Basic fire processes

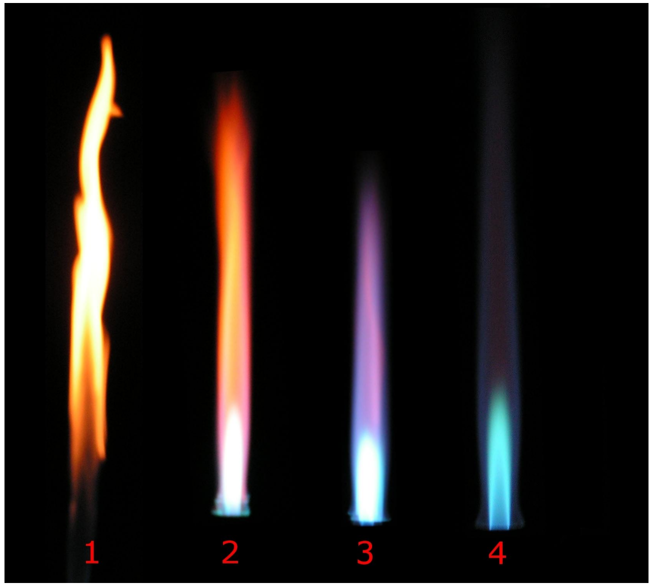
What's a fire ?

The rapid oxidation (combustion) of a material (the fuel) releasing heat, light and various reaction products (*adapted from standard definitions*)

Contrary to many combustion devices (engines, bunsen burner,...) :

- fire is a self-sustained process,
- often uncontrolled.

Fire spreading in a grass fuel



Bunsen Burner (combustion device)

Basic fire processes

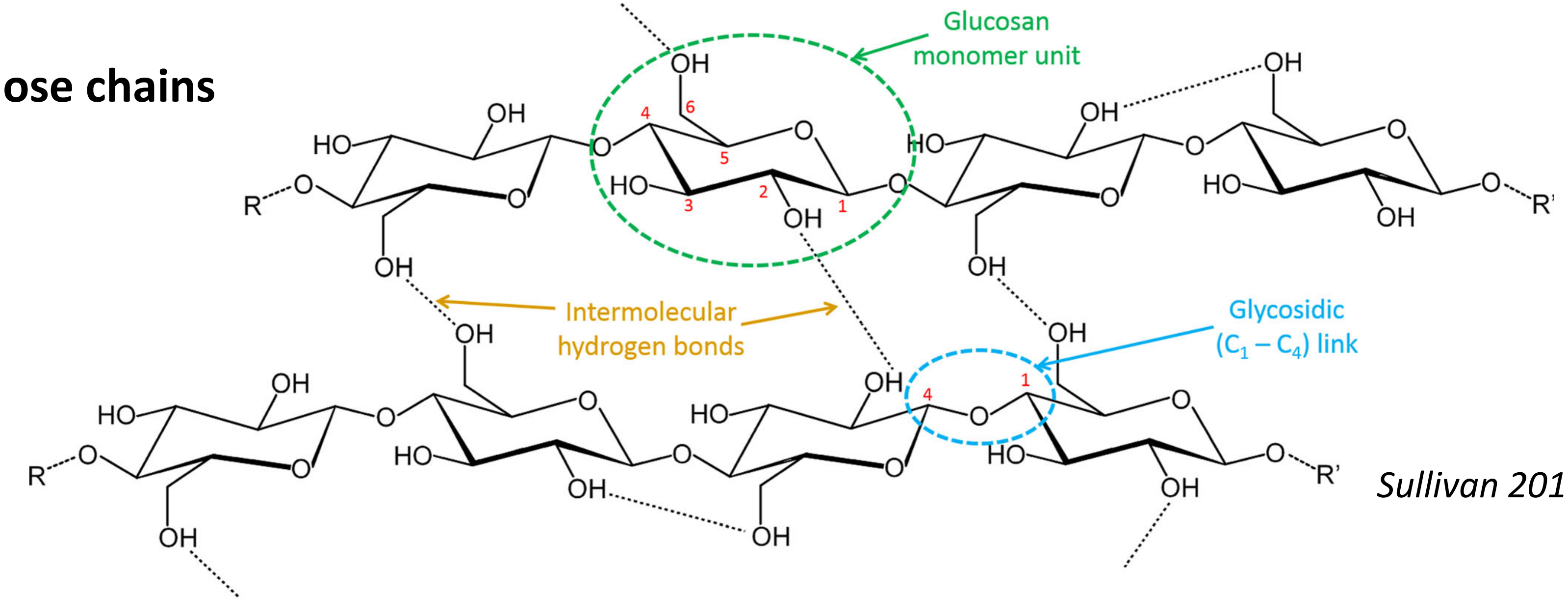
Common fuels

All include carbon in any form (hydrocarbons, alcohols, carbohydrates)

Gasesous : methane (natural gas), propane, ethylen, ...
Liquid : alcohols, gasoline
Solid : coal, synthetic polymers, <u>wood and other natural fibers</u>

Wood and other biomass fuels are mostly composed of natural polymers of carbohydrates (Cm(H20)n) : cellulose, hemicelluloses and lignin.

Cellulose chains



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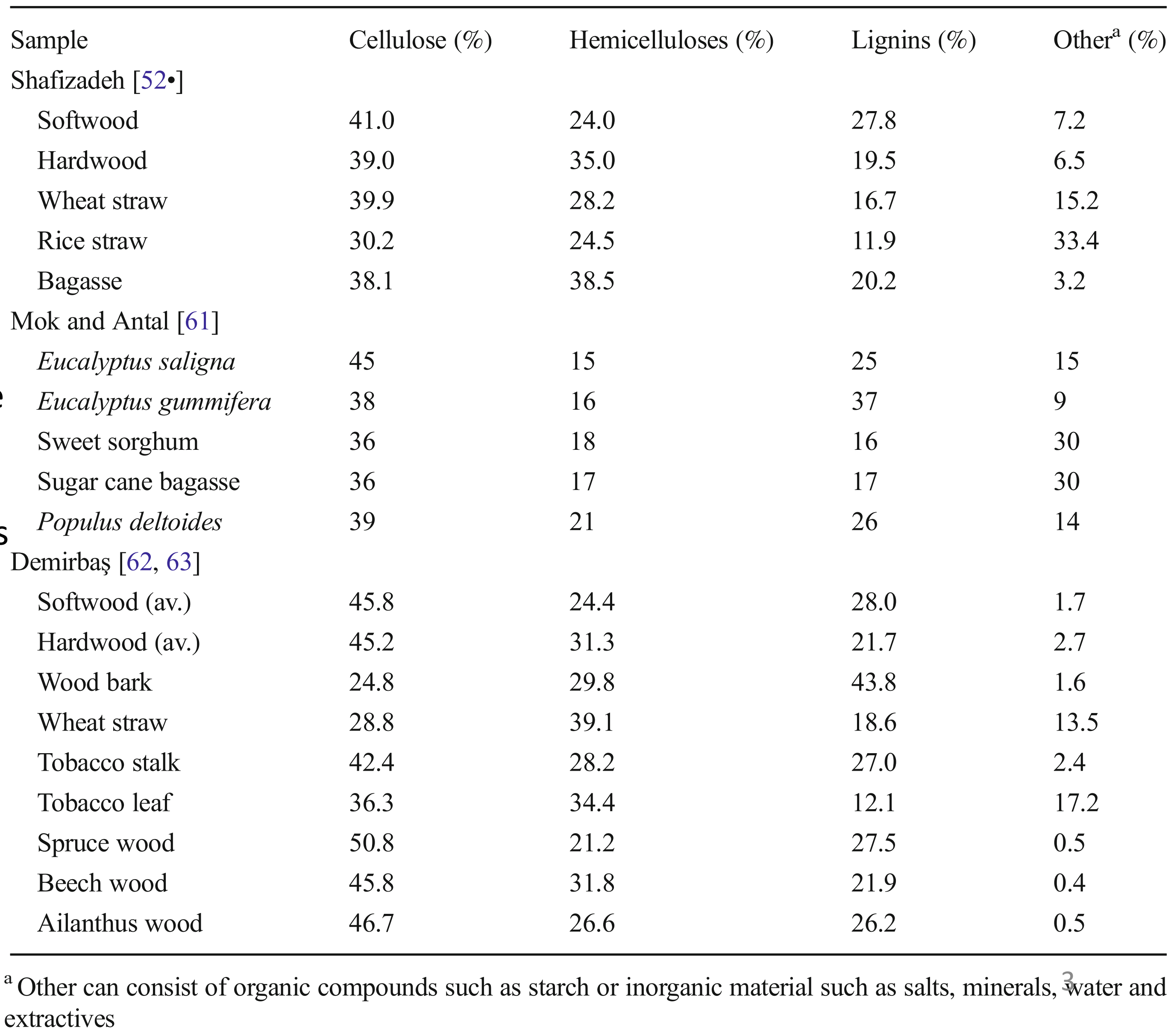
Basic fire processes

