Ignition and burning of wooden structures exposed to radiation heat from flames and firebrands

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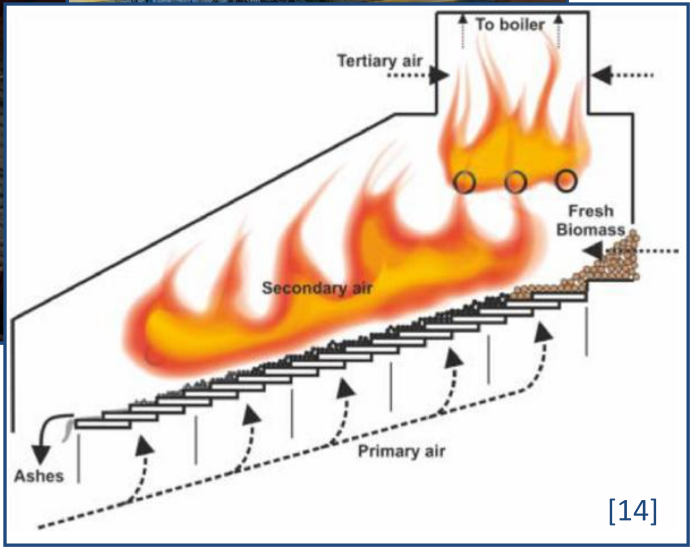
WHAT IS THE RELATIONSHIP?



AGENDA

- Fundamentals on wood ignition
- Experiments on wood ignition
- Modeling and simulation of wood ignition
- Research gaps: heat transfer, fluid mechanics, pyrolysis, combustion

Fundamentals

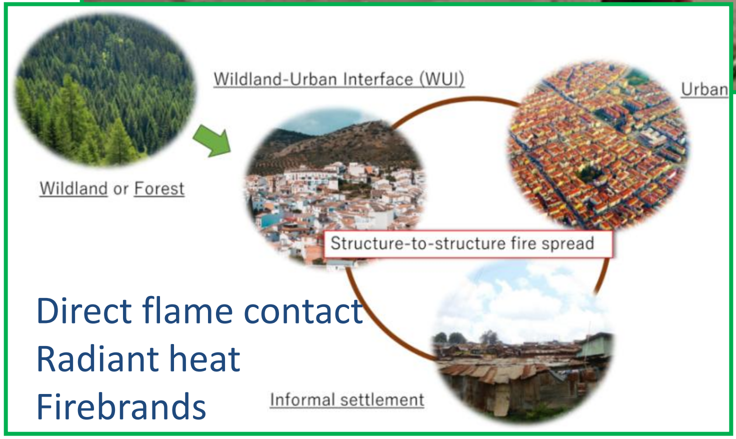
Experiments

Models

Research gaps

INTRODUCTION

- Emphasis on the essential role of fire safety in wooden structures for the welfare of communities
- Investigation of ignition of wooden surfaces under varying thermal conditions
- In-depth analysis within the framework of LOF&BE fires (e.g. WUI, informal settlements and urban fires)



Direct flame contact
Radiant heat
Firebrands

[2, 30]

INTRODUCTION

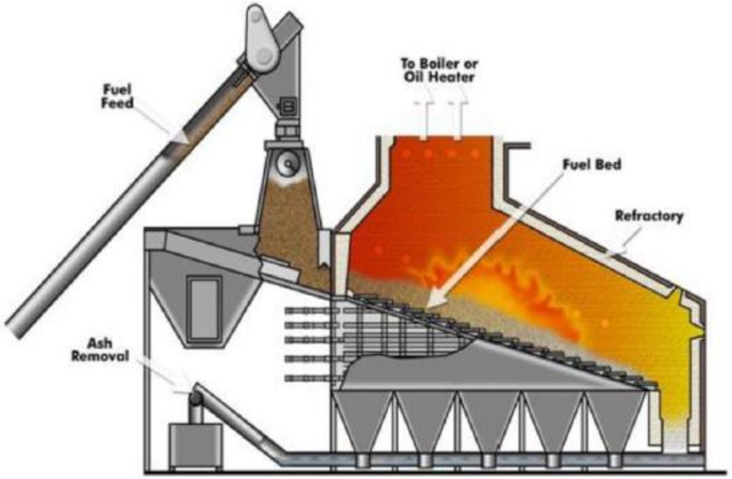
- Fundamentals on wood ignition also applies to energy systems and buildings

Biomass appliances

- ✓ Domestic wood heating
- ✓ Grate biomass combustors
- ✓ Fluidized bed combustors

Timber buildings

- ✓ High-rise buildings
- ✓ Historical and cultural heritage buildings

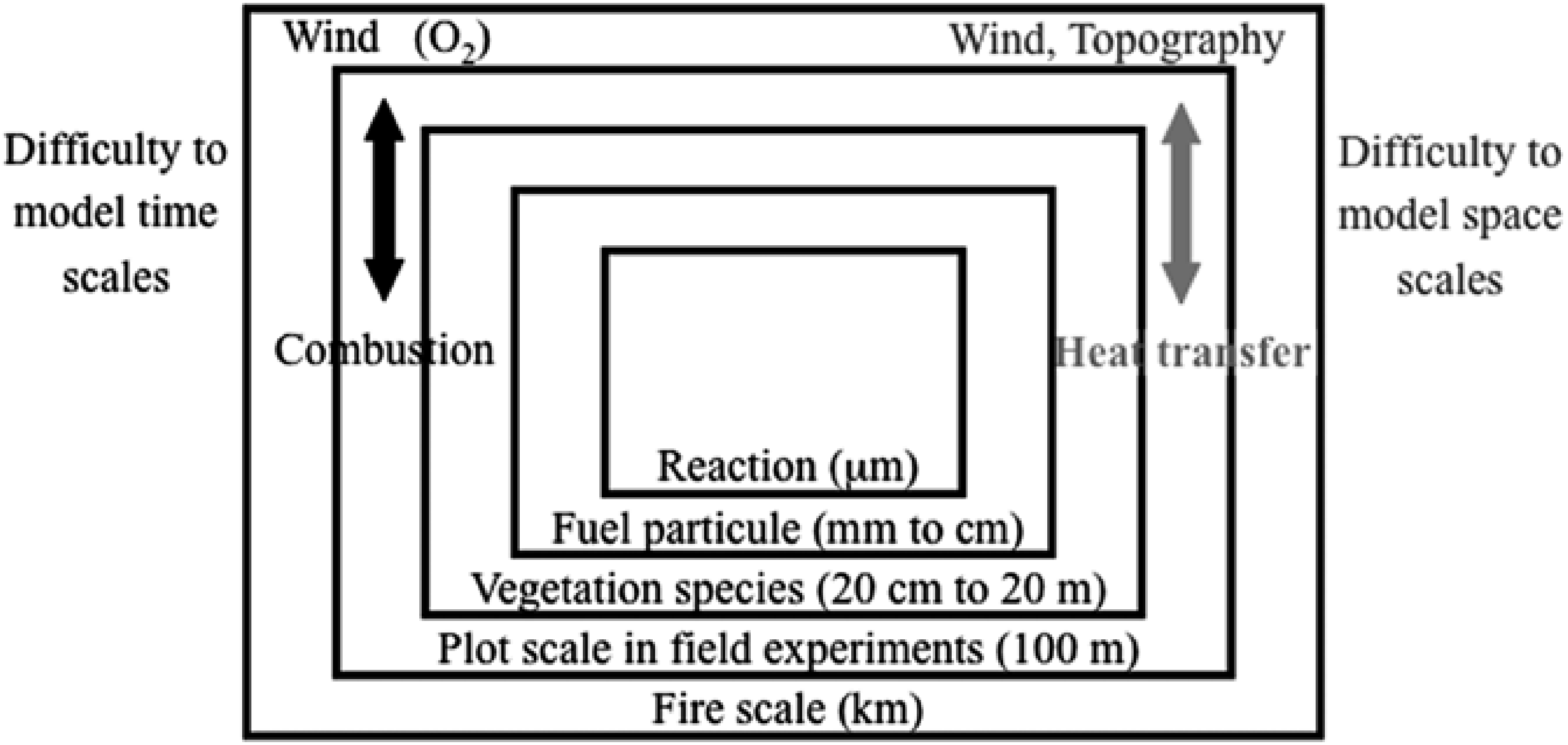


Schematic of a biomass grate combustor [14]

20-storey mass-timber building in Sweden [15]

INTRODUCTION

- Space and time scales involved



Source: Simeoni [22]

INTRODUCTION

- Processes involved in fire development:

Thermal processes

Physical processes

Chemical processes

Failure processes

- ✓ Heat transfer
- ✓ Pyrolysis
- ✓ Production of gas volatiles
- ✓ Volume change
- ✓ Water evaporation
- ✓ Internal gas pressure
- ✓ Properties of permeability and porosity
- ✓ Mechanical behavior

- Four types of combustible materials:

Wood

Charring polymer

Non-charring polymer

Intumescent polymer

Source: Shi and Chew [19]

INTRODUCTION

- Brief history on fire thermophysical processes modeling:
  - ✓ 1946: Bamford and Malan, *The combustion of wood - Part I*, Mathematical Proceedings of the Cambridge Philosophical Society
  - ✓ 1965: Tinney, *The combustion of wooden dowels in heated air*. Symp (Int) Combustion
  - ✓ 1972: Kung, *A mathematical model of wood pyrolysis.* Combust Flame
  - ✓ 1987: Perre, *Measurements of softwoods' permeability to air: importance upon the drying model*. Int Commun Heat Mass Transfer
  - ✓ 1990: Aerts and Rageland, *Pressurized downdraft combustion of woodchips*. Twenty-third symposium (international) on combustion
  - ✓ 1992: McManus and Springer, *High temperature thermomechanical behavior of carbon–phenolic and carbon–carbon composites, I. Analysis*. Journal Compos Mater

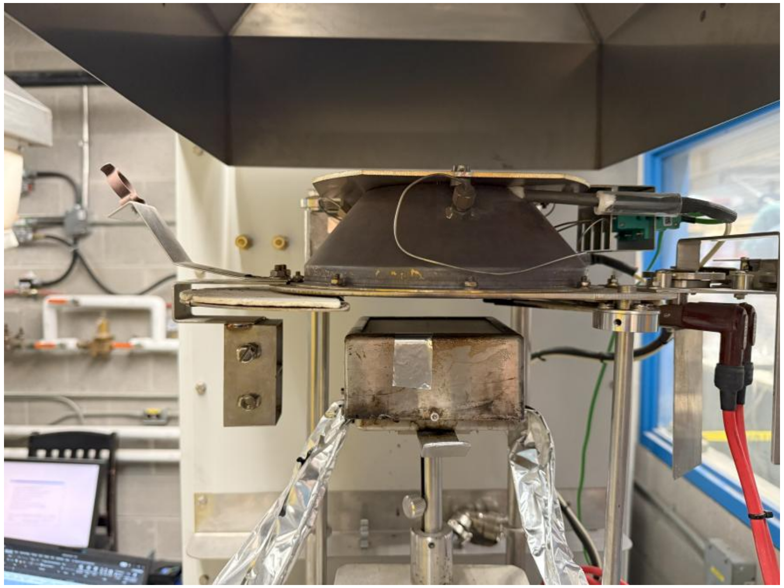
Afterwards, most studies are related to the determination of kinetic data and properties of wood and other relevant materials for fire applications.

Source: Shi and Chew [19]

INTRODUCTION

- Experiments: ignition data currently available is closely related to the methodology employed to get it [3]:
  - ✓ Nature of the test procedures
  - ✓ Facilities, instruments and devices used
  - ✓ Post-processing (data analysis) method

FPA [4]



Cone calorimeter

Title of this lecture:
Ignition and burning of wooden structures exposed to radiation heat from flames and firebrands

Firebrands?

[33]

FIREBRANDS

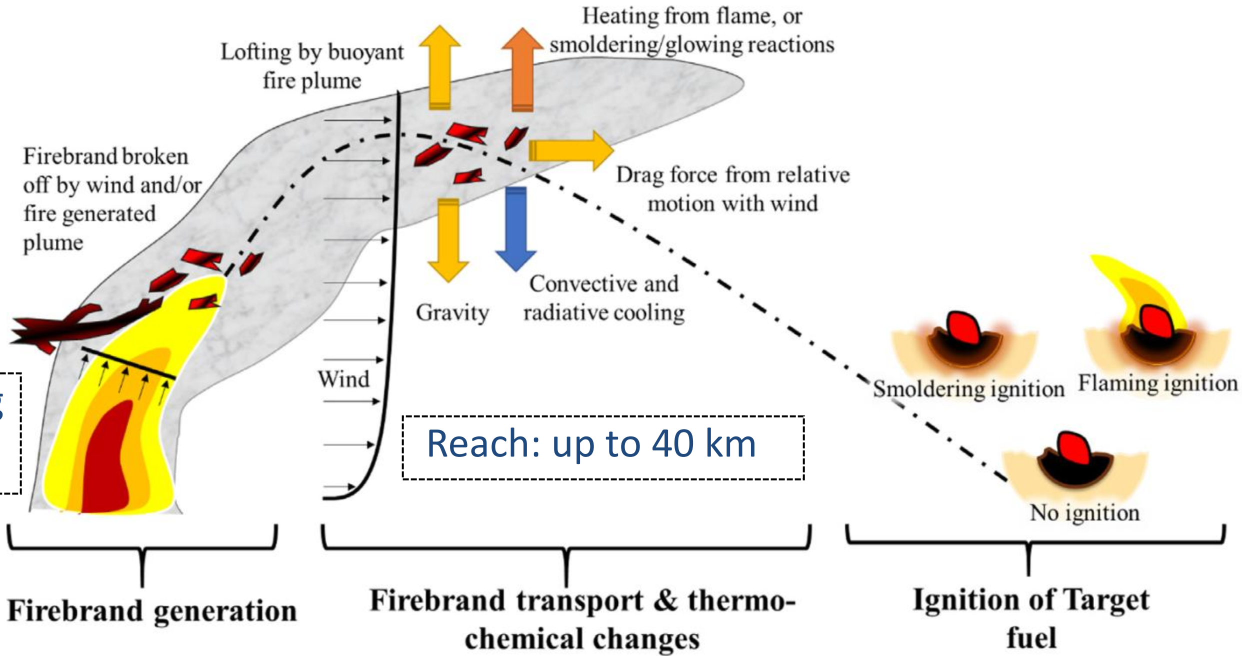
When vegetation and structures burn in large outdoor fires, pieces of burning material, known as firebrands, are generated, become lofted, and may be carried by the wind.

