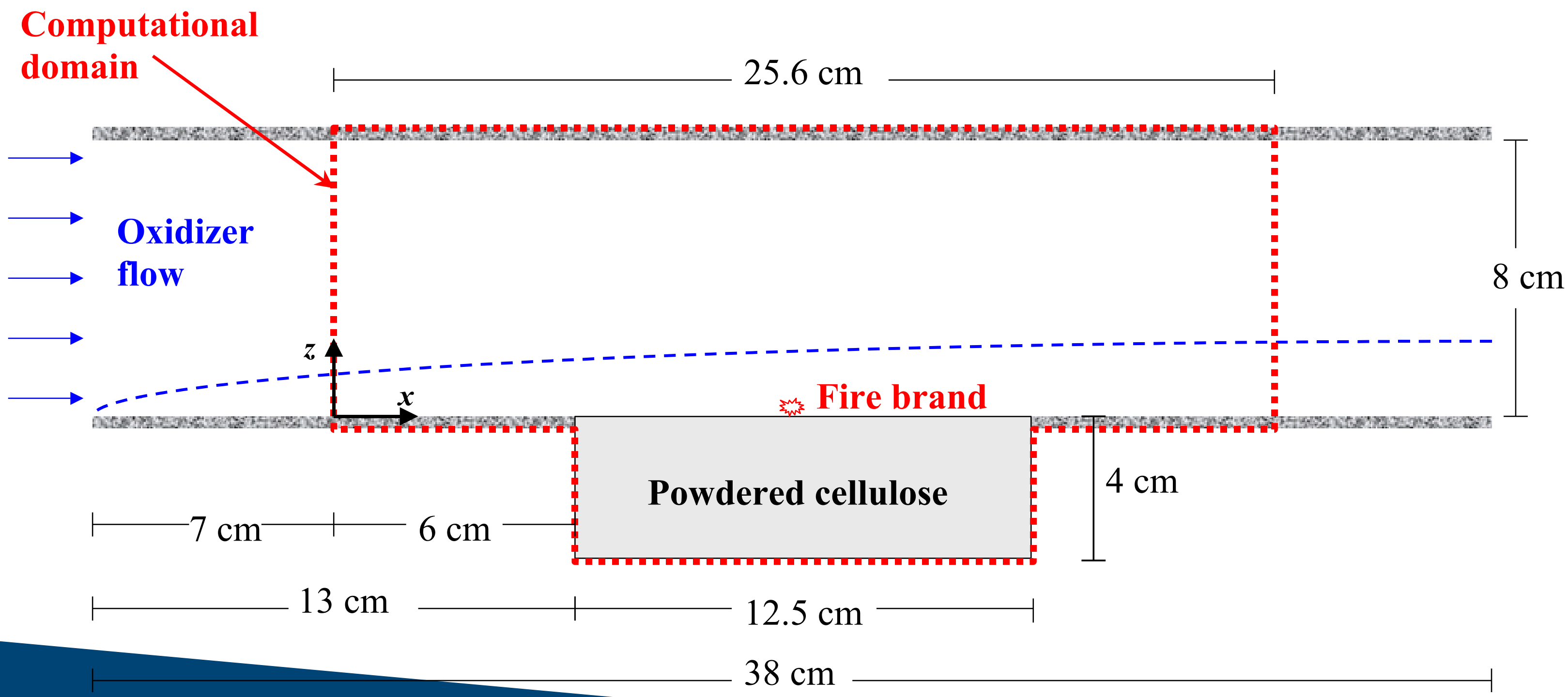


1-D Finite Volume Scheme with implicit time stepping



Numerical Model: Firebrand Ignition

- 2D schematic of experimental wind tunnel and its computer model representation:



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Solid-phase Governing Equations (1)

Conservation of solid mass:

$$\frac{\partial \overline{\rho}}{\partial t} = -\dot{\omega}'''_{fg}$$

Conservation of solid species:

$$\frac{\partial \left(\overline{\rho} Y_i\right)}{\partial t} = \dot{\omega}'''_{fi} - \dot{\omega}'''_{di}$$

Conservation of gas mass:

$$\frac{\partial \left(\rho_g \overline{\psi}\right)}{\partial t} + \frac{\partial \dot{m}''_x}{\partial x} + \frac{\partial \dot{m}''_z}{\partial z} = \dot{\omega}'''_{fg}$$

Conservation of gas species:

$$\frac{\partial \left(\rho_g \overline{\psi} Y_j\right)}{\partial t} + \frac{\partial \left(\dot{m}''_x Y_j\right)}{\partial x} + \frac{\partial \left(\dot{m}''_z Y_j\right)}{\partial z} = -\frac{\partial \dot{j}''_{j,x}}{\partial x} - \frac{\partial \dot{j}''_{j,z}}{\partial z} + \dot{\omega}'''_{fj} - \dot{\omega}'''_{dj}$$

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Solid-phase Governing Equations (2)

Conservation of solid energy:

$$\frac{\partial\left(\bar{\rho}\bar{h}\right)}{\partial t}+\frac{\partial\left(\dot{m}_x'' h_g\right)}{\partial x}+\frac{\partial\left(\dot{m}_z'' h_g\right)}{\partial z}=-\frac{\partial \dot{q}_x''}{\partial x}-\frac{\partial \dot{q}_z''}{\partial z}+\dot{Q}_s'''+\sum_{i=1}^{M}\left(\dot{\omega}_{fi}'''-\dot{\omega}_{di}'''\right)h_i$$