Biomass fuels

Table 2 Approximate analysis of some biomass species taken from Shafizadeh [52•], Mok and Antal [61] and Demirbaş [62, 63]. Source: modified from [41••] with permission from Elsevier



Sample	Cellulose (%)	Hemicelluloses (%)	Lignins (%)	Other[a] (%)
Shafizadeh [52•]				
Softwood	41.0	24.0	27.8	7.2
Hardwood	39.0	35.0	19.5	6.5
Wheat straw	39.9	28.2	16.7	15.2
Rice straw	30.2	24.5	11.9	33.4
Bagasse	38.1	38.5	20.2	3.2
Mok and Antal [61]				
Eucalyptus saligna	45	15	25	15
Eucalyptus gummifera	38	16	37	9
Sweet sorghum	36	18	16	30
Sugar cane bagasse	36	17	17	30
Populus deltoides	39	21	26	14
Demirbaş [62, 63]				
Softwood (av.)	45.8	24.4	28.0	1.7
Hardwood (av.)	45.2	31.3	21.7	2.7
Wood bark	24.8	29.8	43.8	1.6
Wheat straw	28.8	39.1	18.6	13.5
Tobacco stalk	42.4	28.2	27.0	2.4
Tobacco leaf	36.3	34.4	12.1	17.2
Spruce wood	50.8	21.2	27.5	0.5
Beech wood	45.8	31.8	21.9	0.4
Ailanthus wood	46.7	26.6	26.2	0.5

[a] Other can consist of organic compounds such as starch or inorganic material such as salts, minerals, water and extractives

Cellulose, hemicelluloses and lignin are non-soluble

Extractives (i.e. soluble) include waxes, resin, simple sugars, starches, proteins, ...,
and volatile organic compounds (VOCs, such as terpenes)

Basic fire processes

Fuels in 'natural' fires

All live and dead elements of vegetation + Soil organic material

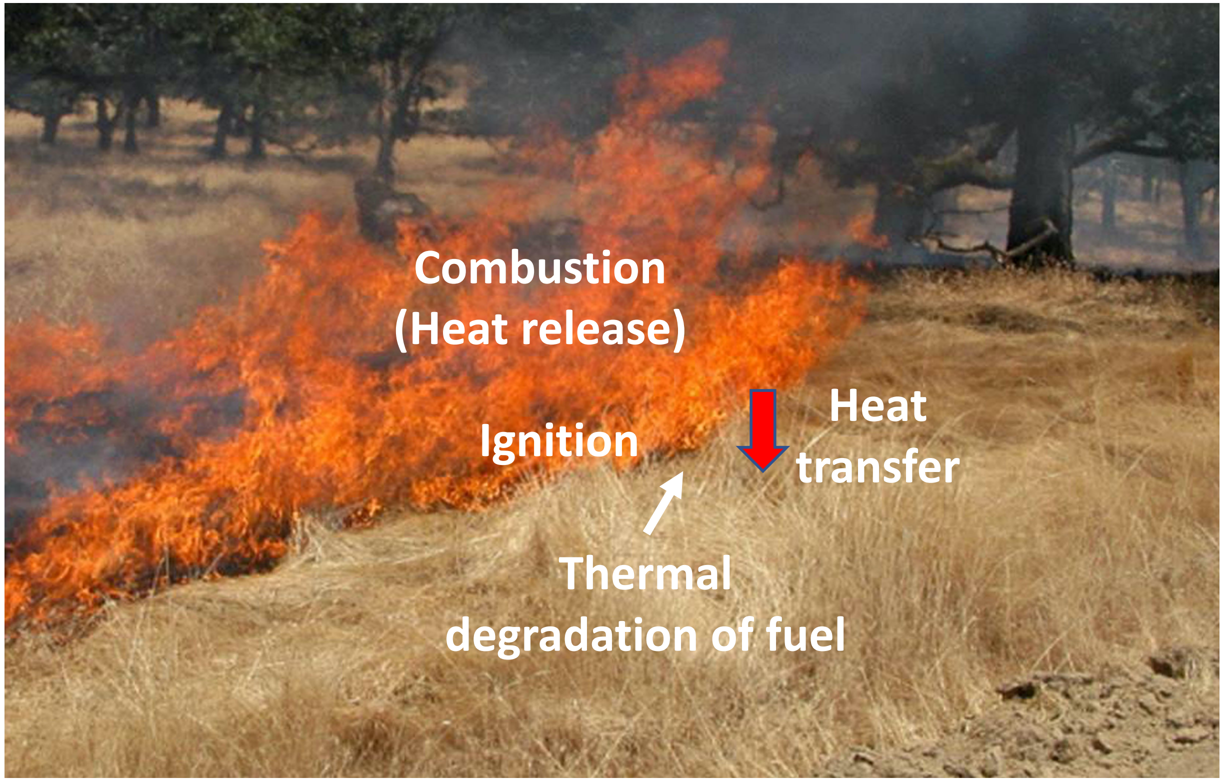
Fine elements (< 6 mm) drive fire spread

Larger fuels, even trunks, may burn (at least partially)