- 1934 Hakodate Fire (Japan): 2,000 fatalities, 11,000 structures lost
- 2018 Camp Fire (CA): 86 fatalities, 18,800 structures lost, 153,000 hectares burnt (SP city area)
- Sub-processes involved:
  - ✓ Generation of firebrands
  - ✓ Their transport by plume lofting and drag forces with the wind
  - ✓ Deposition onto and ignition of fuel beds
  - ✓ Subsequent fire spread

Source: Manzello *et al.* [20], Franklin Fire, CA [21], Santa Rosa, CA [23]

FIREBRANDS

- Firebrand sub-processes:



Mostly ~0.01-3 g
Up to ~100 g

Reach: up to 40 km

Most important aspect of the firebrand problem: whether a firebrand or a shower of firebrands is capable of igniting a fuel bed after landing on it.

If enough energy is transferred from the firebrand to the adjacent fuel bed, the fuel will heat up and may start to pyrolyze.

Source: Manzello *et al.* [20], Lin *et al.* [29]

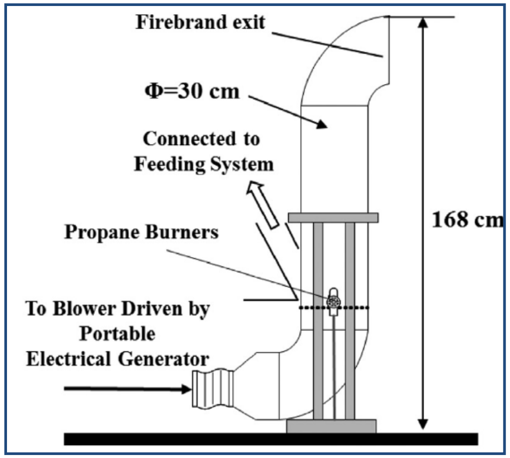
IGNITION INDUCED BY FIREBRANDS

- Depends on:
  - ✓ The size and state of the firebrand: smoldering/glowing, flaming.
  - ✓ Characteristics of the fuel bed on which it lands: temperature, density, porosity, moisture content.
  - ✓ Environmental conditions: temperature, humidity, wind velocity.
- Ignition of wildland fuels
  - ✓ Fine fuels such as grass, leaves, needles, mulch, and compost are typically the easiest and most common type of fuel ignited by firebrands.
- Ignition of structural fuels (WUI, urban and IS fires)
  - ✓ Components vulnerable to ignition by firebrands: roofing, gutters, eaves, vents, siding, windows, glazing, decks, porches, patios, fences, mulches and debris. They are also prone to accumulate fine fuels.

Source: Manzello *et al.* [20], Sonoma RCD [24], Quarles [25]

IGNITION INDUCED BY FIREBRANDS

- Experiments: dragon, real scale, cone with FB, idealized FB, electrical heaters



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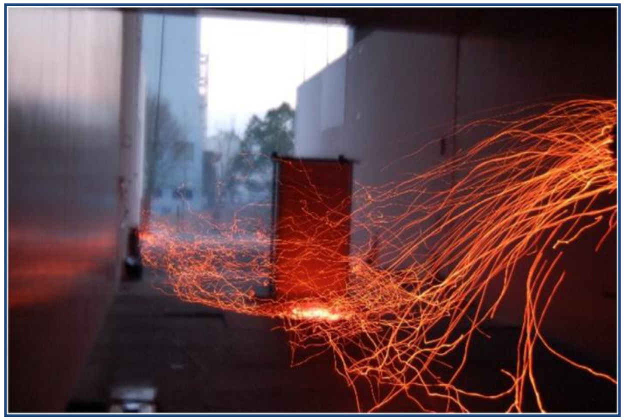
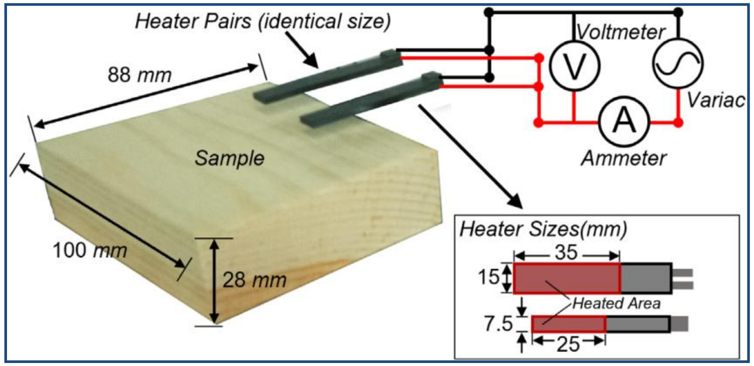




Source: Manzello *et al.* [20], Manzello and Suzuki [30], Zhu and Urban [34], Álvarez *et al.* [35]

IGNITION INDUCED BY FIREBRANDS

- **Very few analytical or modeling studies have been conducted on the ignition of wildland or structural fuels by firebrands or by hot particles.**
- Hot spot ignition theory: the energy content of a particle can be used as an ignition criterion, analogous to the minimum ignition energy concept for gases. This way, if the energy content of a particle is greater than a particular threshold, then ignition occurs.
- The governing equations for a non-reactive hot spot particle/firebrand (subscript p) completely embedded in an infinite fuel bed are:

$$\text{for } 0 < x < r: \quad \rho_p c_p \frac{dT_p}{dt} = \frac{a_p}{V_p} k \nabla T|_{x=r^+}$$

$$\text{for } r \le x < \infty: \quad \rho c_p \frac{\partial T}{\partial T} = \nabla \cdot k\nabla T + \rho A \Delta H \exp\left(-\frac{E}{RT}\right)$$

$$r_{cr} = \delta_{cr}\sqrt{\frac{k}{\rho A \Delta H}\frac{RT_{p0}^2}{E}\exp\left(\frac{E}{RT_{p_0}}\right)}$$

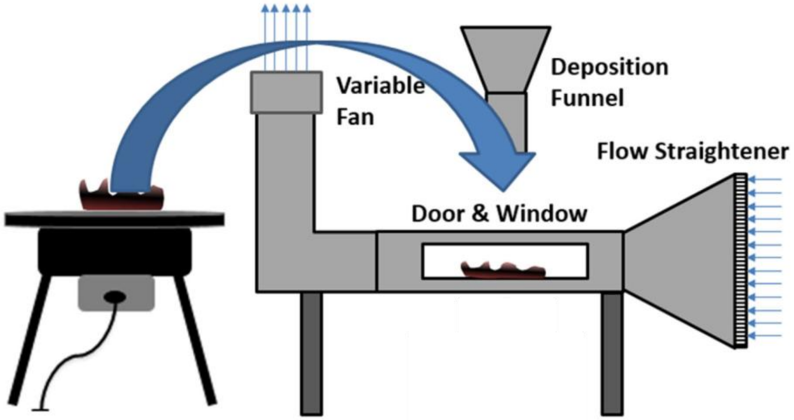
Critical radius for ignition

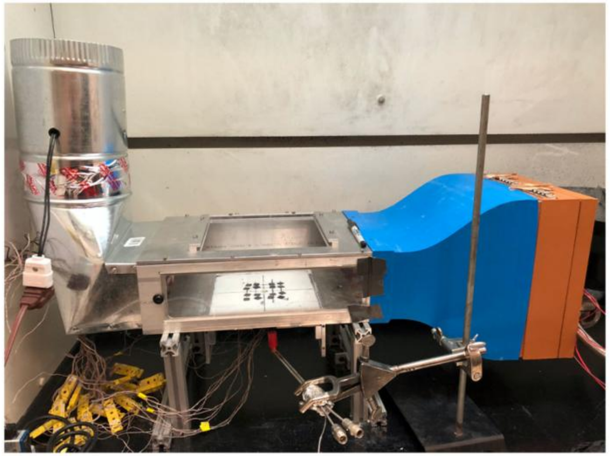
- CFD models: G-Pyro, FDS

Source: Manzello *et al.* [20]

IGNITION INDUCED BY FIREBRANDS

- Research example: critical ignition conditions of wood by cylindrical firebrands
  - ✓ Three dense woody fuels (cedar shingle, plywood, oriented-strand board)
  - ✓ Piles of smoldering cylindrical firebrands were deposited onto the surface
  - ✓ Instruments: in-depth thermocouples, surface HF sensors, video camera
  - ✓ Tests performed in a small-scale wind tunnel (0.5 – 3.5 m/s)



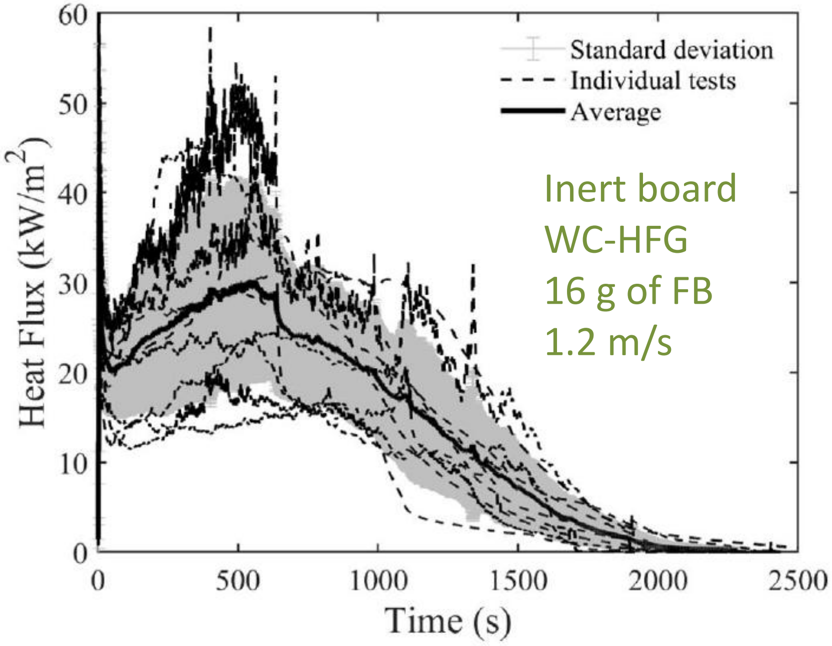


Source: Salehizadeg *et al.* [27]

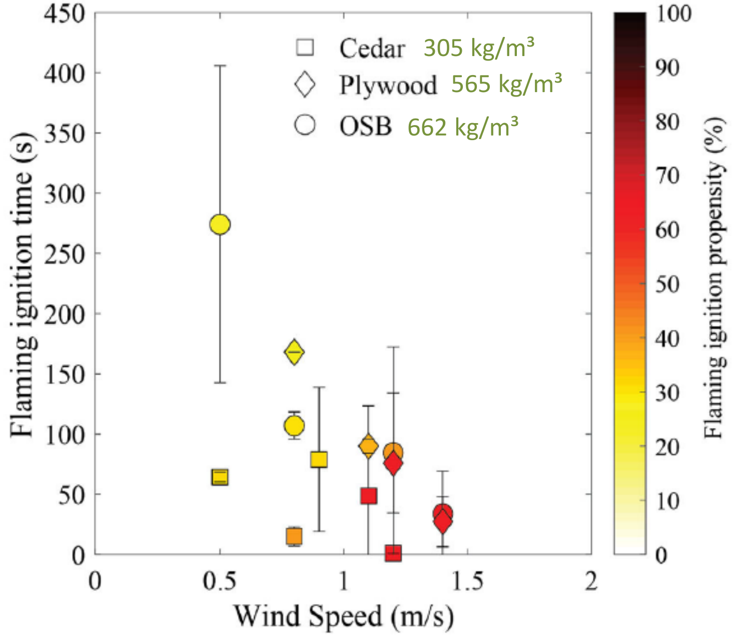
IGNITION INDUCED BY FIREBRANDS

- Research example: critical ignition conditions of wood by cylindrical firebrands

✓ Larger piles (not larger FBs), higher temperatures.
✓ Target fuel density is a key parameter for ignition.
✓ Flaming: function of wind speed.
✓ Ignition occurred while transient heating from the FB pile was increasing.