Conservation of gas energy (thermal equilibrium):

$$T_g = T$$

Pressure evolution equation (from Darcy's law):

$$\frac{\partial}{\partial t}\left(\frac{P\overline{M}\overline{\psi}}{RT_g}\right)=\frac{\partial}{\partial x}\left(\frac{\overline{K}}{\nu}\frac{\partial P}{\partial x}\right)+\frac{\partial}{\partial z}\left(\frac{\overline{K}}{\nu}\frac{\partial P}{\partial z}\right)+\dot{\omega}_{fg}'''$$

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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:

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

Oxidative pyrolysis reaction rate:

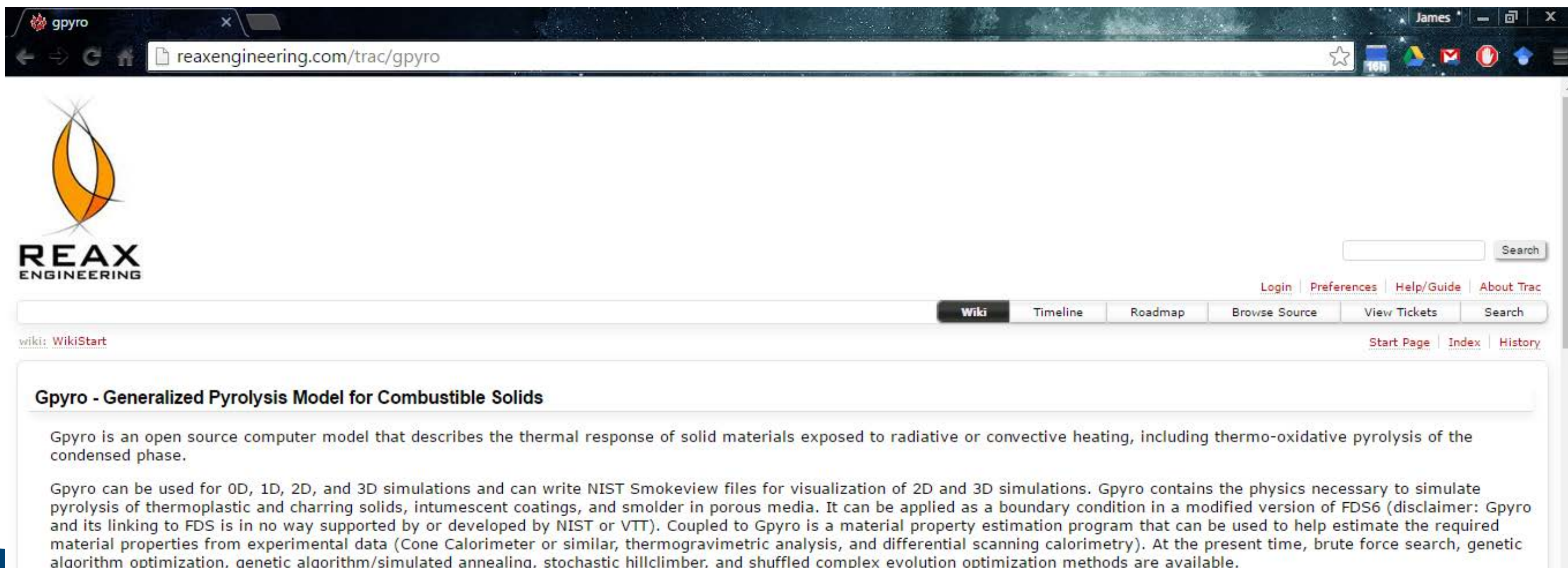
$$\dot{\omega}'''_{dA_k} = \left(\frac{\bar{\rho} Y_{A_k}}{\left(\bar{\rho} Y_{A_k}\right)_\Sigma}\right)^{n_k} \left(\bar{\rho} Y_{A_k}\right)_\Sigma \left[\left(1 + Y_{O_2}\right)^{n_{O_2,k}}\right] Z_k \exp\left(-\frac{E_k}{RT}\right)$$