Basic fire processes

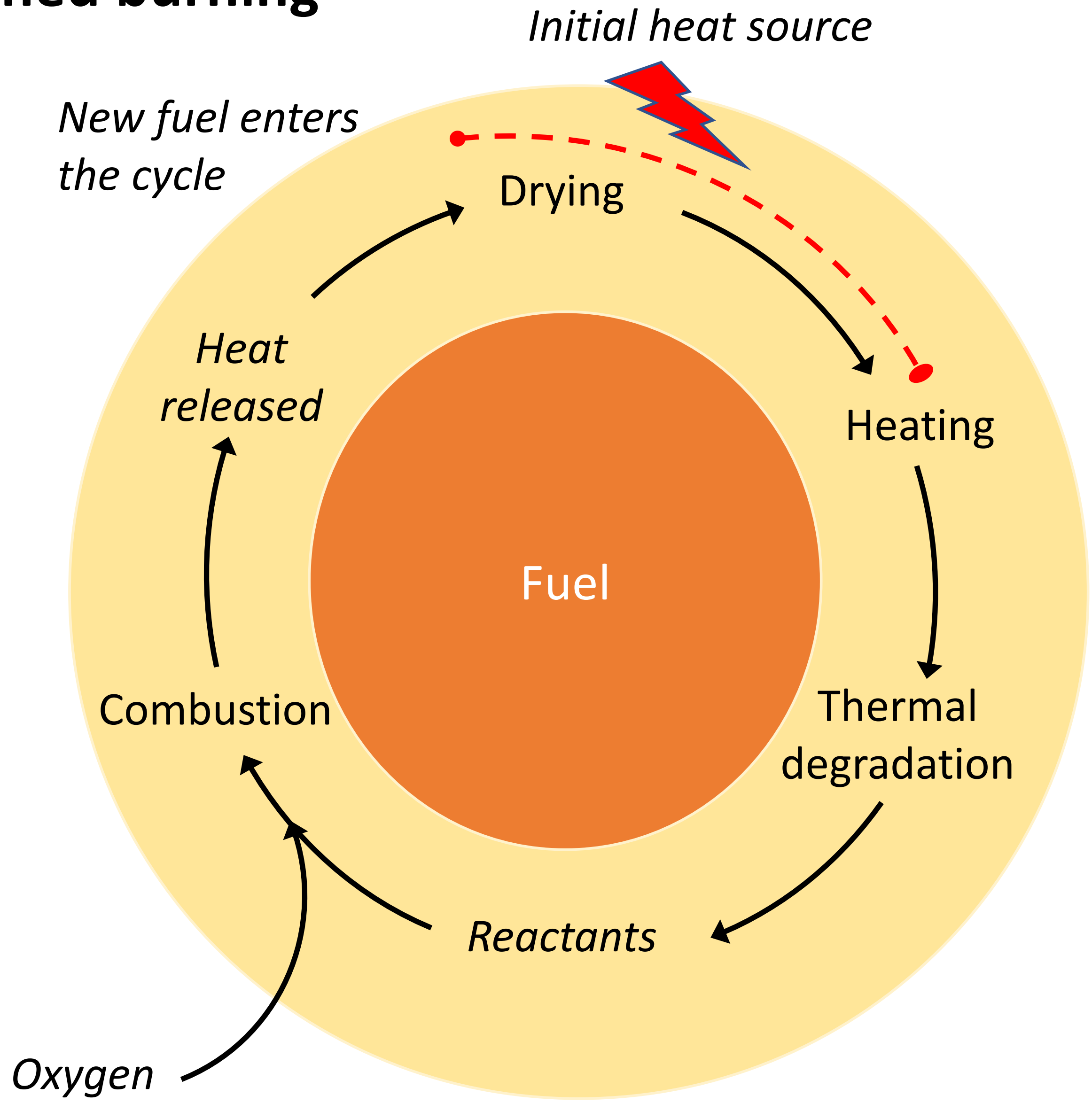
Self-sustained burning

Fundamental processes



Basic fire processes

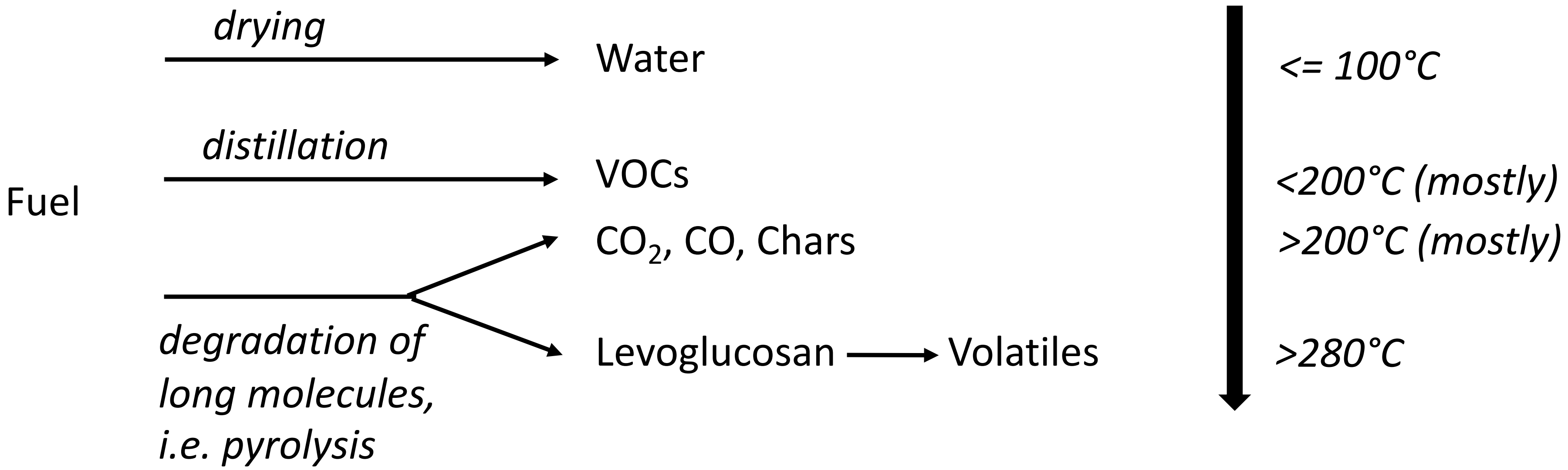
Self-sustained burning



Basic fire processes

Thermal degradation

Under heating, fuels undergo **drying, distillation and pyrolysis**



Fuel

drying → Water — *<= 100°C*

distillation → VOCs — *<200°C (mostly)*

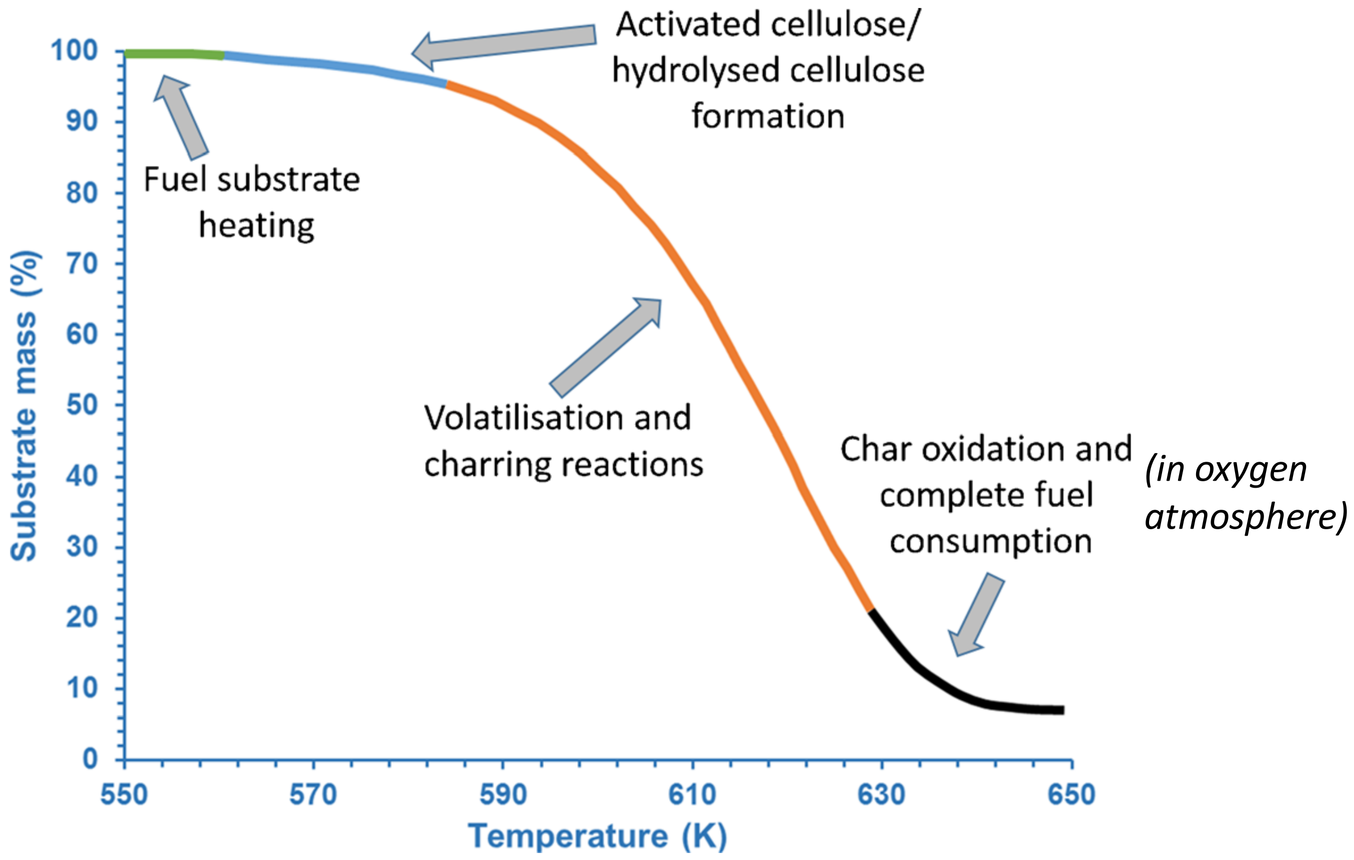
degradation of long molecules, i.e. pyrolysis → CO_2, CO, Chars — *>200°C (mostly)*

→ Levoglucosan → Volatiles — *>280°C*

Basic fire processes

Thermal degradation

Thermo-gravimetric analysis



Activated cellulose/ hydrolysed cellulose formation

Fuel substrate heating

Volatilisation and charring reactions

Char oxidation and complete fuel consumption

(in oxygen atmosphere)

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Basic fire processes

Thermal degradation (details on pyrolysis of cellulose)

Cellulose (usually 40 to 50% of material) has been studied extensively

Two main pathways : char formation and volatilisation

Char formation at low temperature (< 280°C) :

$$\text{Cellulose} \xrightarrow{\text{Heat}} CO_2 + CO + H_2O + \text{Char} + \text{Heat}$$

Char formation at high temperature :

$$\text{Cellulose} + H_20 \xrightarrow{\text{Heat}} \text{Hydrolysed cellulose} \xrightarrow{\text{Heat}} CO_2 + CO + H_2O + \text{Char} + \text{Heat}$$

Volatilisation (high temperature):

$$\text{Cellulose} \xrightarrow{\text{Heat}} \text{Levoglucosan (LG)} \xrightarrow{\text{Heat}} \text{Flammable Volatiles} + \text{Tars (~LG)}$$

Char formation is slightly exothermic
Volatilisation is slightly endothermic

Basic fire processes

Ignition

Ignition is the appearance of combustion, generally accompanied by a flame.