Inert board
WC-HFG
16 g of FB
1.2 m/s

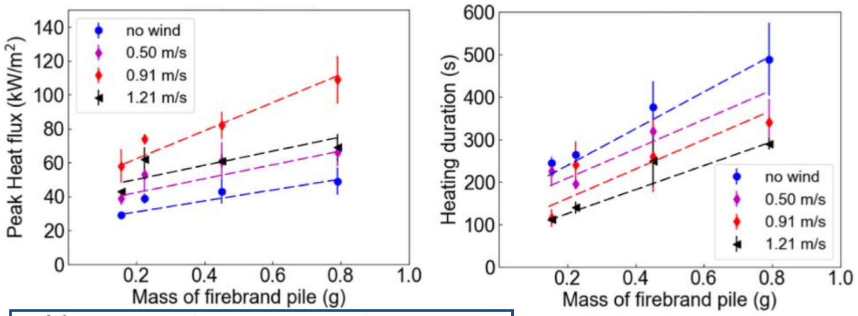


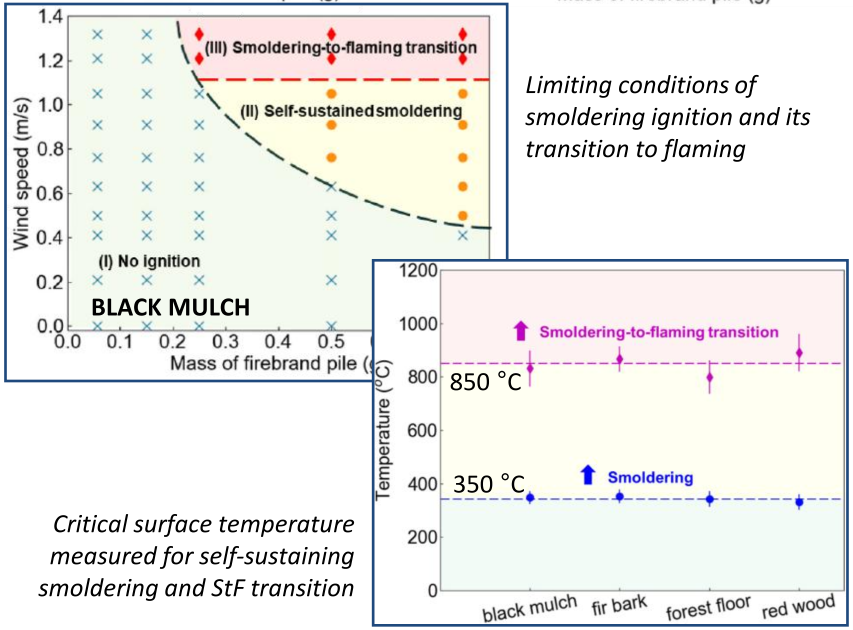
Source: Salehizadeg *et al.* [27]

IGNITION INDUCED BY FIREBRANDS

- Research example: wooden mulch beds exposed to firebrands under wind

- ✓ Critical surface temperature for self-sustained smoldering and StF transition: IR camera (25-650 °C) and color pyrometry (600-1200 °C).
- ✓ Heat flux from piles on inert board: WC-HFG





Limiting conditions of smoldering ignition and its transition to flaming

Critical surface temperature measured for self-sustaining smoldering and StF transition

Source: Lin *et al.* [29]

IGNITION INDUCED BY FIREBRANDS

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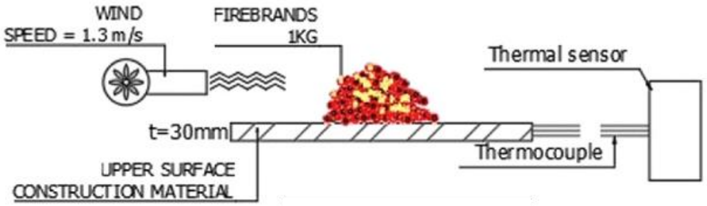
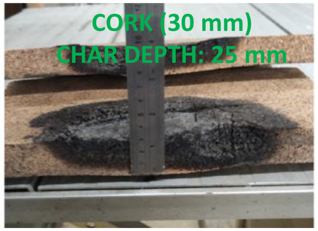
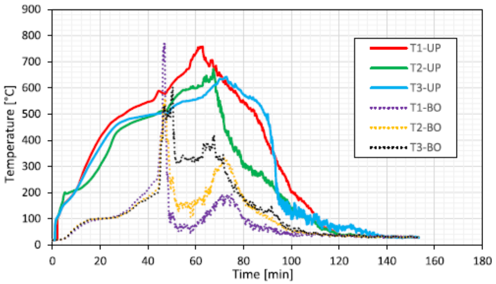
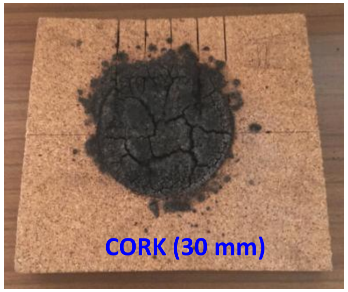
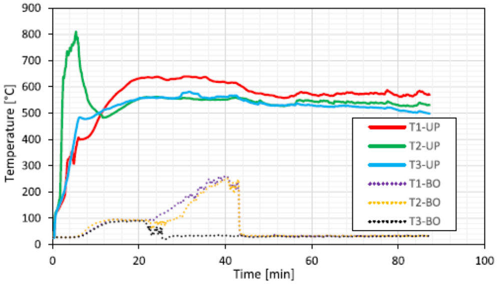
- Research example: reaction of construction materials to firebrand piles

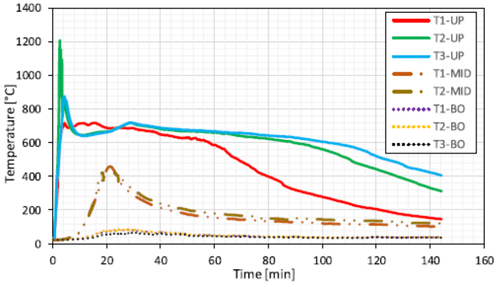












Source: Arruda *et al.* [28]

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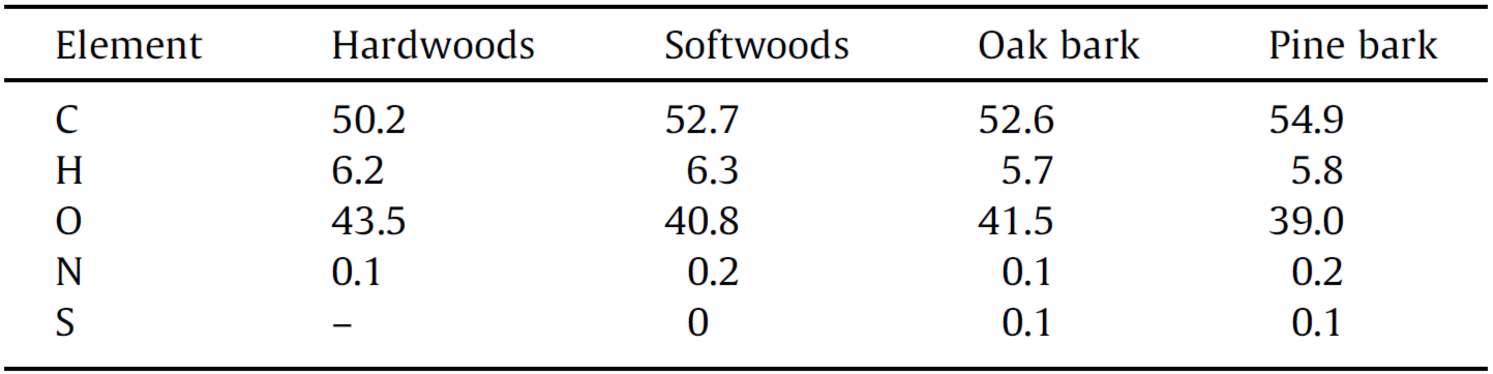
Wood?

[36]

WOOD

- Average weight percentage of elements of woods:



Element	Hardwoods	Softwoods	Oak bark	Pine bark
C	50.2	52.7	52.6	54.9
H	6.2	6.3	5.7	5.8
O	43.5	40.8	41.5	39.0
N	0.1	0.2	0.1	0.2
S	–	0	0.1	0.1

- Wood consists of three major components:
  - ✓ Hemicellulose: 25–35%
  - ✓ Cellulose: 40–50%
  - ✓ Lignin: 16–33%

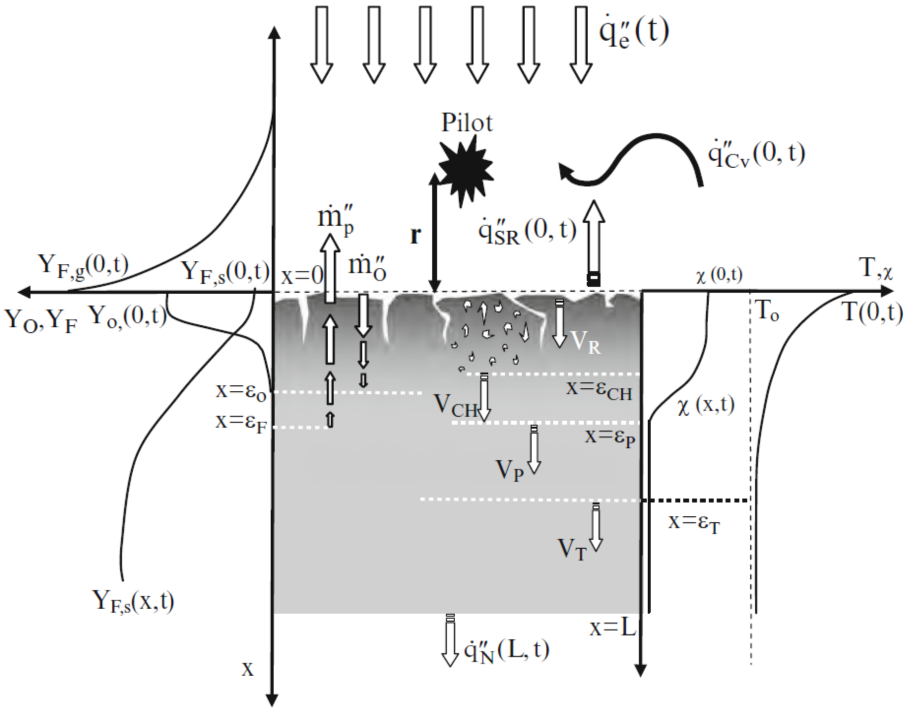
Source: Park *et al.* [18], Shi and Chew [19]

[36]

WOOD IGNITION

PROCESS OF IGNITION

- As the exposed surface of a solid material is subjected to an external heat source, its temperature starts to increase and a series of physical and chemical phenomena takes place.



<u>Interactions:</u>

- ✓ Incident heat
- ✓ Heat losses
- ✓ Solid phase
- ✓ Gas phase

Schematic of the different processes occurring as a material undergoes degradation prior to ignition induced by an external source of heat [3]

Source: Torero [3]

PROCESS OF IGNITION

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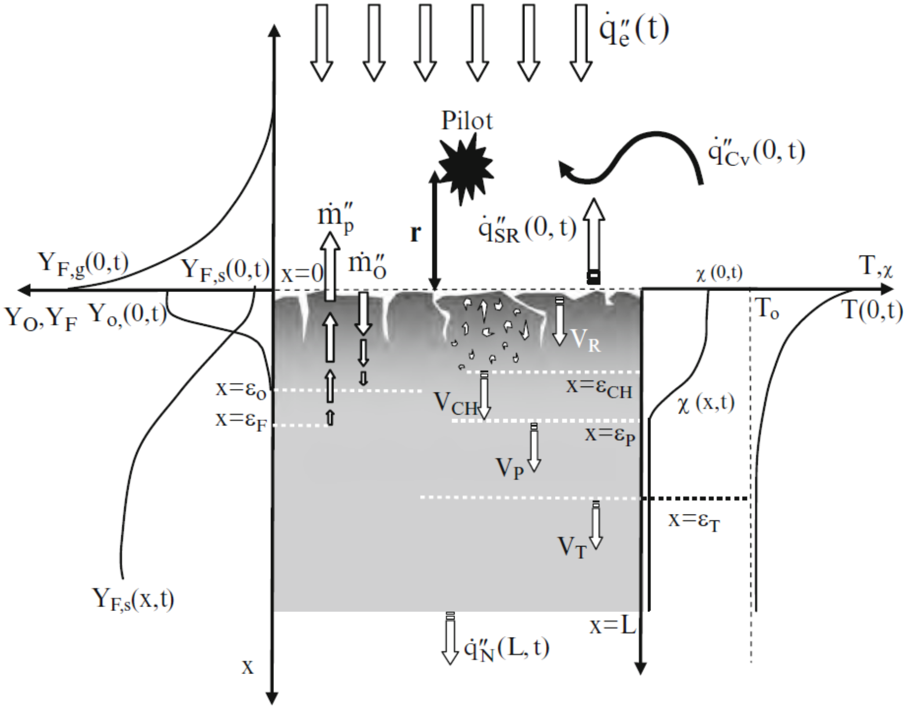

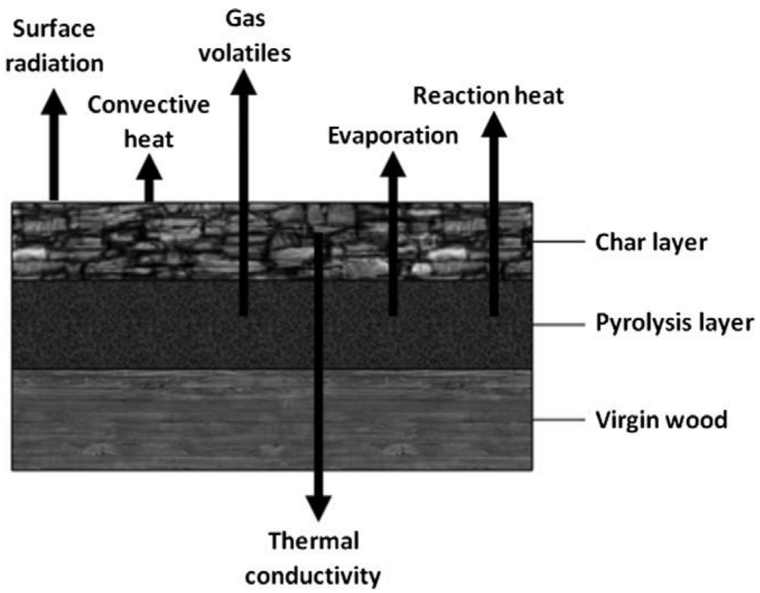

Schematic of the different processes occurring as a material undergoes degradation prior to ignition induced by an external source of heat [3]

Sources: Torero [3], Shi and Chew [19]

SOLID PHASE: PYROLYSIS PROCESS

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- Pyrolysis: solid phase transforms into gas phase.
  - ✓ Generally implies the breakdown of the molecules into different and smaller molecules.
- Pyrolysis reaction rates: Arrhenius-type functions or polynomials

$$\dot{\omega} = A Y_O{}^m Y_S{}^n e^{-E/RT} \qquad \dot{\omega} = C Y_O{}^m Y_S{}^n (T/T_o)^b \qquad (\dot{\omega}[1/s])$$

- Gasification rate per unit volume: $\dot{\omega}'''$, kg/s.m^3
- The process of pyrolysis can be extremely complex and depending on the fuel and heating characteristics can follow distinctively different paths:
  - ✓ Numerous reactions
  - ✓ Influenced by the presence of oxygen
  - ✓ Uncertainties related to the number of steps and their constants, etc.