Computer Code – Gas Phase

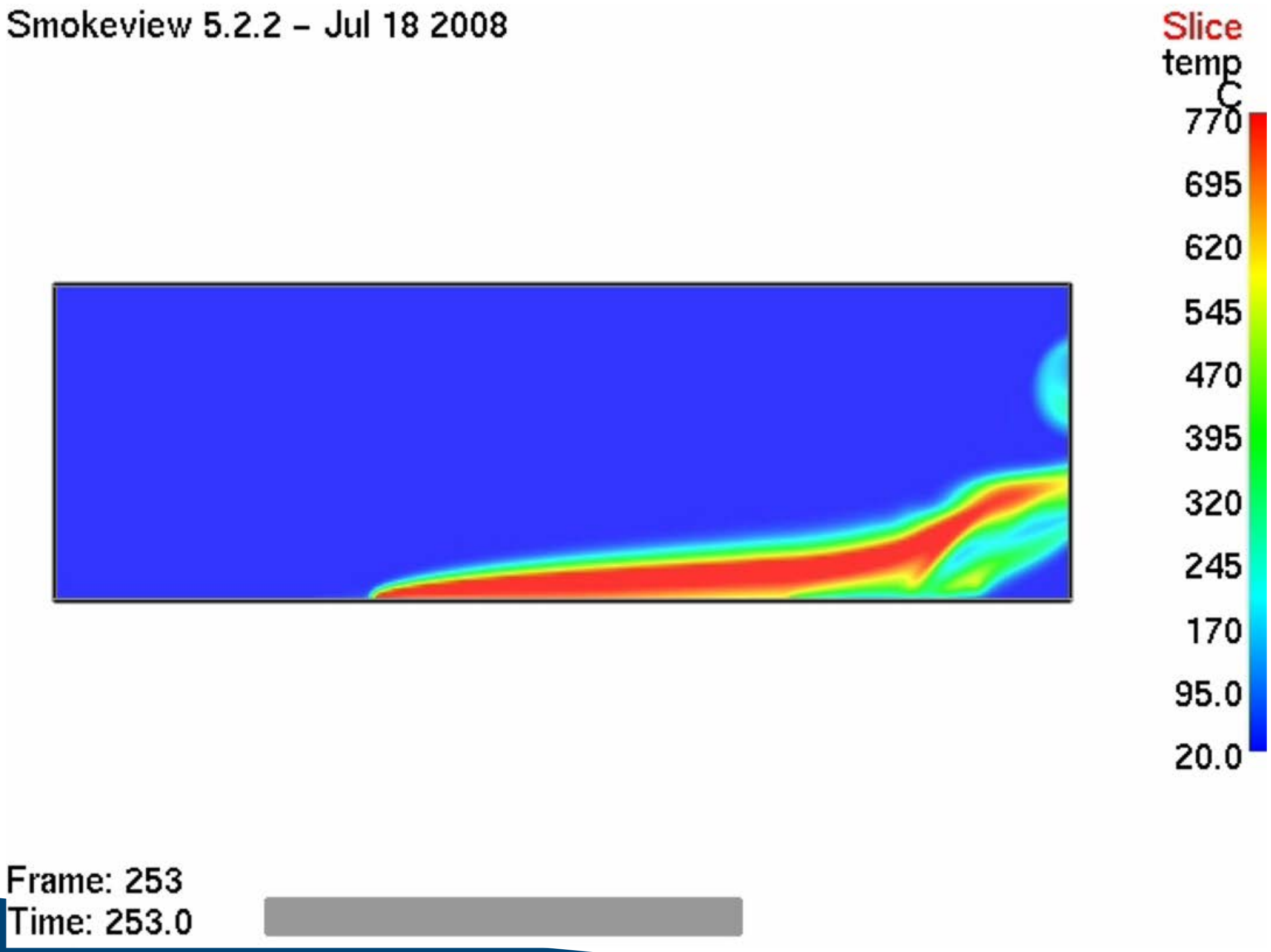
- Fire Dynamics Simulator (FDS)
  - CFD-based fire model developed by NIST and VTT
  - 2D implementation applied here
  - Single step finite rate combustion reaction
  - Ember modeled as volumetric heat source

Computer Code – Solid Phase

- Gpyro – http://reaxengineering.com/trac/gpyro
  - 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