Needs **fuel, heat and oxygen**, but the conditions are more drastic :

1- Most biomass fuels do not burn when **O_2 concentration** is below 15% (atmospheric air normally contains 21% oxygen in volume)

2- Gaseous flammable products (released by distillation and pyrolysis of solid fuel) have lower and upper **flammability limits**, i.e. they don't ignite outside these limits

3- **Fuel heating must be enough, and fast enough,** to get a sufficient flow of flammable products to exceed the lower flammability limit when mixed with the air

In practice, ignition may happen if the woody fuel is "rapidly" heated to a critical temperature:

- 300-350°C with a pilot flame (**pilot-ignition temperature**)
- a higher threshold (600°C) with no pilot (spontaneous ignition temperature)

Pre-heating of the solid fuel elements

Prior to ignition, fuel must be pre-heated to ignition temperature T_{ig}

Both the dry material and the water of the fuel must be heated from ambient temperature T_a (300 K) to T_{ig} (~600 K)

Dry material : $Q_{dig} = Cpd\ (T_{ig} - Ta)$ = 390 J/g (g of dry material)

Liquid water must be heated up to 100°C (T_{boil} =373 K) and then vaporized:

$$Q_w = Cpw(T_{boil} - Ta) + Lv = 2560 \text{ J/g (g of water)}$$

C_{pd} is the specific heat of dry matter (1.3 J/K g)
C_{pw} is the specific heat of liquid water (4.18 J/K g)
L_v is the latent heat of vaporization of water (2257 J/g)

If the water content of fuel is ***FMC*** :

Fuel Moisture Content=mass of water /mass of dry fuel

Then the **heat of pre-ignition of the fuel** is :

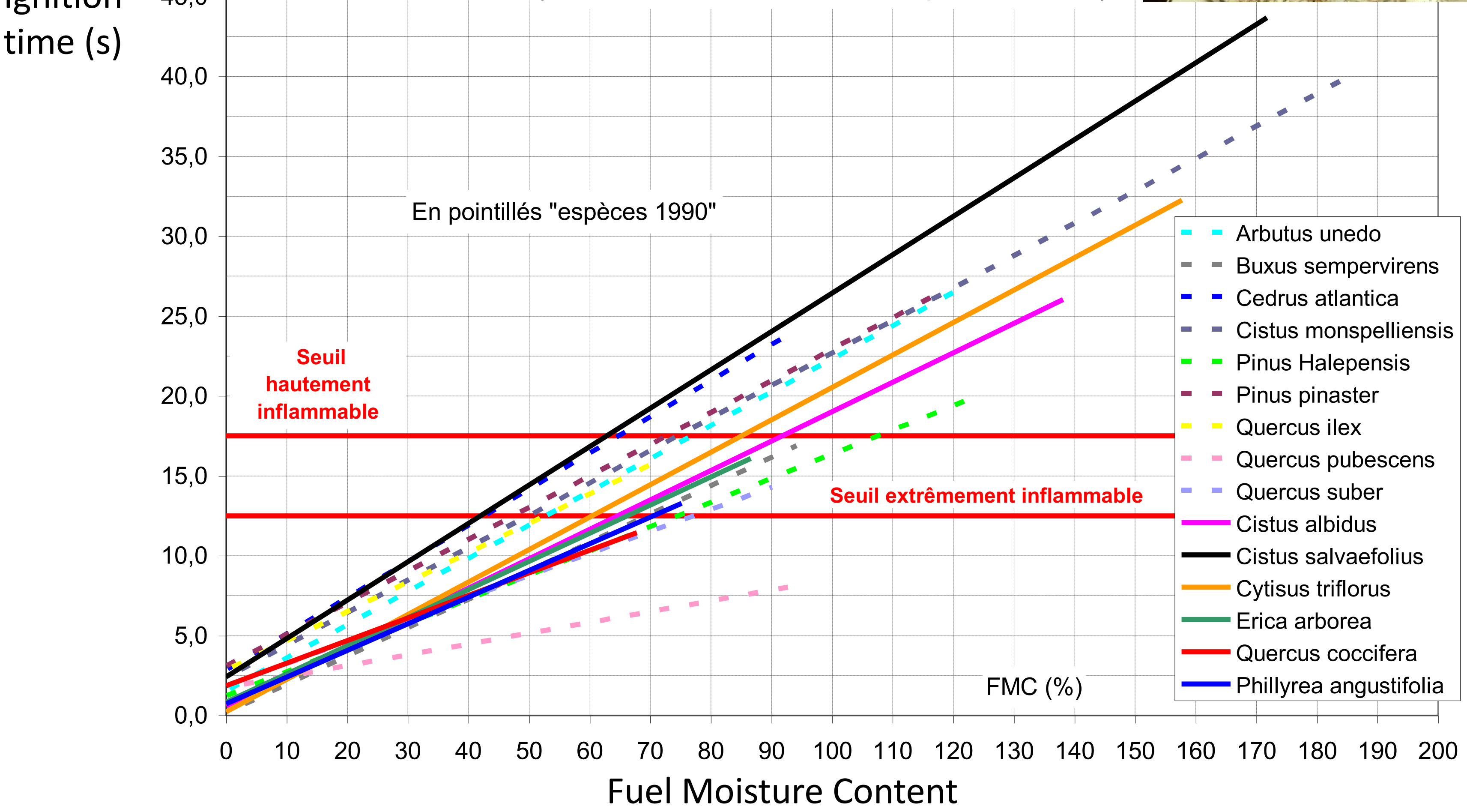
$$Q_{ig} = Qdi_g + FMC\ Qw$$

Basic fire processes

Ignition tests

Compare species samples

Assess moisture effect



Basic fire processes

Combustion

Flaming combustion :

- Products of volatilisation (gaseous fuels) react with oxygen in the air
- Fast reaction controlled by mixing of gaseous fuel and oxygen

Glowing or smouldering (low temperature) combustion :

- Oxidation of chars
- Slower reaction controlled by oxygen diffusion to char surface
- Incomplete combustion, especially smouldering

Flaming

Glowing

Smouldering

Basic fire processes

Combustion products

Complete combustion (theoretical):

- CO_2 and H_2O are the only final products
- O_2 consumption may be computed if fuel composition is known

Combustion is largely incomplete in wildland fires, which is measurable thanks to the Equivalent Oxygen to Fuel Ratio (EOFR):

$$\text{EOFR}=\frac{moles\ of\ oxygen\ actually\ consumed}{moles\ of\ oxygen\ consumed\ in\ complete\ combustion}$$

Typical emission factors of wood combustion (g per 1000 g of fuel)

95% of carbon released in CO2, CO and CH4

Type of combustion :	Complete	Flaming	Smoldering
EOFR	1.00	0.93	0.80
Water (H_2O)	559	546	523
Carbon dioxide (CO_2)	1821	1632	1283
Carbon monoxide (CO)	0	90	257
Methane (CH_4)	0	3	9
Other hydrocarbons	0	2	6
Particulate matter (PM)	0	9	25

In *Fire Science*, Springer, 2021

Basic fire processes

Combustion products

Significance : impacts to the atmosphere, air pollution

CO_2 is the most abundant species by far, but relatively inert

Other, less abundant, products raise specific concerns :

- CO: toxicity
- CH_4: high global warming potential
- NMOCs*, Nitrogen molecules, Sufur dioxid (SO_2) : toxicity, impacts on atmospheric chemistry
- PM : toxicity, impacts on radiative forcing

*NMOCs : Non-methane organic compounds, a number of molecules each representing very low contribution

Basic fire processes

Combustion products

Modified Combustion Efficiency (MCE) and emission factors (g/kg) for different fire types

Data from airborne or tower-based measurements above fires (Urbanski 2014)