Wood pyrolysis involves many physical and chemical processes: heat transfer, moisture evaporation, decomposition kinetics, pressure build up in the solid, changes in material properties with the extent of pyrolysis and temperature, anisotropic property behavior.

Sources: Torero [3], Park *et al.* [18]

SOLID PHASE: PYROLYSIS PROCESS

- Example of a reduced kinetic mechanism for polyurethane (PU), obtained by TGA and GA:

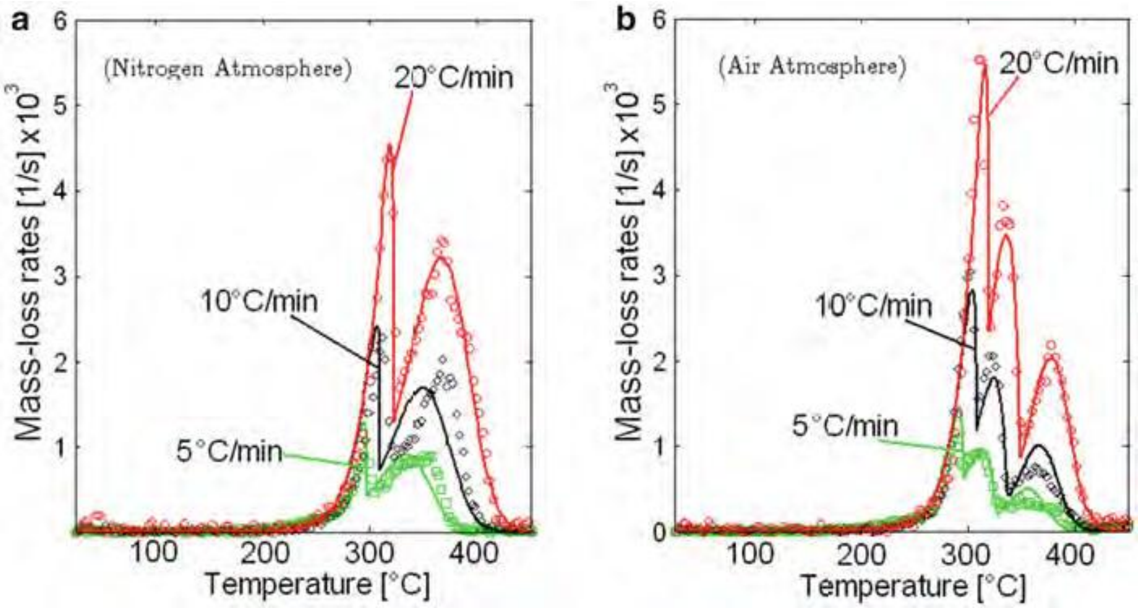
$$\left.\begin{array}{ll} \text{Step i} = 1 & \text{PU} \rightarrow \nu_{\beta,\,\text{p}}\,\beta\text{-PU} + \nu_{\text{g},\,\text{p}}\,\text{Gas} \\ \text{Step i} = 2 & \beta\text{-PU} \rightarrow \nu_{\text{c},\,\text{p}\beta}\,\text{Char} + \nu_{\text{g},\,\text{p}\beta}\,\text{Gas} \end{array}\right\} \text{Purely thermal degradation}$$

$$\left.\begin{array}{ll} \text{Step i} = 3 & \left\{\begin{array}{l} \text{PU} + \nu_{\text{O2},\,\text{o}}\,\text{O}_2 \rightarrow \nu_{\text{c},\text{o}}\,\text{Char} + \nu_{\text{g},\text{o}}\,\text{Gas} \\ \beta\text{-PU} + \nu_{\text{O2},\,\text{o}}\,\text{O}_2 \rightarrow \nu_{\text{c},\text{o}}\,\text{Char} + \nu_{\text{g},\text{o}}\,\text{Gas} \end{array}\right. \\ \text{Step i} = 4 & \text{Char} + \nu_{\text{O2},\,\text{c}}\,\text{O}_2 \rightarrow \nu_{\text{r},\text{c}}\,\text{Residue} + \nu_{\text{g},\text{c}}\,\text{Gas} \end{array}\right\} \text{Oxidation}$$

Source: Rein *et al.* [5]

SOLID PHASE: PYROLYSIS PROCESS

- Inert Atmosphere *vs.* Air atmospheres: effect of heating rate on MLR



TGA data for polyurethane extracted from reference [6] (symbols) superposed to the reduced kinetic model from reference [7] (lines) for inert atmosphere (a) and air (b)

Such qualitative and quantitative agreement is not usual for materials commonly present in fire.

The problem of establishing the chemistry of pyrolysis is not solved in fire research.

- ✓ TGA data above: heating rates 5-20 °C/min
- ✓ Typical fires: 10-200 °C/min

Sources: Torero [3], Chao *et al.* [6], Lautenberger *et al.* [7]

SOLID PHASE: PYROLYSIS PROCESS

- Example of a reaction model for the combustion of moist wood exposed to moderate thermal irradiances:

Moisture evaporation rate

$$\omega_d = -A_d e^{-\frac{E_d}{RT}} \rho_M$$

Wood decomposition

$$W \rightarrow \nu_C C + \nu_T T + \nu_G G$$

$$\omega_p = -A_p e^{-\frac{E_p}{RT}} \rho_W$$

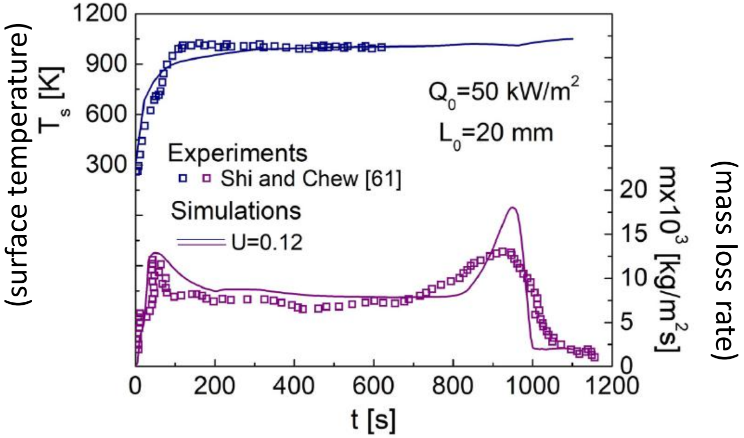
Char oxidation

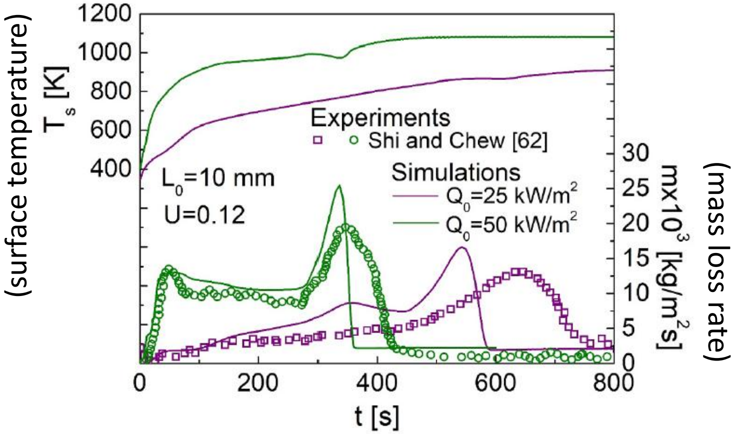
$$C + (\nu_{CO} / 2 + \nu_{CO_2}) O_2 \rightarrow \nu_{CO} CO + \nu_{CO_2} CO_2$$

$$\omega_C = -A_C e^{-\frac{E_C}{RT}} \rho_C \rho_{O_2}$$

Products CO/CO_2

$$\frac{\nu_{CO}}{\nu_{CO_2}} = A_{cpd} e^{-\frac{E_{cpd}}{RT}}$$





Kinetics parameters and properties from literature.

Source: Galgano and Di Blasi [16]

SOLID PHASE: PYROLYSIS PROCESS

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- Example of a model for the oxidative pyrolysis of wood:

Gpyro: open-source generalized pyrolysis model

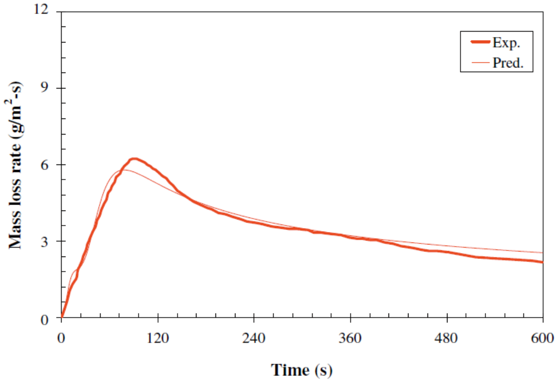
$$\text{wet wood} \rightarrow \nu_{\text{dw}}\text{dry wood} + \nu_{H_2O}H_2O$$

$$\text{dry wood} \rightarrow \nu_{\text{char}}\text{char} + \nu_{\text{tp}}\text{thermal pyrolysate} \rightarrow + O_2 \rightarrow \text{pyrolysate oxidation products}$$

$$\text{dry wood} + \nu_{O_2\text{dw}}O_2 \rightarrow \nu_{\text{char}}\text{char} + \nu_{\text{op}}\text{oxidative pyrolysate}$$

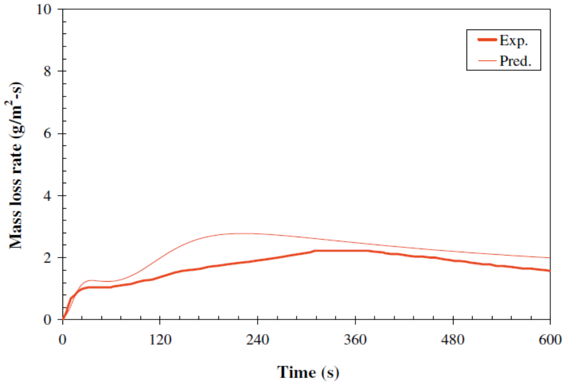
$$\text{char} + \nu_{O_2\text{char}}O_2 \rightarrow \nu_{\text{ash}}\text{ash} + \nu_{\text{cop}}\text{char oxidation products}$$

Kinetics parameters and properties from GA optimization.



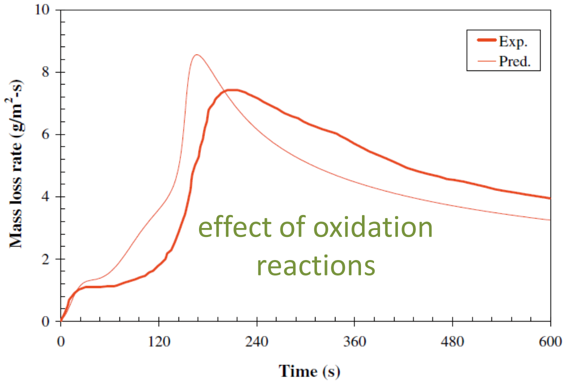
MLR of white pine 40 kW/m² irradiance in nitrogen

MLR controlled by a heat balance



MLR of white pine 25 kW/m² irradiance in nitrogen

MLR controlled by a decomposition kinetics



effect of oxidation reactions

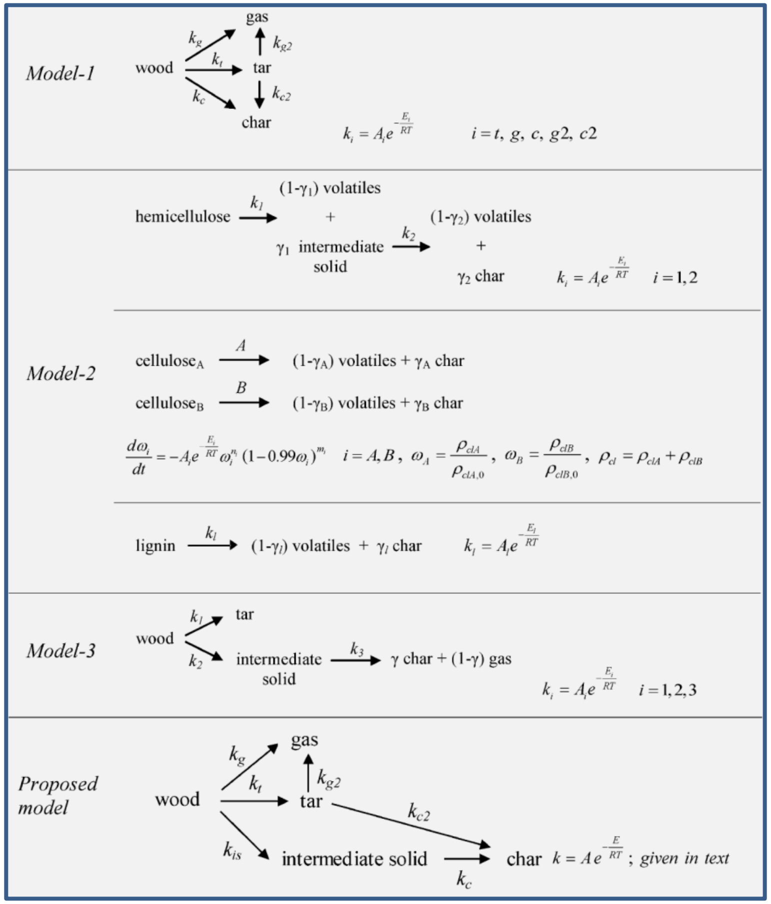
MLR of white pine 25 kW/m² irradiance in oxidative atmosphere (21.5% O_2)

Source: Lautenberger and Fernandez-Pello [17]

SOLID PHASE: PYROLYSIS PROCESS

- Example: heat and mass transfer processes during wood pyrolysis

Wood spheres (1” dia) were pyrolyzed in a vertical tube furnace.