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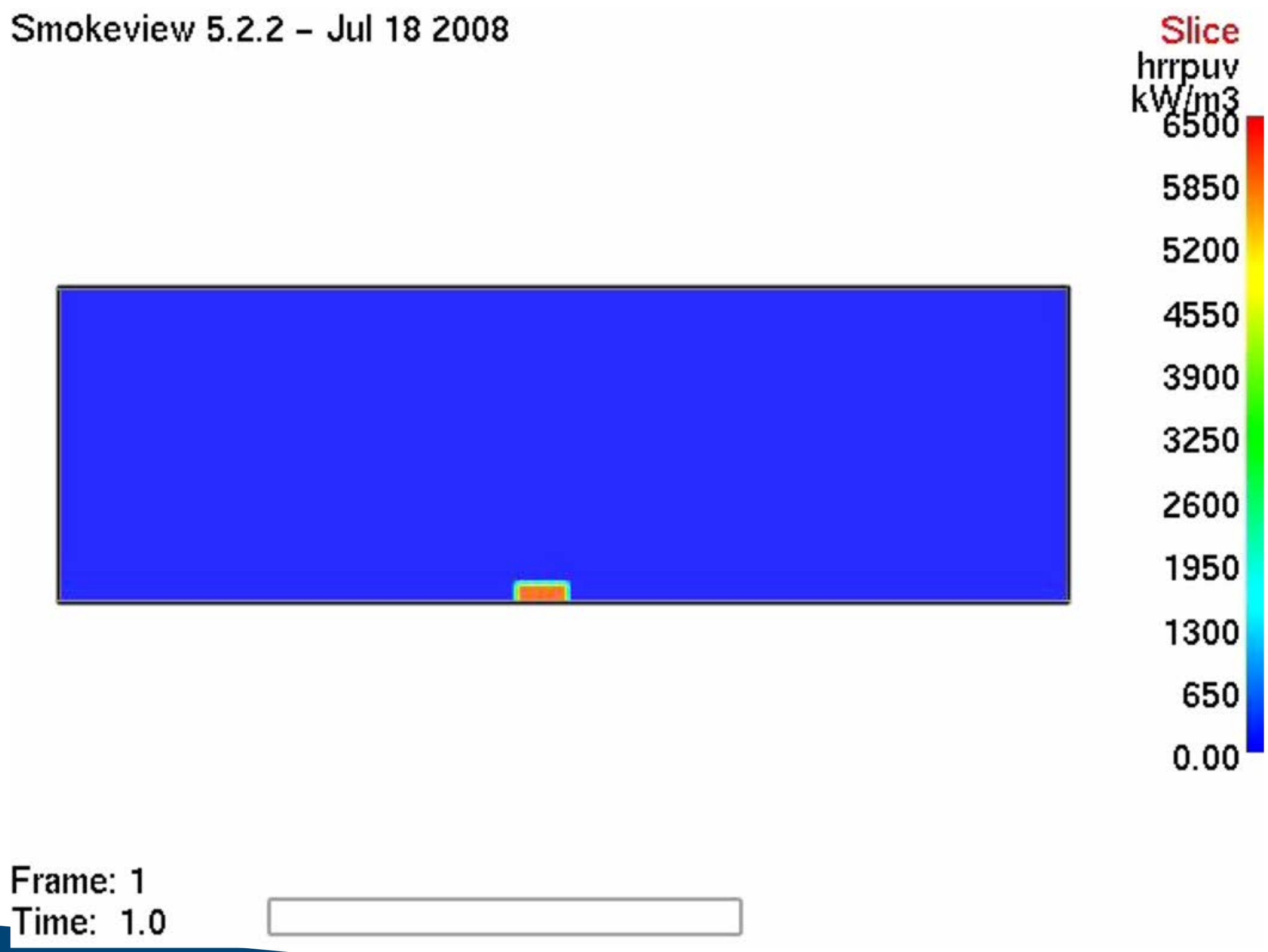
Flaming Ignition – Gaseous Reaction Rate



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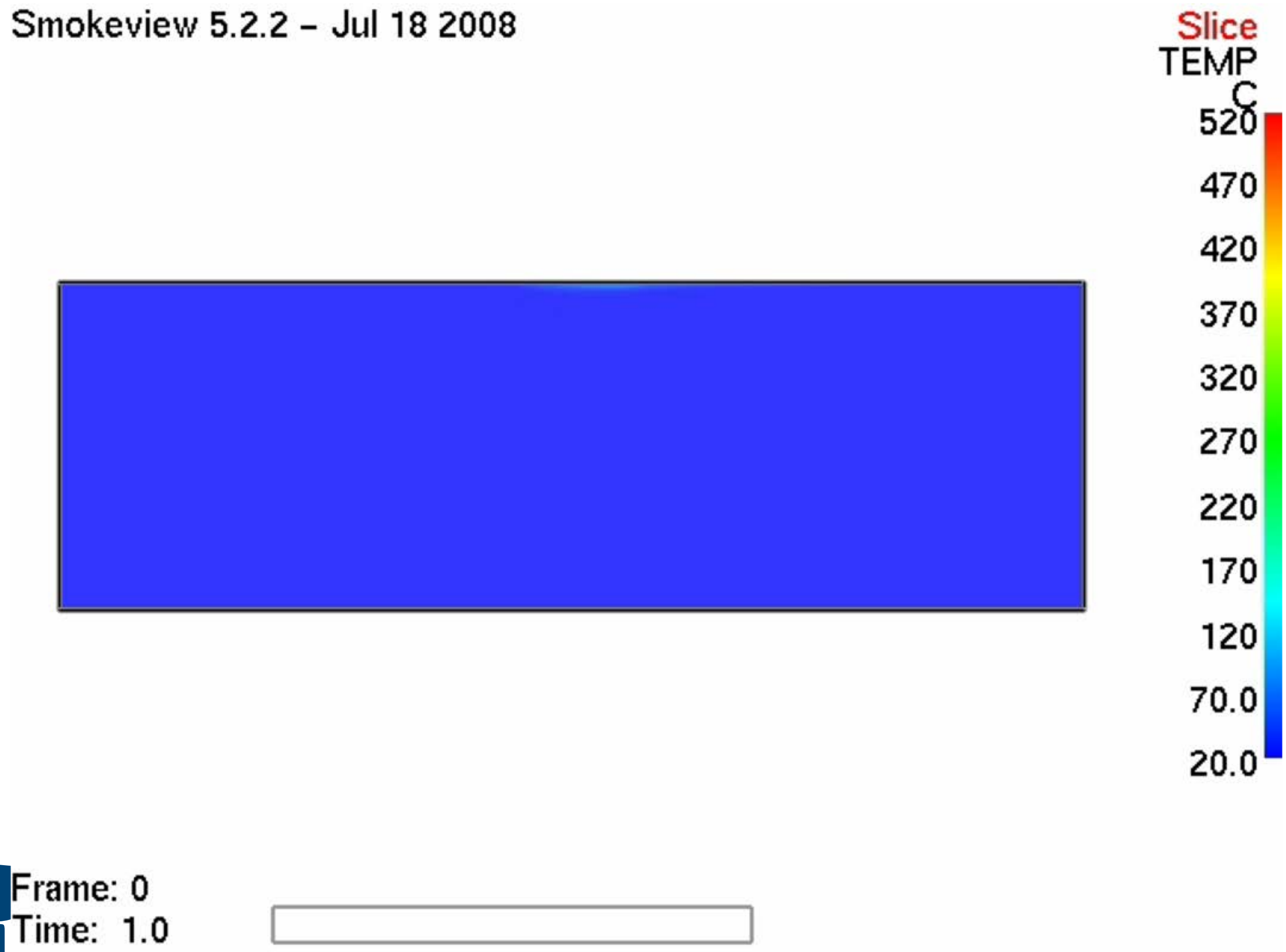
Flaming Ignition – Solid Temperature