	Prescribed fires			Wildfires	
	Northwest conifer forest	Western Shrubland	Grassland	Northwest conifer forest	Boreal forest
MCE	0.906	0.935	0.947	0.883	0.917
Carbon dioxide (CO_2)	1598	1674	1705	1600	1641
Carbon monoxide (CO)	105	74	61	135	95
Methane (CH_4)	4.86	3.69	1.95	7.32	3.38
NMOCs	47.3	24.6	23.9	59.6	38.3
PM < 2.5 μm	17.6	7.06	8.51	23.2	21.5
Nitrogen molecules	3.75	3.93	3.68	3.66	2.2

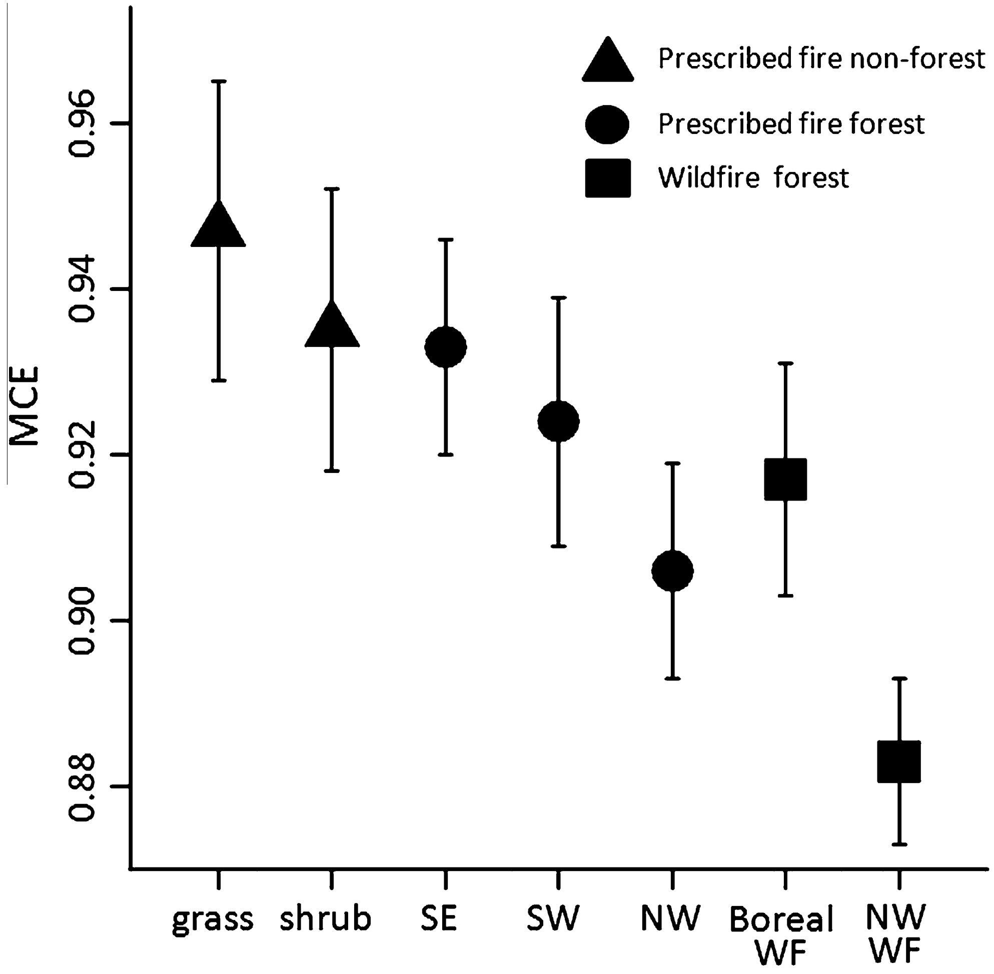
MCE = $CO_2/(CO_2+CO)$, an indicator of smoldering vs flaming activity

Orders of magnitude are similar among fire types, but significant differences appear (uncertainties reported in Urbanski 2014) :

e.g. more efficient combustion in grasslands and shrublands (see next Figure)

Basic fire processes

Combustion products



MCE = CO2/(CO2+CO) in products, an indicator of smoldering vs flaming activity

Combustion products

Modified Combustion Efficiency (MCE) and emission factors (g/kg) for smoldering fuels

Data from ground-based measurements (Urbanski 2014)

	Stumps and Logs	**Temperate forest duff/soil**	**Boreal forest duff/soil**
MCE	0.796	0.752	0.790
Carbon dioxide (CO_2)	1408	1305	1436
Carbon monoxide (CO)	229	271	244
Methane (CH_4)	13.9	7.47	8.42
NMOCs	84.9	247	183
PM < 2.5 μm	33	50	20.6
Nitrogen molecules	0.48	3.34	3.34

As expected, pollutants are much more represented over these smoldering fuels than above flaming fires with a significant convection column transporting smokes to the upper atmosphere.

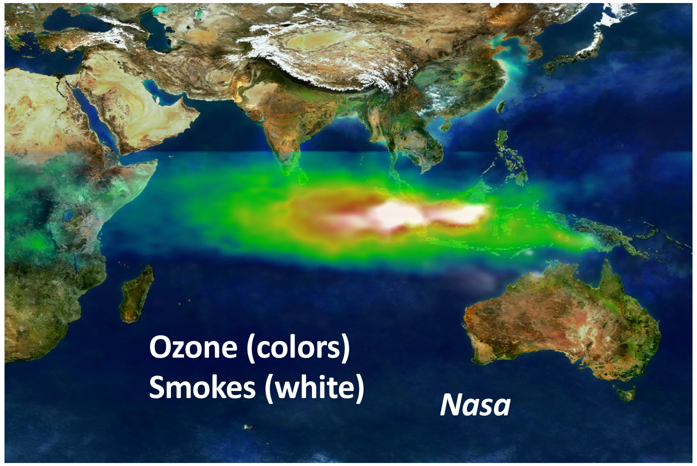
Basic fire processes

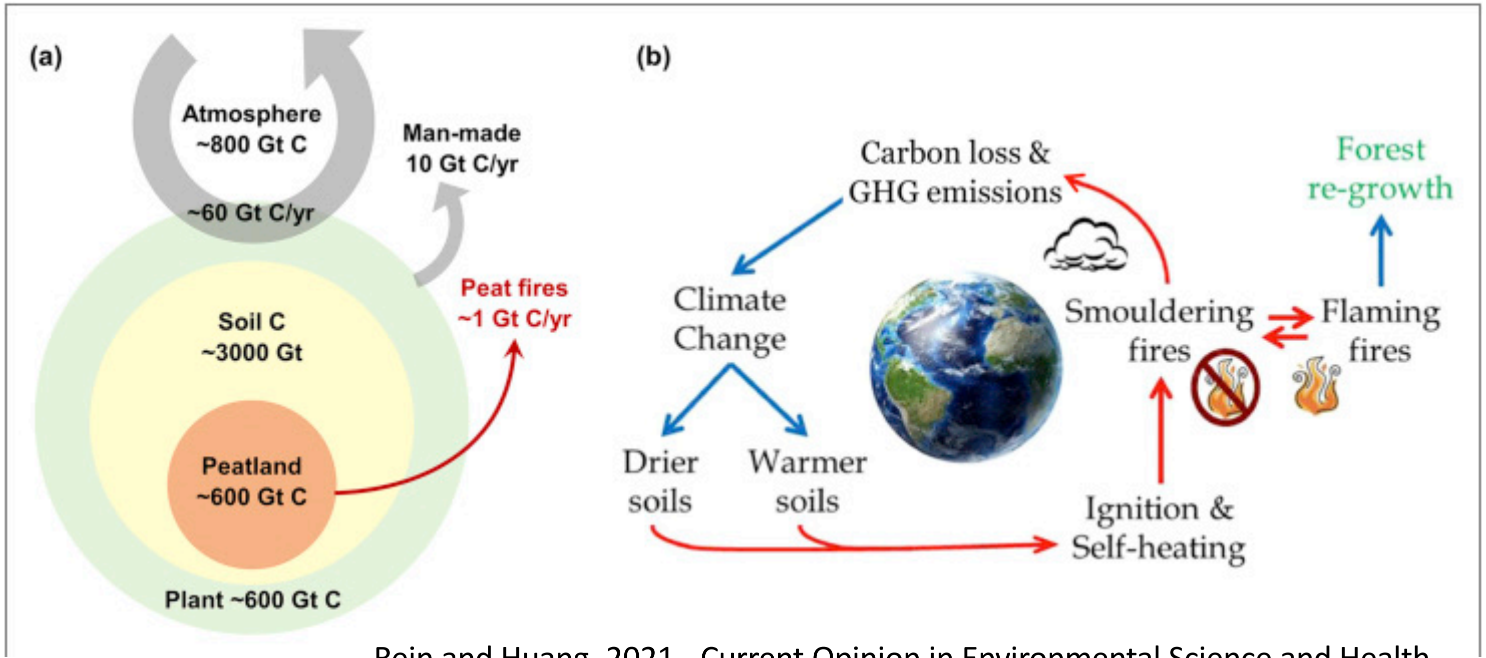
JL Dupuy - INRAe URFM

Combustion products

Peat fires release huge amount of carbon and pollutants, with significant impacts to the carbon cycle (feedback) and the human health (haze)