Model-1

wood $\xrightarrow{k_g}$ gas; wood $\xrightarrow{k_t}$ tar; wood $\xrightarrow{k_c}$ char; tar $\xrightarrow{k_{g2}}$ gas; tar $\xrightarrow{k_{c2}}$ char

$k_i = A_i e^{-\frac{E_i}{RT}}$ $\quad i = t,\ g,\ c,\ g2,\ c2$

Model-2

hemicellulose $\xrightarrow{k_1}$ $(1\text{-}\gamma_1)$ volatiles + γ_1 intermediate solid $\xrightarrow{k_2}$ $(1\text{-}\gamma_2)$ volatiles + γ_2 char $\quad k_i = A_i e^{-\frac{E_i}{RT}}$ $\quad i = 1, 2$

cellulose$_A$ $\xrightarrow{A}$ $(1\text{-}\gamma_A)$ volatiles + γ_A char

cellulose$_B$ $\xrightarrow{B}$ $(1\text{-}\gamma_B)$ volatiles + γ_B char

$$\frac{d\omega_i}{dt} = -A_i e^{-\frac{E_i}{RT}} \omega_i^{n_i} (1-0.99\omega_i)^{m_i} \quad i = A, B,\ \omega_A = \frac{\rho_{clA}}{\rho_{clA,0}},\ \omega_B = \frac{\rho_{clB}}{\rho_{clB,0}},\ \rho_{cl} = \rho_{clA} + \rho_{clB}$$

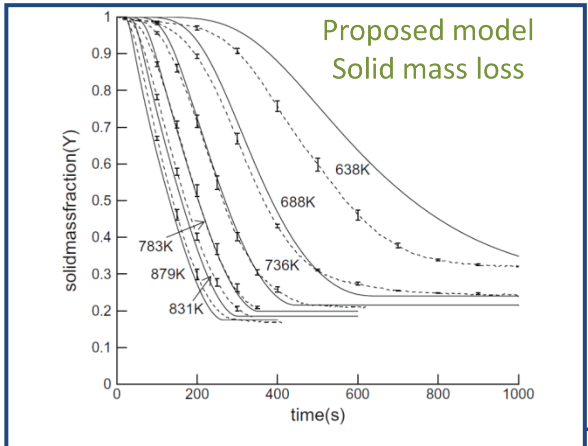
lignin $\xrightarrow{k_l}$ $(1\text{-}\gamma_l)$ volatiles + γ_l char $\quad k_l = A_l e^{-\frac{E_l}{RT}}$

Model-3

wood $\xrightarrow{k_1}$ tar; wood $\xrightarrow{k_2}$ intermediate solid $\xrightarrow{k_3}$ γ char + $(1\text{-}\gamma)$ gas $\quad k_i = A_i e^{-\frac{E_i}{RT}}$ $\quad i = 1, 2, 3$

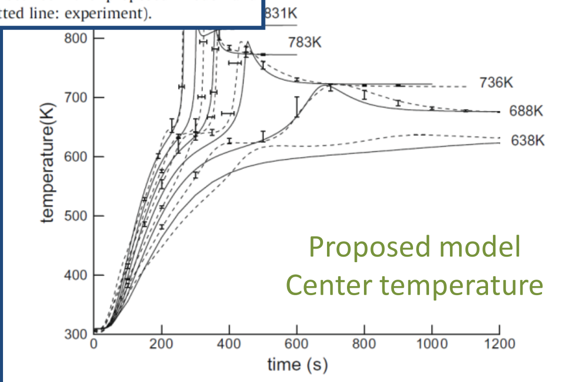
Proposed model

wood $\xrightarrow{k_g}$ gas; wood $\xrightarrow{k_t}$ tar; wood $\xrightarrow{k_{is}}$ intermediate solid $\xrightarrow{k_c}$ char; tar $\xrightarrow{k_{g2}}$ gas; tar $\xrightarrow{k_{c2}}$ char $\quad k = A e^{-\frac{E}{RT}}$; *given in text*



Proposed model
Solid mass loss

Fig. 11. Solid mass fraction comparisons between the proposed model and experiments (solid line: proposed model, dotted line: experiment).



Proposed model
Center temperature

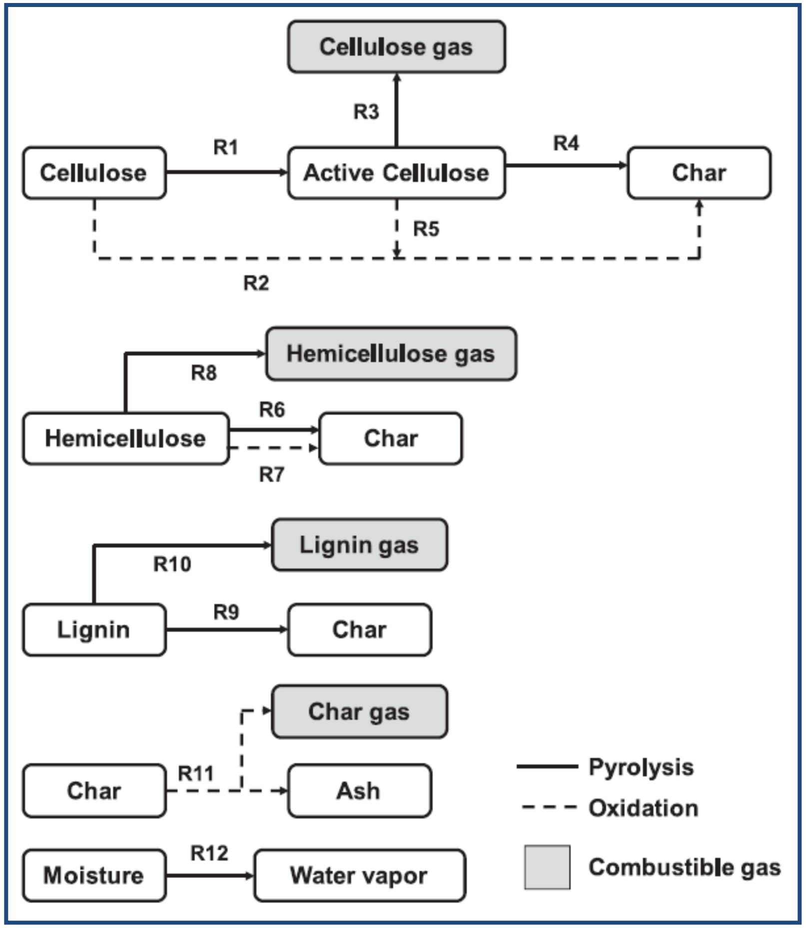
Fig. 13. Center temperature comparisons between the proposed model and the experiment (solid line: proposed model, dotted line: experiment).

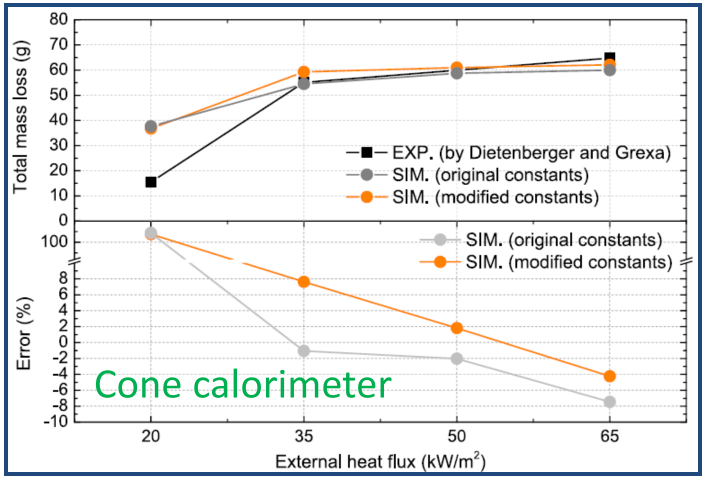
Kinetics parameters from literature and best fit to experiments.

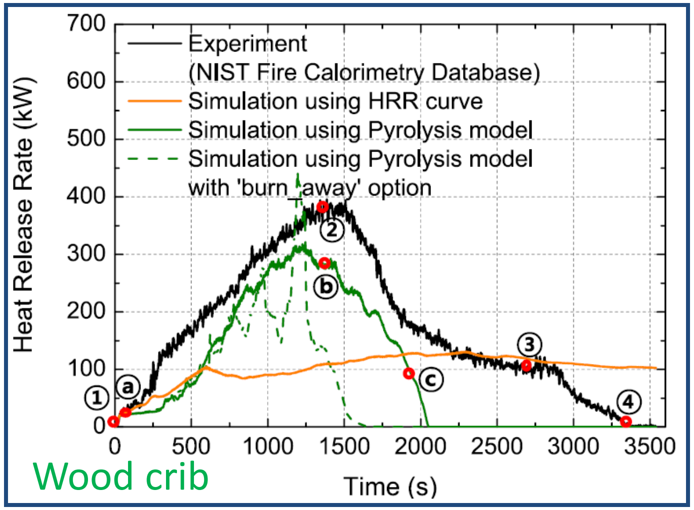
Source: Park *et al.* [18]

SOLID PHASE: PYROLYSIS PROCESS

- Example: detailed pyrolysis model for wood crib fires







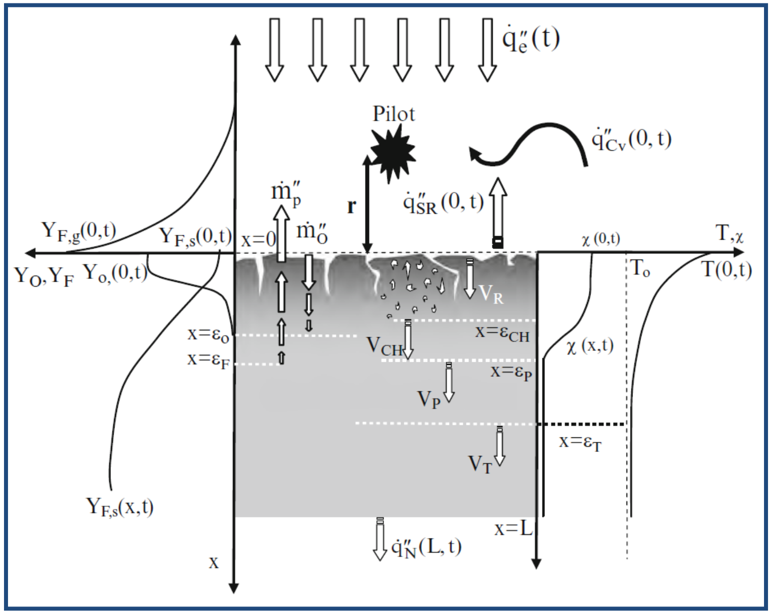
Kinetics parameters from literature and best fit to experiments.

Source: Kim [31]

SOLID PHASE

PRODUCTION OF GASEOUS FUEL

- Before flaming ignition can occur, fuel in the gas phase needs to be produced.
- As temperature increases the pyrolysis reaction rates increase and the solid fuel starts its degradation.
- Given the temperature distribution within the material, the rates of decomposition are a function of *x*, with larger production of pyrolyzates close to the surface and lower production in-depth.
- Due to interactions between pyrolysis and oxidation reactions, pyrolyzates are composed by inert gases (e.g. water vapor), totally oxidized gases (e.g. CO_2), partially oxidized gases (e.g. CO), and fuels (e.g. CH_4, H_2) [8].
- Very few data is available on the degradation products of most materials relevant to fire.