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Concluding Remarks

- 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

Acknowledgements

- This research was supported by National Science Foundation Award No. CBET-1066520, Reax Engineering, The Maynard Endowed Chair at UCB, a NSF Graduate Research Fellowship and a NDSEG Fellowship.
- The author would like to thank the multiple colleagues, current and former students that contributed to the work presented here. Particularly relevant are the contributions of James Urban and Chris Lautenberger. Also relevant are the contributions and comments of Jose Torero, Stephen Tse, Ralph Anthenien, Guillermo Rein, David Rich, Casey Zak, Rory Hadden, Sarah Scott, Sara McAllister, Sonia Fereres, Andres Osorio and Andres Fuentes. The help of many undergraduate students is also acknowledged.

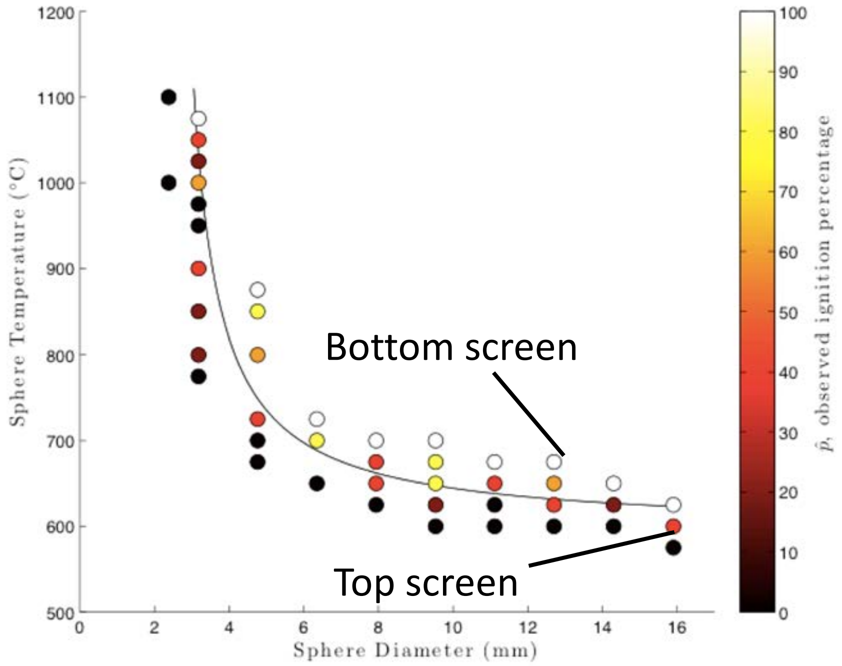
Particle Material Properties

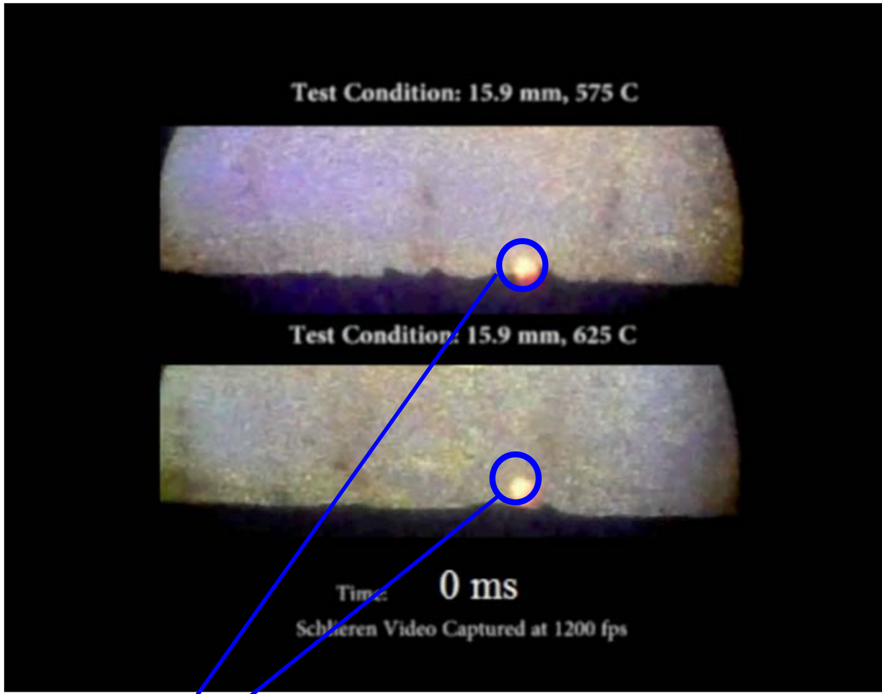
	Stainless Steel	Brass	Aluminum (solid)	Aluminum (molten)	Copper
k (W/mK)	21.5	120	237	90	390
α (mm^2/s)	5.1	38	90	33	114
ρc_p (MJ/m^{3}K)	3.2	3.3	2.4	2.71	3.43
ΔT_m (°C)	1400 - 1420	915 - 955	650	n/a	1015
Δh_m (MJ/kg)	n/a	n/a	390	n/a	n/a