Peat fires, 1997, Indonesia





Rein and Huang, 2021 - Current Opinion in Environmental Science and Health

Basic fire processes

Combustion heat release

The heat released by combustion may be computed when reactants and products are known. By convention, energy release (exothermicity) is negative

Net energy release (**Δ**H) =

Energy to form the bonds of products + Energy to break the bonds of reactants

<0 → = – "bond energy"

> 0 → = "bond energy"

Example : combustion of methane

Reactants				*Products*		
CH_4	+	$2\ O_2$	$\longrightarrow$	CO_2	+	$2\ H_2O$
4 C-H bonds		*2 O=O double bonds*		*2 C=O double bonds*		*4 O-H bonds*

$$\Delta H = -\,2 \times \underset{\substack{\uparrow \\ C=O}}{804} - 4 \times \underset{\substack{\uparrow \\ O\text{-}H}}{460} + 4 \times \underset{\substack{\uparrow \\ C\text{-}H}}{413} + 2 \times \underset{\substack{\uparrow \\ O=O}}{497} = -\,802 \text{ kJ/mol} = -\,50.1 \text{ kJ/g}$$

Another way to compute the heat of combustion is to use the enthalpies of formation of products and reactants.

Basic fire processes

Combustion heat release

The *heat of combustion* of woody fuels can be computed considering the following reaction, where $C_6H_9O_4$ represents an average composition of the dry fuel :

$$C_6H_9O_4 \quad + \quad 6.25\ O_2 \quad \longrightarrow \quad 6\ CO_2 \quad + \quad 4.5\ H_2O$$

In mass:

145 g *woody fuel* + 200 g *oxygen* ⟶ 260 g *carbon dioxid* + 81 g *water*

High heat of combustion : ΔHH_{fuel} = 20.1 kJ/g, when the final state of *water* is liquid

Low heat of combustion : ΔH_{fuel} = 20.1 − 1.4 = 18.7 kJ/g, when the final state of *water* is vapor

Incomplete combustion releases less heat.

But it is better to measure the heat of combustion, as the exact composition of the material is usually unknown

Basic fire processes

Combustion heat release

The *heat of combustion* of a burning material depends on the material (composition) and on the fire conditions (temperature, oxygen supply, water content).
Indeed, both influence the proportion of pyrolysis products, which have different heats of combustion

Pyrolysis product	High heat of combustion ΔHH (kJ/g)
Chars (C)	32
CO	10
CH4	50
Levoglucosan	17

Combustion heat release

The *heat of combustion* of woody fuels varies with their composition and the proportion of char produced (data from Rothermel 1976)

Substance	Proportion of char produced	Higher heat of combustion ΔHH (kJ/g)
Cellulose and hemicellulose (50-75%)	0.092*	16.1
Lignin (15-35%)	0.624	24.5
Extractives (0.2-15%)	0.285	32.3

*the amount of char produced increases when silica-free minerals are present.
Extractives include volatile organic compounds, which are highly flammable substances

Minerals tend to inhibit flaming combustion, promoting char formation.

Combustion heat release

Combustion characteristics of different fuel elements (from Susott 1982)

Fuel type	Ash content (%)	Fraction of char (%)	Higher heat of combustion (kJ/g)	Energy for volatiles (kJ/g)	Energy for char (KJ/g)
Grasses	6.5-9.5	22-25	19.4-20.2	12.0-12.2	7.1-8.2
Foliage	1.5-7.1	25-34	20.6-23.3	10.9-15.8	7.5-10.6
(Small) Stems	2.2-6.1	22-28	20.0-22.4	10.9-15.2	7.2-9.1
Wood	0.2-0.6	15-24	19.6-21.0	12.6-14.6	5.0-7.6
Rotten wood	0.2-0.2	21-41	20.3-23.1	10.4-13.6	6.8-12.6
Bark	0.5-17.7	28-47	21.5-24.0	7.7-12.8	8.9-14.3
Duff	31.2-34.1	35-39	20.3-23.3	8.9-11.1	11.4-12.2

Note that the heat of combustion is not so variable

Combustion heat release

Combustion characteristics of Mediterranean fuels (from Madrigal et al 2011)

Measurements :
GHC (MJ/kg) : Gross heat of combustion (high heat of combustion measured with bomb calorimeter)
PHRR (kW/m^2) : peak heat release rate
THR (MJ/m^2) : total heat release
TTI (s) : time to ignition of the sample
FD (s) : Flaming duration
MLR (g/s) : peak mass loss rate

Note :
The initial sample load is 10g/100 cm^2, i.e. 1kg/m^2. Thus, THR can also be expressed as MJ/kg and compared with GHC.

Figure 1. **a General view of the MLC device. b Detail of the thermopile. c Detail of methane burner used to calibrate thermopiles. d Porous holder with *Pinus pinaster* dead litter, immediately before a test.**