Sources: Torero [3], Kashiwagi and Nambu [8]

SOLID PHASE

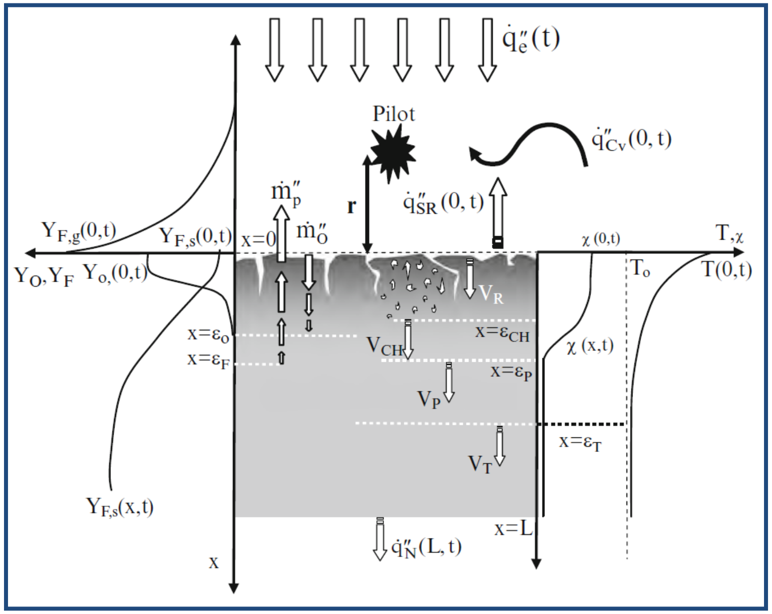
PRODUCTION OF GASEOUS FUEL

- The total gaseous fuel production at the surface per unit area

Integration over the region where fuel is being produced

$$\dot{m}''_P(0,t) = \int_0^{\varepsilon_F} \underbrace{\chi(x,t)}_{(i)} \left(\underbrace{Y_{F,s}(x,t)}_{(ii)} \sum_{i=1}^{i=N} \underbrace{\left[A_i Y_O^{m_i}(x,t) Y_S^{n_i}(x,t) e^{-E_i/RT(x,t)} \right]}_{(iii)} \right) dx$$

(*i*) Function of permeability, porosity, pressure and fractures within the material
(*ii*) Mass fraction of flammable gases present in the local products of degradation (global contribution of all compounds that can be further oxidized)
(*iii*) Arrhenius reaction rates

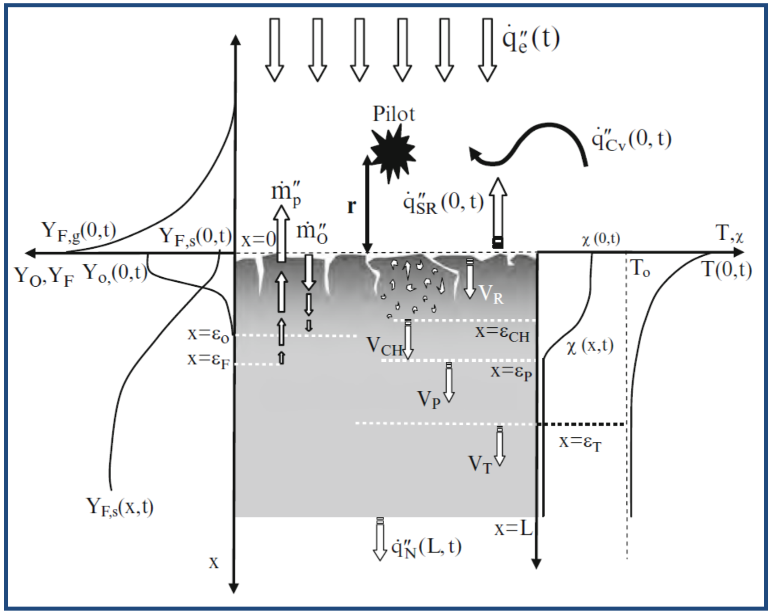


Sources: Torero [3], Kashiwagi and Nambu [8]

SOLID PHASE: CHARRING

- Charring has an impact on both heat and mass transport.
- Role of charring on ignition:
  - ✓ Charring materials pyrolysis leads to the production of gaseous fuel (pyrolyzate) and a residual solid phase char.
  - ✓ Char is mainly a carbonaceous solid that could be further decomposed.
  - ✓ The secondary decomposition could be complete, leading to an inert ash or to a secondary char that can be further decomposed.

- *V_R*: exposed surface (boundary between solid and gas) regression rate. Boundary where complete consumption of the fuel is achieved.
- Carbonaceous chars can reach high temperatures leading in many cases to vigorous oxidation (surface glowing) that can be the catalyser for gas phase ignition.



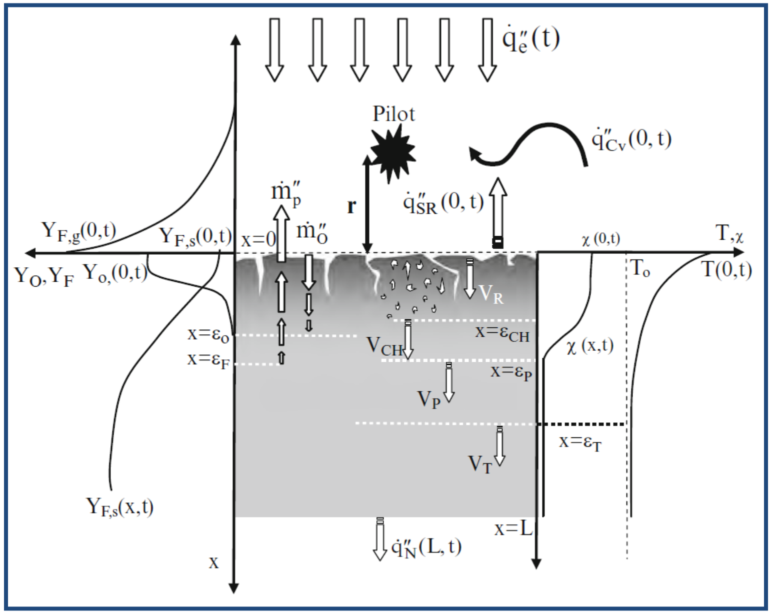
Source: Torero [3]

SOLID PHASE: THERMAL DEPTH

- V_T: velocity at which the thermal wave travels through material.
- $\varepsilon_T(t)$: the end of the region that has been heated
  - *$L > \varepsilon_T$: Semi-infinite solid*

    The thermal wave is far from the end of the sample. The fuel can be treated as a semi-infinite solid ($L \rightarrow \infty$).
  - *$\varepsilon_T \geq L$: Thermally-thick and thermally-thin solid*

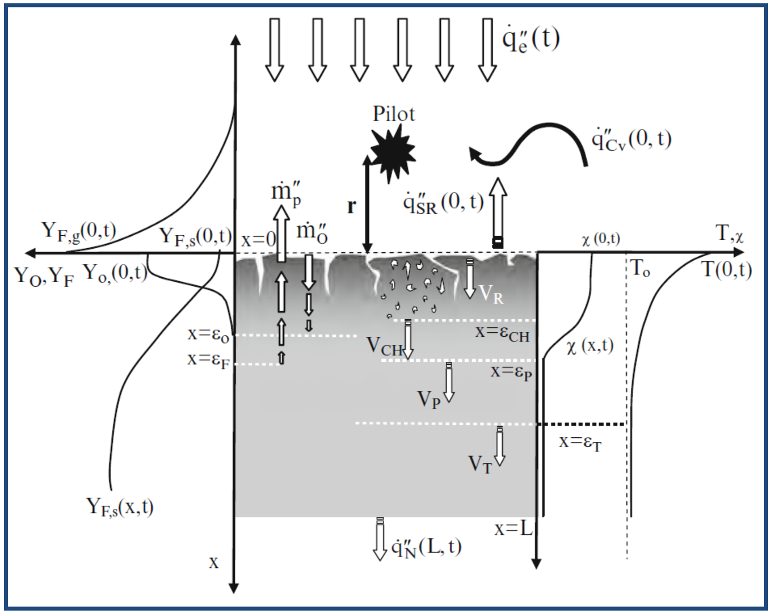
    The thermal wave has reached the end of the sample.
    - ✓ *Thermally-thick: a significant thermal gradient exists within the solid before ignition (Bi ~ 1)*
    - ✓ *Thermally-thin: gradient is negligible for most of the time before ignition (Bi<<1)*



Sources: Torero [3]

SOLID PHASE:
PYROLYSIS AND CHARRING DEPTHS

- ε_P: depth at which the chemistry can be assumed to be significant (for $x > \varepsilon_P$ the solid can be considered inert).
- V_P: propagation velocity of the pyrolysis front.
- The relevant thermal properties are: ρ(x,t), k(x,t), c(x,t)
  - ✓ Known for common materials, while still unknown for materials typically present in fires (wood, complex plastics, composites, etc.).
- ε_C: charring front depth, which moves at a velocity V_{CH}.
  - ✓ Char properties are still the permeability, the density, thermal conductivity and specific heat but precise values are mostly unknown for most chars issued of materials relevant to fires.



Sources: Torero [3]

SOLID PHASE:
WATER EVAPORATION

- Endothermic phase change process that can have a significant effect on the temperature distribution in the solid.
- Generally incorporated to the energy equation as a heat sink where some rate function is created to describe the conversion from one phase to the other. The simplest procedure is to assign a critical temperature to the phase change (i.e. 100°C for water).
- The thermal wave can only proceed once the transition (liquid-vapour) has been completed.

Sources: Torero [3]

SOLID PHASE: TEMPERATURE DISTRIBUTION

- 1946: Bamford *et al.* (wood board heated by a flame modeled as T_{surf})

$$K\frac{\partial^2 T}{\partial x^2} - q\frac{\partial w}{\partial t} = c\rho\frac{\partial T}{\partial t}$$

- 1972: *Kung et al.* (wood slabs heated externally)

$$\bar{\rho}\bar{C}_{ps}\frac{\partial \bar{T}}{\partial \bar{t}} = \frac{\partial}{\partial \bar{x}}\left(\bar{k}\frac{\partial \bar{T}}{\partial \bar{x}}\right) + \bar{M}_g\bar{C}_{pg}\frac{\partial \bar{T}}{\partial \bar{x}} + \frac{\partial \bar{\rho}}{\partial \bar{t}}\left[\bar{Q}_p - \int_1^{\bar{T}}\left(\frac{\bar{C}_{pa}}{1-\bar{\rho}_f} - \frac{\bar{\rho}_f\bar{C}_{pc}}{1-\bar{\rho}_f} - \bar{C}_{pg}\right)d\bar{T}\right]$$

- 2010: Park *et al.* (wood spheres in a vertical tube furnace)

$$(C_w\rho_a + C_w\rho_{is} + C_c\rho_c + \varepsilon C_{pt}\rho_t + \varepsilon C_{pg}\rho_g)\frac{\partial T}{\partial t} + (C_{pt}\rho_t + C_{pg}\rho_g)V\frac{\partial T}{\partial r} = \frac{1}{r^2}\frac{\partial T}{\partial r}\left(r^2\lambda\frac{\partial T}{\partial r}\right) + Q$$

$$Q = -(k_t\Delta h_t + k_g\Delta h_g + k_{is}\Delta h_{is})\rho_a - k_c\Delta h_c\rho_{is} - (k_{c2}\Delta h_{c2} + k_{g2}\Delta h_{g2})\rho_t$$

- Software FDS – Fire Dynamics Simulator

$$\rho_s c_s\frac{\partial T_s}{\partial t} = \frac{\partial}{\partial x}\left(k_s\frac{\partial T_s}{\partial x}\right) + \dot{q}_s''' \qquad \dot{q}_s''' = \dot{q}_{s,c}''' + \dot{q}_{s,r}''' \qquad \dot{q}_{s,c}'''(x) = -\sum_{\alpha=1}^{N_m}\sum_{\beta=1}^{N_{r,\alpha}} r_{\alpha\beta}(x)H_{r,\alpha\beta}$$

SOLID PHASE:
TEMPERATURE DISTRIBUTION

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- 1946: Bamford *et al.* (wood board heated by a flame modeled as T_{surf})

Char region

Decomposing region (570-720 K)

Heating region: virgin wood (0-570 K)

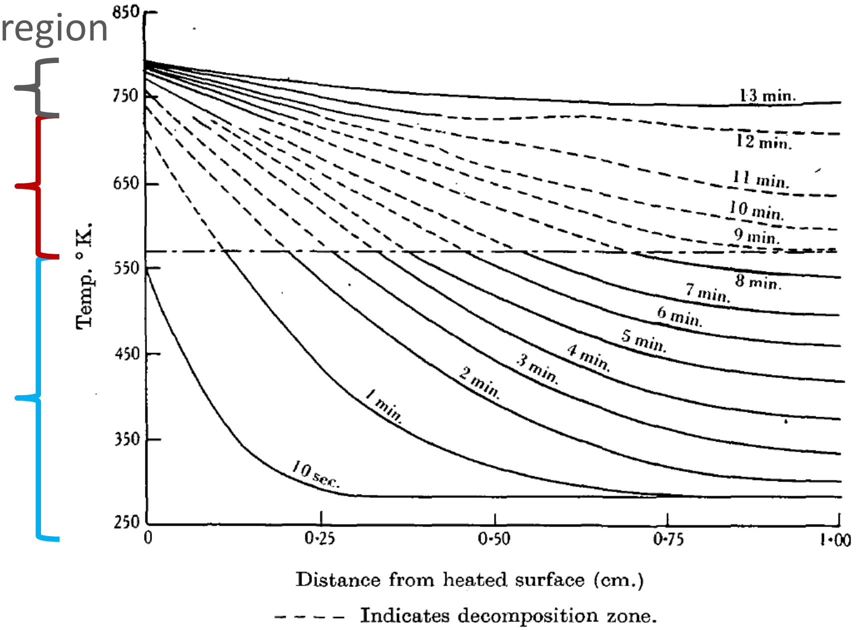


Fig. 2. Temperature-space curves (2 cm. sheet).