Fuel Bed Properties

Fuel	Density [kg/m³]	MC [%]	Chemical Composition	d_{char} [mm]
Cellulose Powder	363 ± 34.4	6.5 ± 2	100% α – Cell.	0.4
Cellulose Strips	45 ± .2	7.3 ± 2		5
Pine Needles	59 ± 1.0	8.5 ± 2	38-42% Cellulose 13-21% Lignin 6-8% Ash [33]	2
Grass Blend Powder	299 ± 2.4	6.9 ± 2	33-45% α – Cell. 22-27% Hemi-Cell. 6-15% Lignin 5-7% Protein 8-10% Ash	0.5
Grass Blend	79 ± 1.0	7.6 ± 2		7.5

Schlieren Videos: Large Particles





Schlieren Artifact

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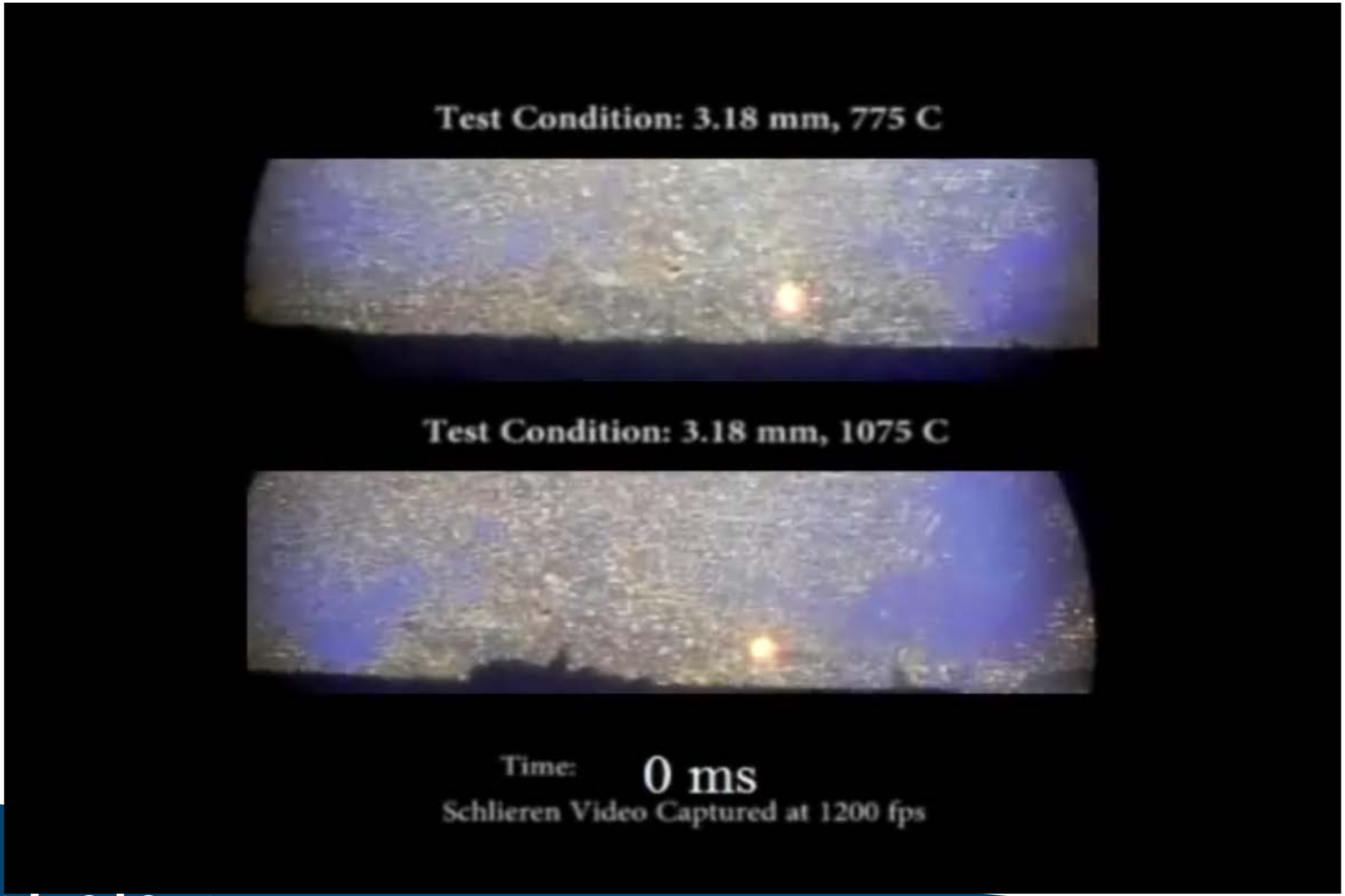
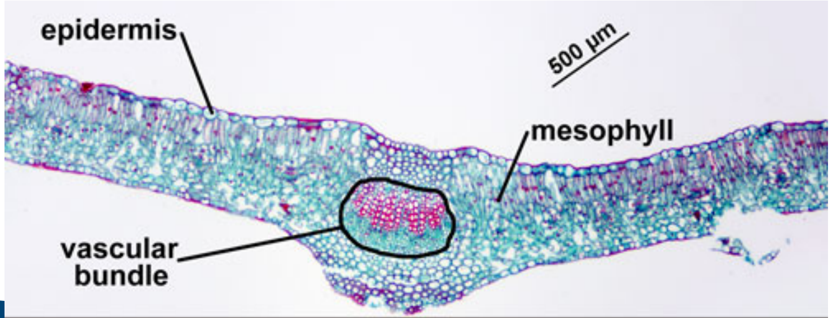
Schlieren Videos: small particles