Basic fire processes

Combustion heat release

GHC (MJ/g) : Gross heat of combustion
(high heat of combustion measured with bomb calorimeter)
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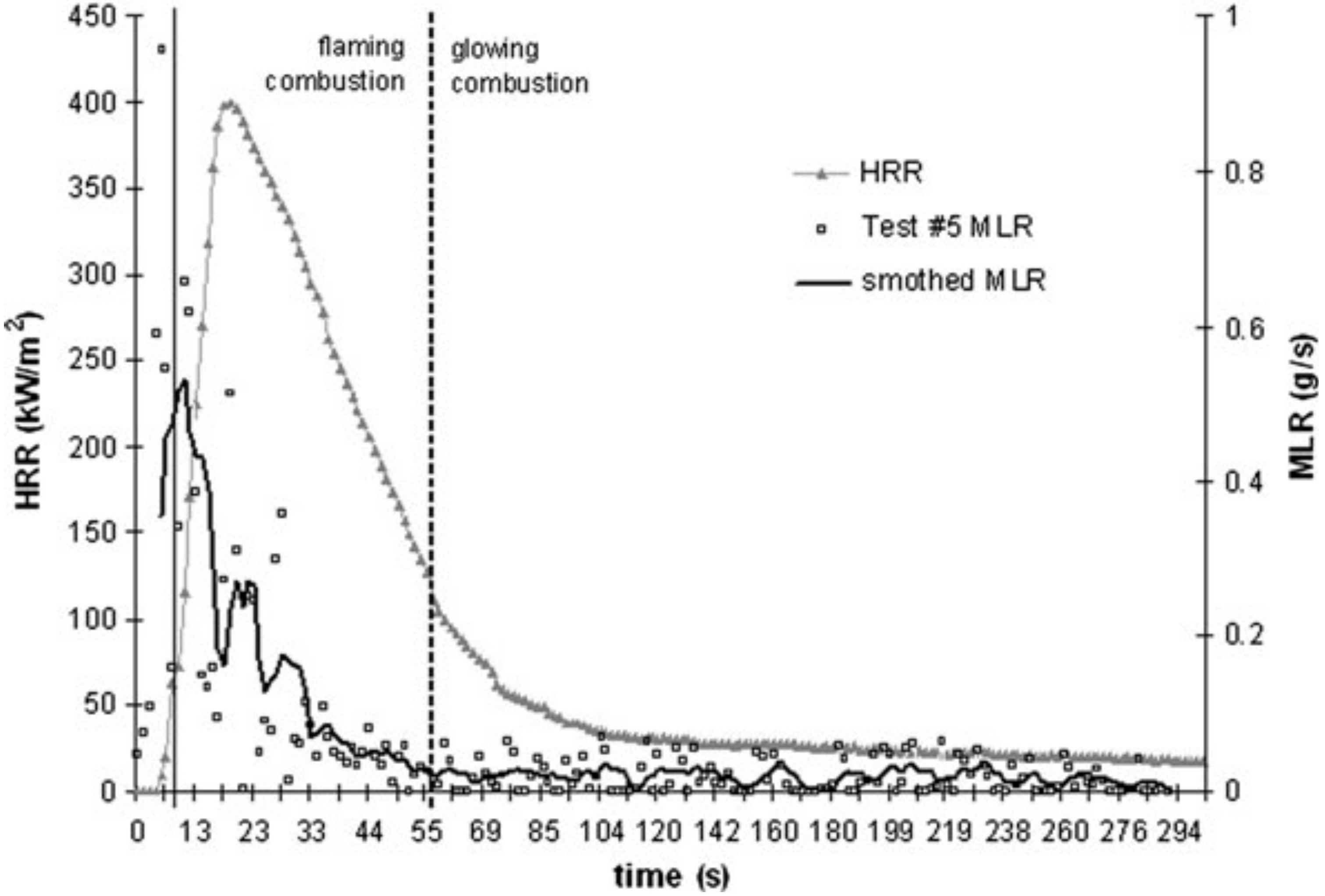
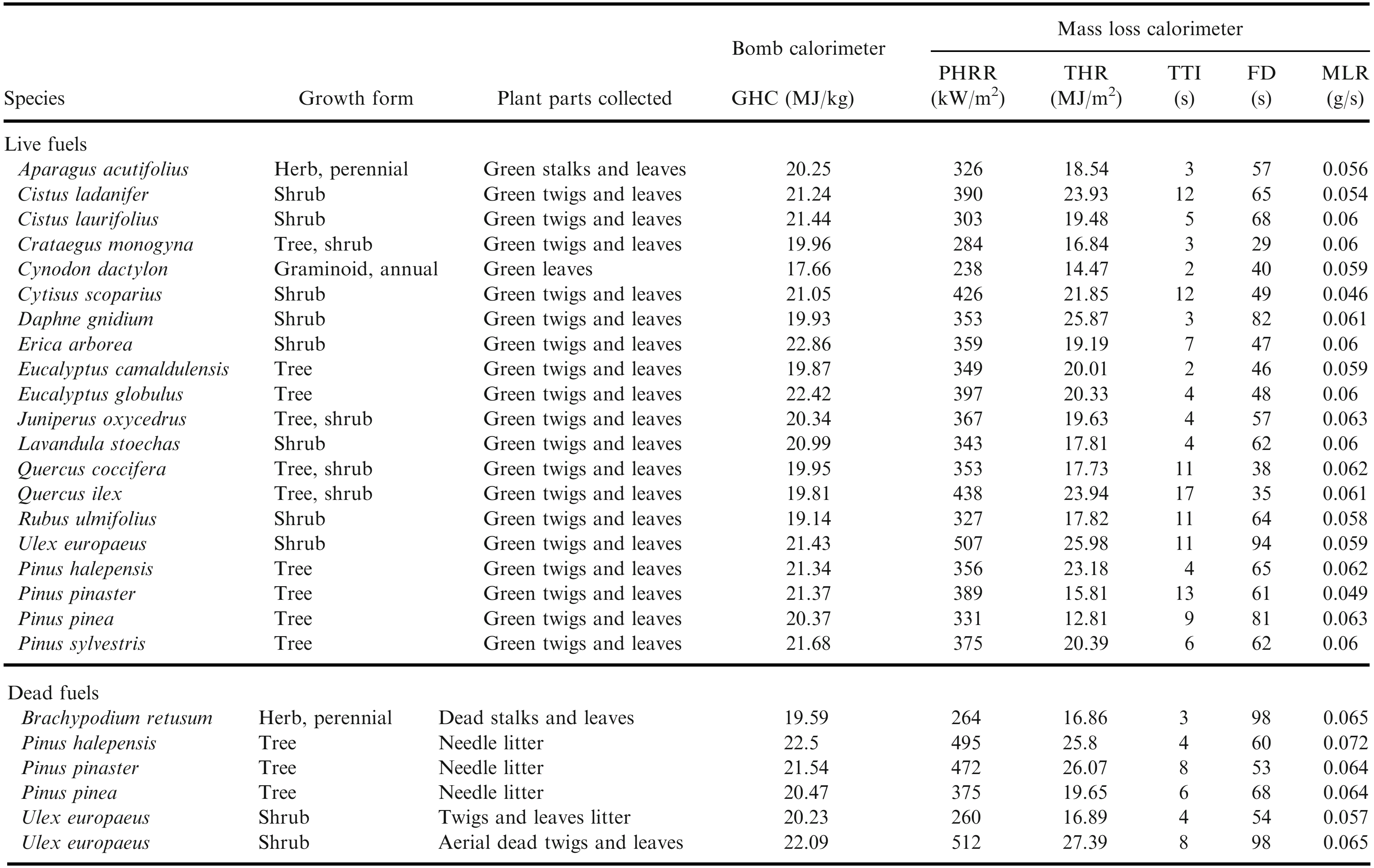


Combustion heat release

Combustion characteristics of Mediterranean fuels (from Madrigal et al 2011)



			Bomb calorimeter	Mass loss calorimeter				
Species	Growth form	Plant parts collected	GHC (MJ/kg)	PHRR (kW/m^2)	THR (MJ/m^2)	TTI (s)	FD (s)	MLR (g/s)
Live fuels								
Aparagus acutifolius	Herb, perennial	Green stalks and leaves	20.25	326	18.54	3	57	0.056
Cistus ladanifer	Shrub	Green twigs and leaves	21.24	390	23.93	12	65	0.054
Cistus laurifolius	Shrub	Green twigs and leaves	21.44	303	19.48	5	68	0.06
Crataegus monogyna	Tree, shrub	Green twigs and leaves	19.96	284	16.84	3	29	0.06
Cynodon dactylon	Graminoid, annual	Green leaves	17.66	238	14.47	2	40	0.059
Cytisus scoparius	Shrub	Green twigs and leaves	21.05	426	21.85	12	49	0.046
Daphne gnidium	Shrub	Green twigs and leaves	19.93	353	25.87	3	82	0.061
Erica arborea	Shrub	Green twigs and leaves	22.86	359	19.19	7	47	0.06
Eucalyptus camaldulensis	Tree	Green twigs and leaves	19.87	349	20.01	2	46	0.059
Eucalyptus globulus	Tree	Green twigs and leaves	22.42	397	20.33	4	48	0.06
Juniperus oxycedrus	Tree, shrub	Green twigs and leaves	20.34	367	19.63	4	57	0.063
Lavandula stoechas	Shrub	Green twigs and leaves	20.99	343	17.81	4	62	0.06
Quercus coccifera	Tree, shrub	Green twigs and leaves	19.95	353	17.73	11	38	0.062
Quercus ilex	Tree, shrub	Green twigs and leaves	19.81	438	23.94	17	35	0.061
Rubus ulmifolius	Shrub	Green twigs and leaves	19.14	327	17.82	11	64	0.058
Ulex europaeus	Shrub	Green twigs and leaves	21.43	507	25.98	11	94	0.059
Pinus halepensis	Tree	Green twigs and leaves	21.34	356	23.18	4	65	0.062
Pinus pinaster	Tree	Green twigs and leaves	21.37	389	15.81	13	61	0.049
Pinus pinea	Tree	Green twigs and leaves	20.37	331	12.81	9	81	0.063
Pinus sylvestris	Tree	Green twigs and leaves	21.68	375	20.39	6	62	0.06
Dead fuels								
Brachypodium retusum	Herb, perennial	Dead stalks and leaves	19.59	264	16.86	3	98	0.065
Pinus halepensis	Tree	Needle litter	22.5	495	25.8	4	60	0.072
Pinus pinaster	Tree	Needle litter	21.54	472	26.07	8	53	0.064
Pinus pinea	Tree	Needle litter	20.47	375	19.65	6	68	0.064
Ulex europaeus	Shrub	Twigs and leaves litter	20.23	260	16.89	4	54	0.057
Ulex europaeus	Shrub	Aerial dead twigs and leaves	22.09	512	27.39	8	98	0.065