Char region

Decomposing region (570-720 K)

Heating region: virgin wood (0-570 K)

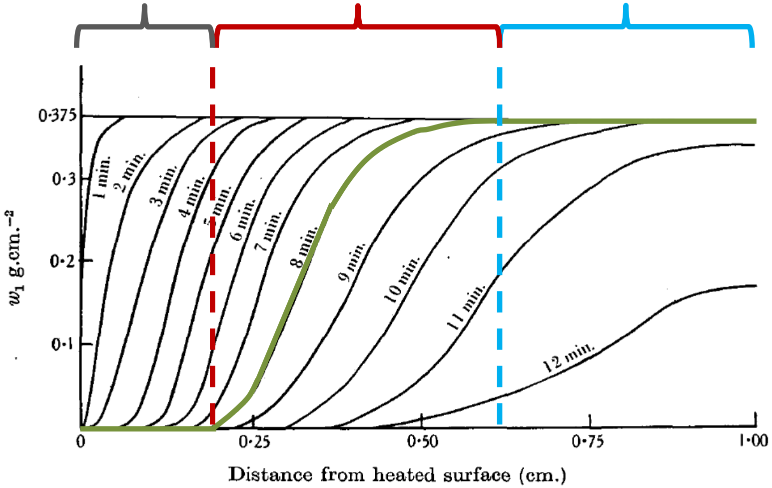
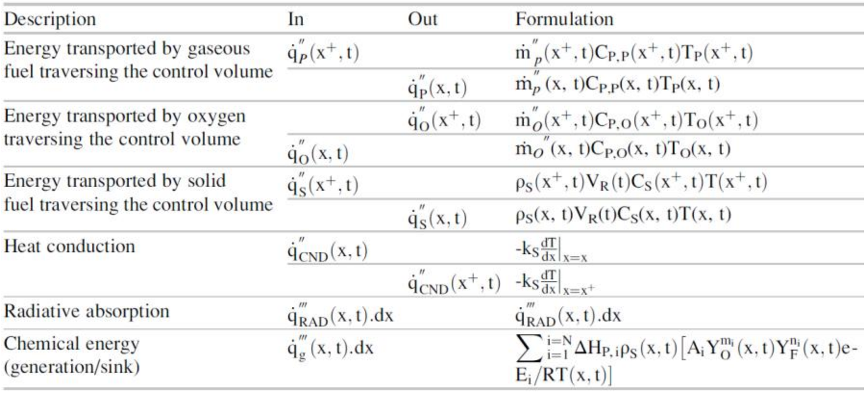


Fig. 3. *w*-curves (2 cm. sheet).

Mass of volatile products per cm^3 of wood

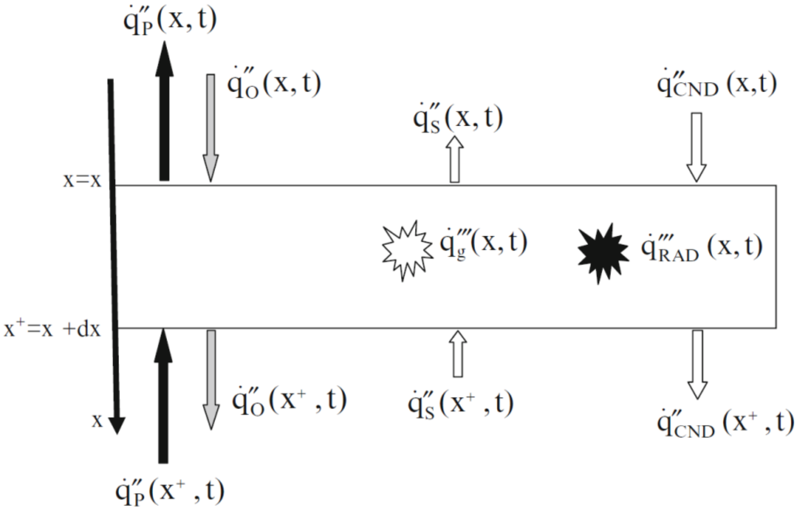
SOLID PHASE:
TEMPERATURE DISTRIBUTION

- Energy balance:



Description	In	Out	Formulation
Energy transported by gaseous fuel traversing the control volume	$\dot{q}''_P(x^+,t)$		$\dot{m}''_p(x^+,t)C_{P,P}(x^+,t)T_P(x^+,t)$
		$\dot{q}''_P(x,t)$	$\dot{m}''_p(x,t)C_{P,P}(x,t)T_P(x,t)$
Energy transported by oxygen traversing the control volume		$\dot{q}''_O(x^+,t)$	$\dot{m}''_O(x^+,t)C_{P,O}(x^+,t)T_O(x^+,t)$
	$\dot{q}''_O(x,t)$		$\dot{m}_O''(x,t)C_{P,O}(x,t)T_O(x,t)$
Energy transported by solid fuel traversing the control volume	$\dot{q}''_S(x^+,t)$		$\rho_S(x^+,t)V_R(t)C_S(x^+,t)T(x^+,t)$
		$\dot{q}''_S(x,t)$	$\rho_S(x,t)V_R(t)C_S(x,t)T(x,t)$
Heat conduction	$\dot{q}''_{CND}(x,t)$		$-k_S\frac{dT}{dx}\Big\vert_{x=x}$
		$\dot{q}''_{CND}(x^+,t)$	$-k_S\frac{dT}{dx}\Big\vert_{x=x^+}$
Radiative absorption	$\dot{q}'''_{RAD}(x,t).dx$		$\dot{q}'''_{RAD}(x,t).dx$
Chemical energy (generation/sink)	$\dot{q}'''_g(x,t).dx$		$\sum_{i=1}^{i=N}\Delta H_{P,i}\rho_S(x,t)\left[A_iY_O^{m_i}(x,t)Y_F^{n_i}(x,t)e\text{-}E_i/RT(x,t)\right]$

Typical control volume for $x < \varepsilon_p$ showing the main heat transfer mechanisms



$$E_{CV} = \rho_S(x,t)C_S(x,t)T(x,t)\ dx$$

$$\frac{\partial E_{CV}}{\partial t} = \left[\dot{q}''_S(x^+,t) + \dot{q}''_P(x^+,t) + \dot{q}''_0(x,t) + \dot{q}''_{CND}(x,t)\right] - \left[\dot{q}''_O(x+,t) + \dot{q}''_{CND}(x+,t) + \dot{q}''_S(x,t) + \dot{q}''_P(x,t)\right] + \dot{q}'''_{RAD}(x,t)\,dx + \dot{q}'''_g(x,t)\,dx$$

Source: Torero [3]

SOLID PHASE:
TEMPERATURE DISTRIBUTION

- General energy equation for the control volume:

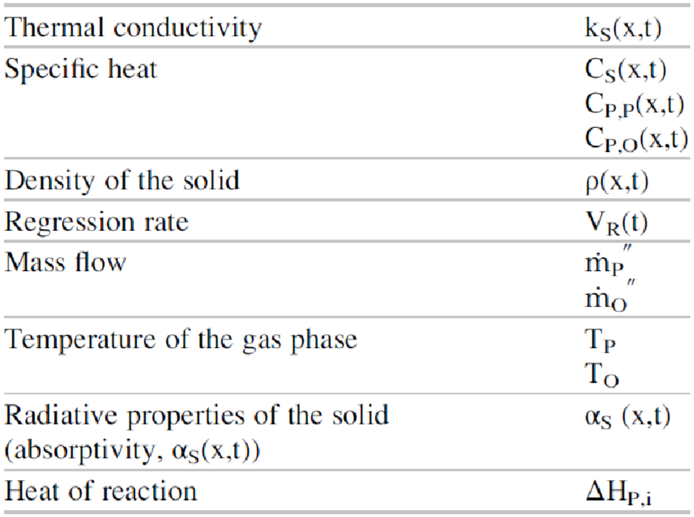
$$\frac{\partial[\rho_S C_S T]}{\partial t} = \frac{\partial}{\partial x}\left[k_S \frac{\partial T}{\partial x}\right] + \frac{\partial\left[m''_P C_{P,P} T_P\right]}{\partial x} - \frac{\partial\left[m''_O C_{P,O} T_O\right]}{\partial x} + \frac{\partial[\rho_S V_R C_S T]}{\partial x} + \dot{q}'''_{RAD}$$

$$+ \sum_{i=1}^{i=N} \Delta H_{P,i}\,\rho_S\left[A_i Y_O^{m_i} Y_S^{n_i} e^{-E_i/RT}\right]$$

- Solution provides temperature distribution *T*(*x*,*t*) along the sample, which is used to compute the fuel production rate, $\dot{m}''_P(0,t)$.

$$\dot{m}''_P(0,t) = \int_0^{\varepsilon_F} \chi(x,t)\left(Y_{F,s}(x,t)\sum_{i=1}^{i=N}\left[A_i Y_O^{m_i}(x,t)\,Y_S^{n_i}(x,t)\,e^{-E_i/RT(x,t)}\right]\right)dx$$

To summarize, temperature distribution is a function of:



Thermal conductivity	$k_S(x,t)$
Specific heat	$C_S(x,t)$ $C_{P,P}(x,t)$ $C_{P,O}(x,t)$
Density of the solid	$\rho(x,t)$
Regression rate	$V_R(t)$
Mass flow	$\dot{m}_P''$ $\dot{m}_O''$
Temperature of the gas phase	T_P T_O
Radiative properties of the solid (absorptivity, $\alpha_S(x,t)$)	$\alpha_S\,(x,t)$
Heat of reaction	$\Delta H_{P,i}$

Source: Torero [3]

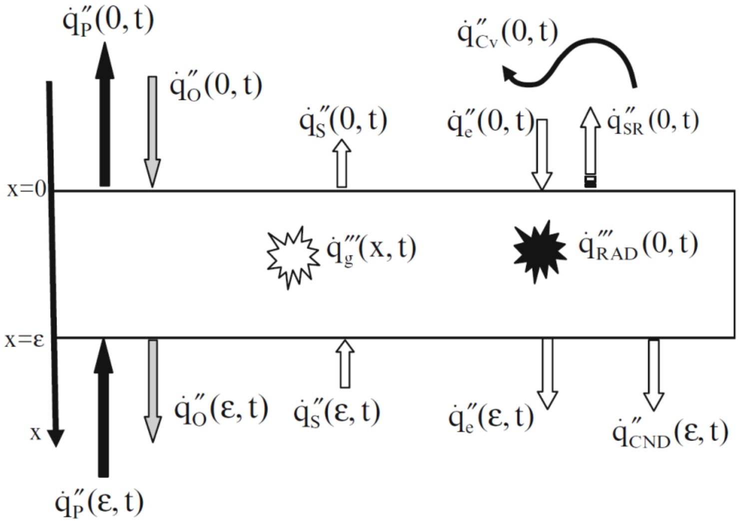
SOLID PHASE:
SURFACE BOUNDARY CONDITIONS

- For the exposed boundary condition (*x* = 0):

$$0 = k_S \frac{\partial T}{\partial x}\bigg|_{x=0^+} - \varepsilon_S(0,t)\sigma\left(T^4(0,t) - T_0^4\right) - h_{Cv}(t)\left(T(0,t) - T_0\right)$$

- For the back end boundary condition (*x* = *ε*), assumed to be in direct contact with another solid:

$$0 = -k_S \frac{\partial T}{\partial x}\bigg|_{x=L^-} + k_B \frac{\partial T_B}{\partial x}\bigg|_{x=L^+}$$



Boundary control volume for x = 0 showing the main heat transfer mechanisms

Source: Torero [3]

GAS PHASE

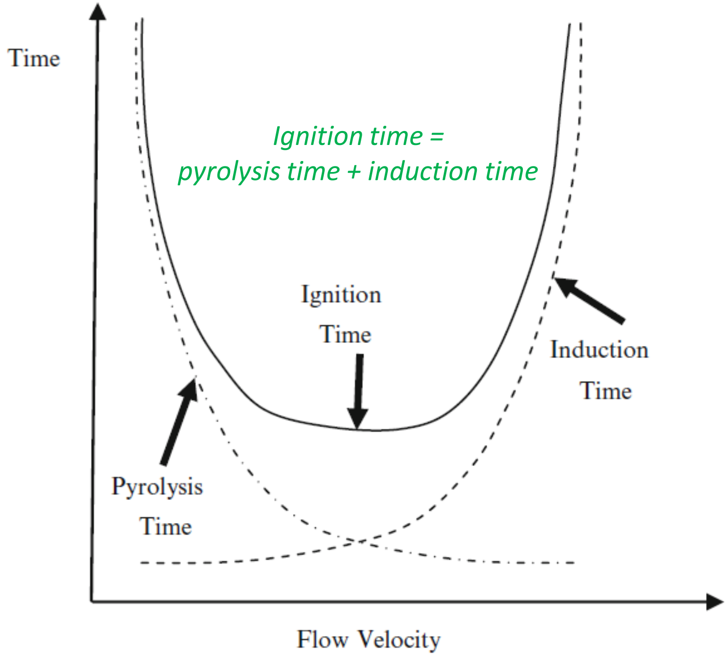
- After the onset of pyrolysis, gas begins to emerge from the fuel surface, initially in very small quantities, but as ε_F and T(x,t) increase the fuel mass flux will increase.
- The emerging fuel will encounter the ambient oxidizer and eventually produce a flammable mixture.
- Given that fuel is migrating into the oxidizer flow, the definition of a flammable mixture is not a simple one.
  - ✓ *In standard test methods the ambient flow is well defined.*
  - ✓ *In real fires, flow fields are defined by the flames themselves and by the geometry of the environment (obstacles, fuel geometry, etc.) with the possibility of complex flow patterns.*

Nevertheless, from a phenomenological perspective, to achieve ignition, what is required is to achieve a flammable condition (fuel concentration between LFL and UFL) in at least one location in the gas phase.