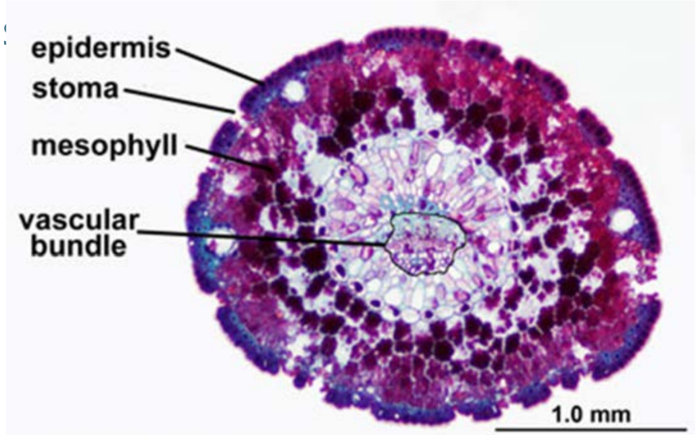


Structural differences

- 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 specie:



Syringa (lilac) leaf, cross section



Pine needle cross section

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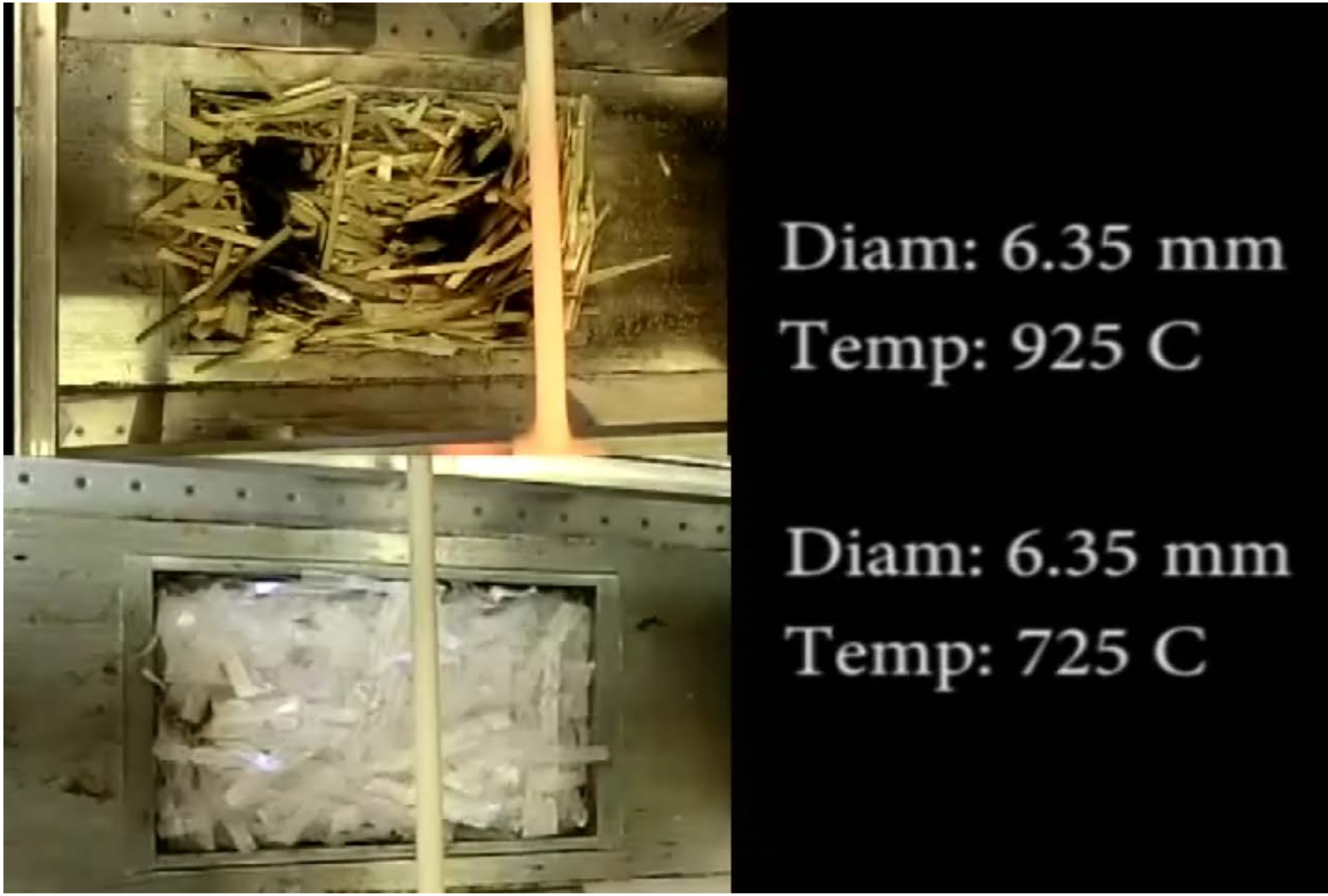
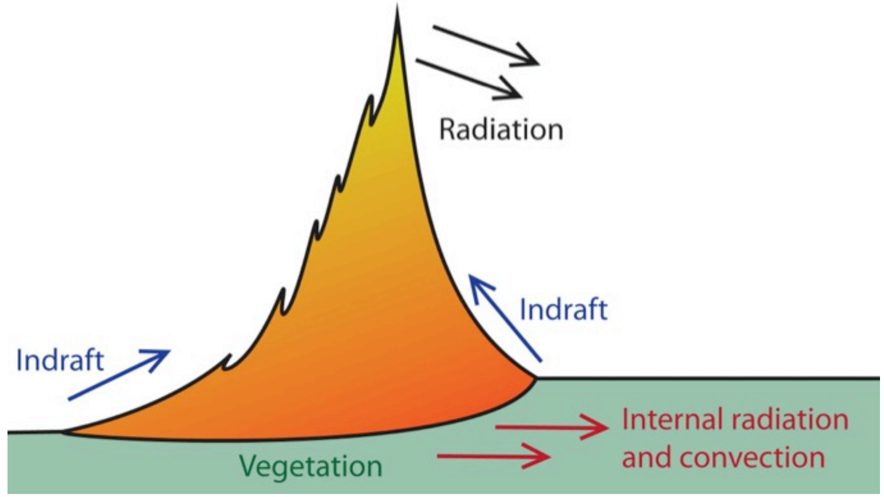
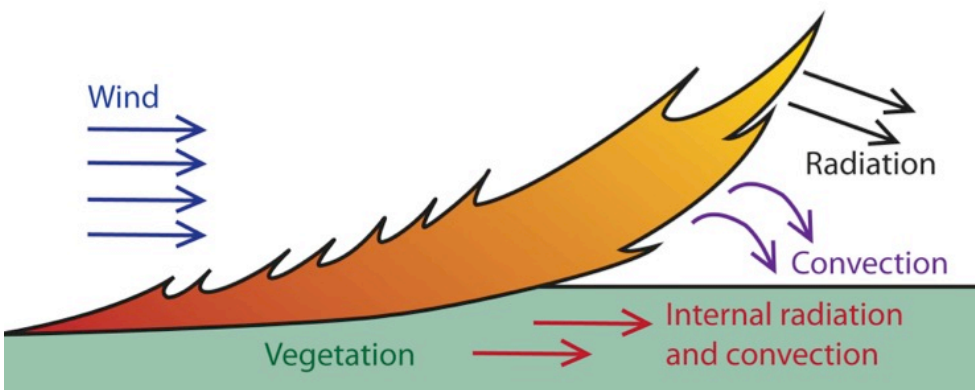