Source: Torero [3]

GAS PHASE:
AUTO-IGNITION

- Once a flammable mixture has been attained, this mixture needs to increase in temperature until a combustion reaction can occur.
  - Pyrolysis time: the time required to attain a flammable mixture.
  - Induction time: the time for the mixture to reach a temperature at which ignition can occur.



Schematic of the characteristic times involved in the ignition of a solid fuel [9, 10 ,11]. In these experiments the heat to initiate the combustion reaction is provided by a hot flow impinging on a fuel surface that acts as a heat sink.

Source: Torero [3], Fernandez-Pello [9,10], Niioka [11]

GAS PHASE:
PILOTED IGNITION

- Including a pilot flame or a hot spot is a practical experimental simplification that has a basis on reality, since in most ignition scenarios there will be a region of high temperature.
- The presence of a pilot strongly simplifies the gas phase processes and reduces the influence of environmental variables.
- In the presence of a pilot, ignition can be assumed at the moment where a flammable mixture (LFL) is attained at the location of the pilot.
- To attain the LFL at the pilot location it is necessary to resolve the momentum and mass transport equations simultaneously.

$$\rho_0 \frac{D\vec{u}}{Dt} = -\nabla P + \rho_0 \vec{g} + \mu_0 \nabla^2 \vec{u}$$

$$\rho_0 \frac{DY_{O,g}}{Dt} = \rho_0 D_{F,O} \nabla^2 Y_{O,g}$$

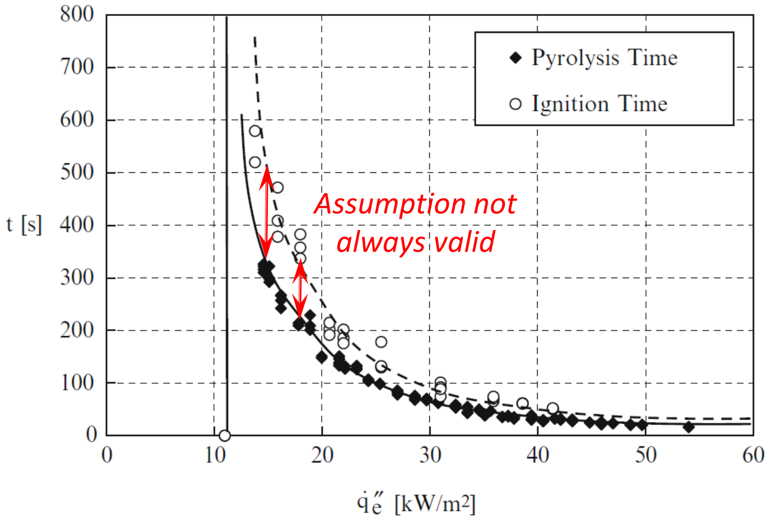
$$\rho_0 \frac{DY_{F,g}}{Dt} = \rho_0 D_{F,O} \nabla^2 Y_{F,g}$$

Source: Torero [3]

SIMPLIFICATIONS TO SOLVE T(x,t):
THE INERT SOLID ASSUMPTION

- The assumption that the solid remain inert until ignition is probably the most far reaching of all proposed simplifications.
    - ✓ As a result of this assumption the energy equation is dramatically simplified:

$$\frac{\partial[\rho_S C_S T]}{\partial t} = -\frac{\partial}{\partial x}\left[-k_S \frac{\partial T}{\partial x}\right] + \dot{q}'''_{RAD}$$



Characteristic ignition delay times (t_{ig}) and times to the onset of pyrolysis (t_p) for PMMA and a wide range of external heat fluxes extracted [12]. Onset of pyrolysis or ignition did not occur below 11 kW/m^2

Sources: Dakka *et al.* [12], Torero [3]

SIMPLIFICATIONS TO SOLVE T(x,t):
ABSORPTION OF RADIATION & GLOBAL PROPERTIES

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- The next major simplifications that are commonly accepted are to assume that most of the incident heat flux is absorbed ($\alpha(t) \approx 1$) at the surface and that the thermal properties of the solid can be considered invariant. This results in:

$$\frac{\partial[\rho_S C_S T]}{\partial t} = -\frac{\partial}{\partial x}\left[-k_S \frac{\partial T}{\partial x}\right] + \dot{q}'''_{RAD} \longrightarrow \overline{\rho}_S \overline{C}_S \frac{\partial[T]}{\partial t} = \overline{k}_S \left[\frac{\partial^2 T}{\partial x^2}\right]$$

  - ✓ The exposed boundary condition ($x = 0$) reads as:

$$\begin{aligned} 0 &= k_S \left.\frac{\partial T}{\partial x}\right|_{x=0^+} - \varepsilon_S(0,t)\sigma\left(T^4(0,t) - T_0^4\right) - h_{Cv}(t)\left(T(0,t) - T_0\right) \\ &\downarrow \\ 0 &= \overline{k}_S \left.\frac{\partial T}{\partial x}\right|_{x=0^+} + \dot{q}''_e - \sigma\left(T^4(0,t) - T_0^4\right) - h_{Cv}(t)\left(T(0,t) - T_0\right) \end{aligned}$$

- There is little true justification in the literature to support these assumptions, nevertheless they are of practical use.

Source: Torero [3]

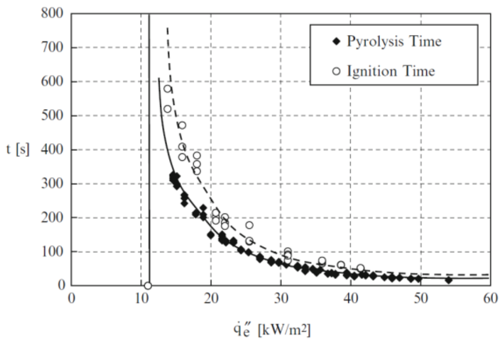
SIMPLIFICATIONS TO SOLVE T(x,t):

IGNITION CONDITION

- If the solid is assumed to be inert until ignition and the gas phase heat exchange can be summarized into a single total heat transfer coefficient (h_T) this amounts to the assumption that *ignition will occur at the onset of pyrolysis* and that this process can be simply characterized by the attainment of a ***characteristic surface temperature*** that is commonly labelled the ***ignition temperature***, T_{ig}.
- If the sample is suddenly exposed to an external heat flux, then the time delay between exposure and ignition is named the ***ignition delay time***, t_{ig}.
  - ✓ These two parameters represent then the entire process of ignition.

Critical heat flux for ignition: *for* t_{ig} *infinitely long, there will be no gradients of temperature within the solid and surface heat losses will be equivalent to the heat input.*

$$T_{ig} = T_0 + \frac{\dot{q}''_{0,ig}}{h_T}$$



Source: Torero [3]

SIMPLIFICATIONS TO SOLVE T(x,t): SOLUTION

- Imposing a constant external heat flux ($\dot{q}_e'' =$ constant) and using all the above assumptions allows for an analytical solution for *T*(*x*,*t*):

$$T(x,t) - T_0 = \frac{\dot{q}_e''}{(h_T)}\left[\mathrm{erfc}\left(\frac{x}{\sqrt{4\bar{\alpha}_D t}}\right) - e^{\frac{(h_T)}{\sqrt{\alpha_D}\sqrt{\bar{k}_S\bar{\rho}_S\bar{C}_S}}x} + \frac{(h_T)^2}{\bar{k}_S\bar{\rho}_S\bar{C}_S} t\,\mathrm{erfc}\left(\frac{(h_T)}{\sqrt{\bar{k}_S\bar{\rho}_S\bar{C}_S}}t^{\frac{1}{2}} + \frac{x}{\sqrt{4\bar{\alpha}_D t}}\right)\right]$$

- The surface temperature, *T*(0,*t*) = T_s(t), is obtained from:

$$T_s = T_0 + \frac{\dot{q}_e''}{(h_T)}\left[1 - e^{\left(\frac{(h_T)^2}{\bar{k}_S\bar{\rho}_S\bar{C}_S}\right)t}\,\mathrm{erfc}\left(\frac{(h_T)}{\sqrt{\bar{k}_S\bar{\rho}_S\bar{C}_S}}t^{\frac{1}{2}}\right)\right]$$

Characteristic time:

$$t_c = \frac{\bar{k}_S\bar{\rho}_S\bar{C}_S}{(h_T)^2}$$

- To obtain the ignition delay time (t_{ig}), T_s is substituted by T_{ig}:

$$T_{ig} = T_0 + \frac{\dot{q}_e''}{(h_T)}\left[1 - e^{\frac{t_{ig}}{t_c}}\,\mathrm{erfc}\left(\left(\frac{t_{ig}}{t_c}\right)^{\frac{1}{2}}\right)\right]$$

Source: Quintiere [13], Torero [3]

SIMPLIFICATIONS TO SOLVE T(x,t): SOLUTION

$$T_{ig} = T_0 + \frac{\dot{q}_e''}{(h_T)}\left[1 - e^{\frac{t_{ig}}{t_c}}\operatorname{erfc}\left(\left(\frac{t_{ig}}{t_c}\right)^{\frac{1}{2}}\right)\right]$$

- In order to solve for the ignition delay time (t_{ig}) a first order Taylor series expansion is conducted for two conditions:
  - ✓ High incident heat fluxes where T_{ig} is attained very fast, thus $t_{ig} << t_c$ ($t_{ig}/t_c \rightarrow 0$):

$$\frac{1}{\sqrt{t_{ig}}} = \frac{2}{\sqrt{\pi}\sqrt{\overline{k_S}\,\overline{\rho_S}\,\overline{C_S}}}\,\frac{\dot{q}_e''}{(T_{ig} - T_0)}$$

(independent of h_T)

  - ✓ Low incident heat fluxes where $t_{ig} \geq t_c$ ($t_{ig}/t_c \rightarrow \infty$):

$$\frac{1}{\sqrt{t_{ig}}} = \frac{\sqrt{\pi}\sqrt{\overline{k_S}\,\overline{\rho_S}\,\overline{C_S}}}{h_T}\left[1 - \frac{h_T(T_{ig} - T_\infty)}{\dot{q}_e''}\right]$$

Source: Quintiere [13], Torero [3]

CALL FOR RESEARCHERS

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“fundamental combustion research community may play a leading role” [26]

“fundamental experimental science community is more important than ever to address the problems of a vastly diverse and growing world. … a necessary step to develop the next generation of computational tools to properly address the LOF problem and in turn develop requisite mitigation strategies.” [30]

experiments	models	heat transfer	material properties
real scale	phenomenology	combustion	data acquisition and analysis
lab scale	applications	fluid flow	mechanical behavior

Source: International FORUM of Fire Research Directors [26], Manzello and Suzuki [30]

CALL FOR RESEARCHERS

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- CI Symposium areas

Fundamental Processes

- ✓ Chemical kinetics
- ✓ Flame dynamics and transport processes
- ✓ Turbulent flames
- ✓ Detonations and high-speed combustion
- ✓ Heterogeneous combustion and processes

Enabling Models, Methods, Tools and Technology

- ✓ Diagnostics and experimental methods
- ✓ Modeling approaches
- ✓ Numerical techniques
- ✓ Enabling concepts

Applications

- ✓ Energy and material conversion and heating processes
- ✓ Low-speed propulsion
- ✓ High-speed propulsion and energetics
- ✓ Fire and safety

- IAFSS Symposium areas

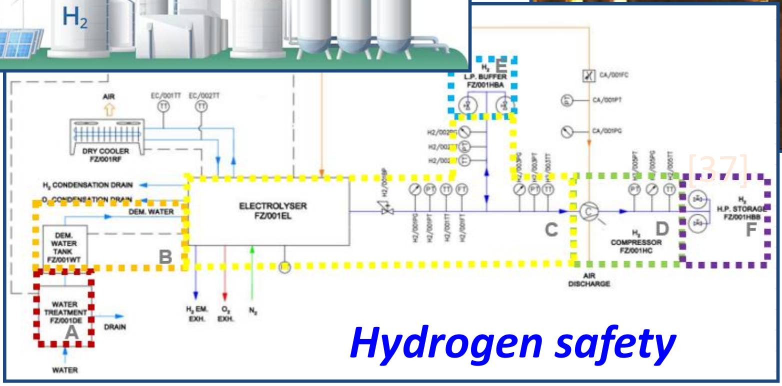
- ✓ Ignition, flame structure, and spread (including pool fires and flame heat transfer)
- ✓ Solid pyrolysis and smoldering
- ✓ Material flammability (including flame retardant materials, flammability testing, fire emissions and their toxicity)
- ✓ Enclosure fire dynamics (including compartment, building, facade, tunnel fires, and smoke transport)
- ✓ Large outdoor fires (wildland, wildland-urban interface fires, and urban conflagrations)
- ✓ Fires in energy systems and industrial installations (including electrical vehicles, hydrogen, photovoltaics, wind turbines, manufacturing and storage facilities)
- ✓ Fire detection and suppression
- ✓ Structure-fire interactions (mechanical response to fires of steel, concrete, timber or composite structures)
- ✓ Evacuation, human behavior, and societal impact of fire
- ✓ Fire risk assessment, performance-based design, and fire forensics

OTHER TOPICS ON FIRE RESEARCH UNDER DEVELOPMENT AT UFRGS

UFRGS FIRE DYNAMICS LABORATORY

- Ignition of wooden structures at the WUI
- Fire retardants and suppressants for wildland fires and for wooden dwellings
- Firefighting devices for wildland fires
- Informal settlement fires
- Fire safety and risk analysis of H_2 systems
- Fire safety of cultural heritage and historic buildings fires

Fire retardants development and testing



Hydrogen safety

National Museum RJ

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Thank you!

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felipecentenoufrgs


Porto Alegre

10th School on COMBUSTION

July 24th, 2025

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