http://www.deanza.fhda.edu/faculty/mccauley/6a-labs-plants-04.htm

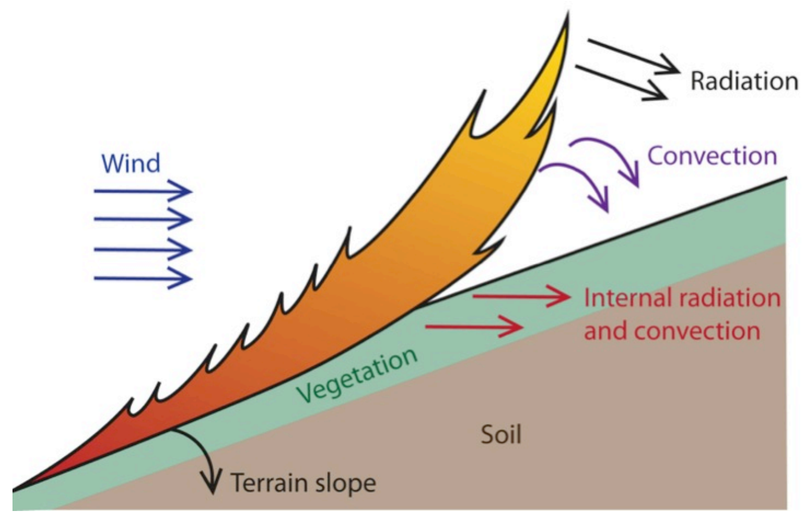

Diam: 6.35 mm
Temp: 925 C
Diam: 6.35 mm
Temp: 725 C

Schematic of Fire Propagation



No wind





Wind and flat terrain

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:

$$V_f = \frac{\dot{q}''_{HRR} \xi \left(1 + \Phi_w + \Phi_s\right)}{\rho_b \varepsilon Q_{ig}}$$