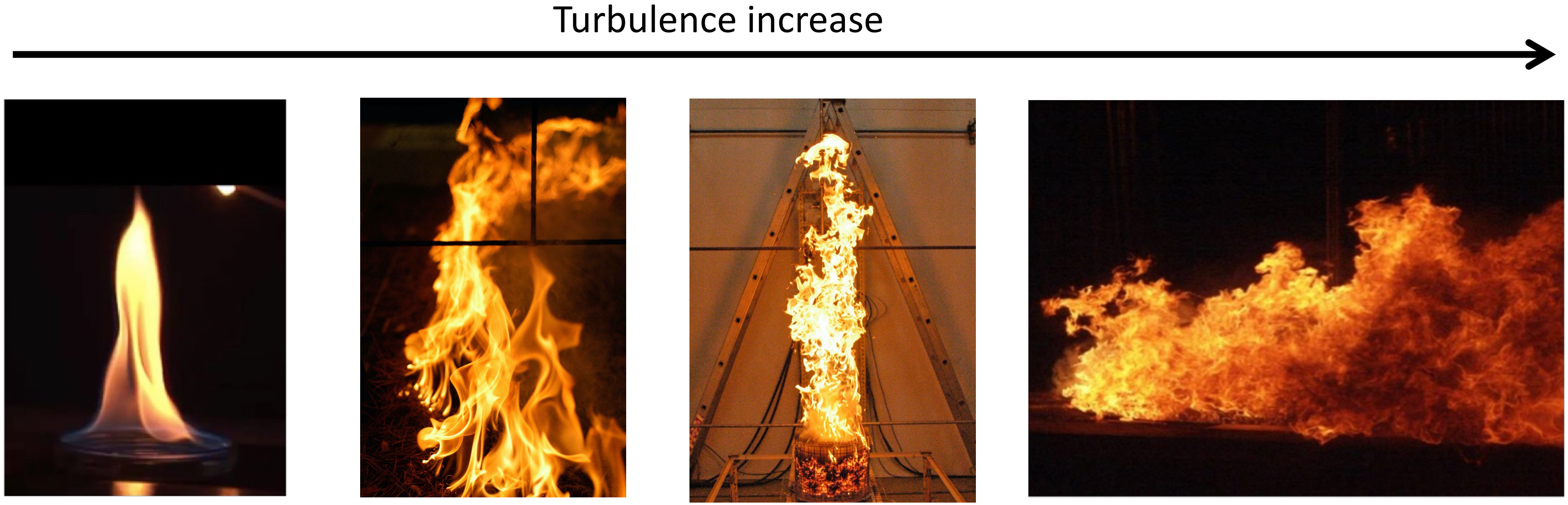
Basic fire processes

Flame - mixing

The locations where the combustion of volatiles occurs (reaction zone)

It is visible in fires thanks to the formation of soot particles radiating in the visible wavelengths (yellow color) at high temperatures

Flames in fires are diffusion flames, i.e. mixing of oxygen and flammable gas realized thanks to molecular and turbulent diffusion



Laminar

Highly turbulent

Basic fire processes

Flame - mixing

Molecular diffusion : driven by concentration gradients of oxygen and gaseous fuel

Turbulent diffusion : driven by eddy chaotic motion
-> much more efficient for mixing than molecular diffusion

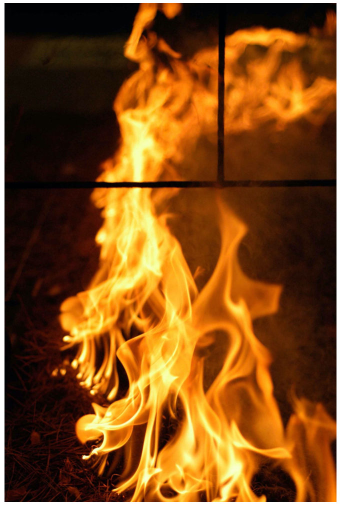
Mixing (which ensures oxygen supply) is fundamental in wildland or natural fires, as it controls the rate of combustion (the speed at which fuel or O_2 is consumed)

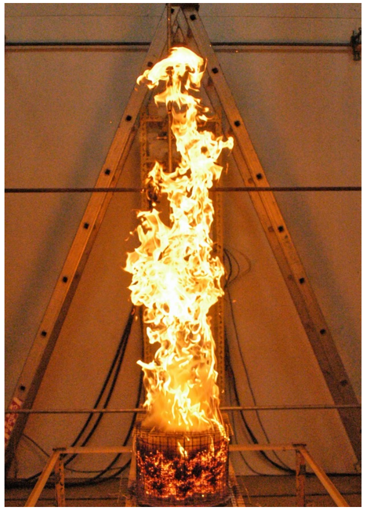
Only
molecular diffusion

Turbulence increase

Dominated by
turbulent diffusion

Laminar





Highly turbulent

Basic fire processes

Flame - temperature

Theoretical (adiabatic) flame temperatures are above 2000°C

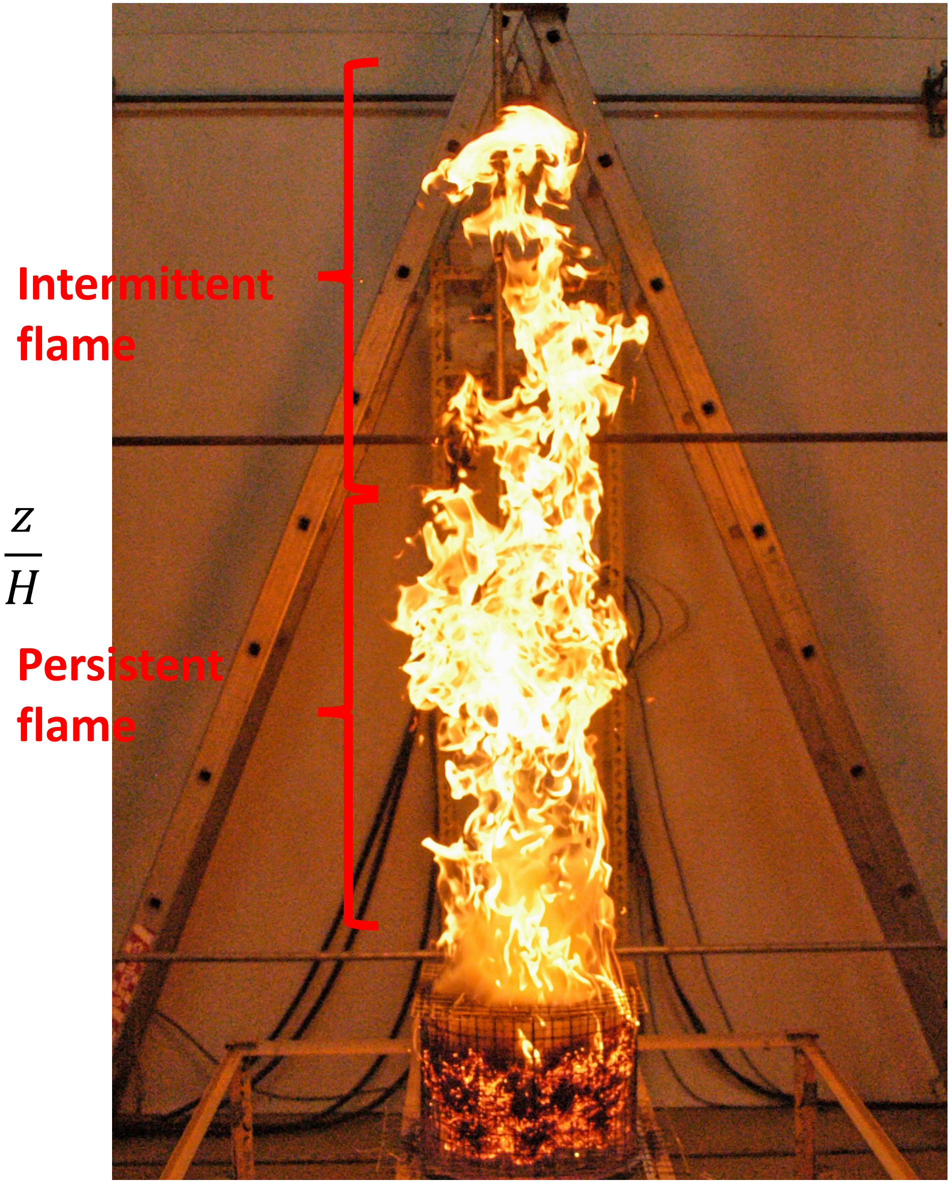
But actual temperature are much lower due to heat losses :

typically 800- 1000°C in average in the core of the flames

$$Z = \frac{z}{H}$$

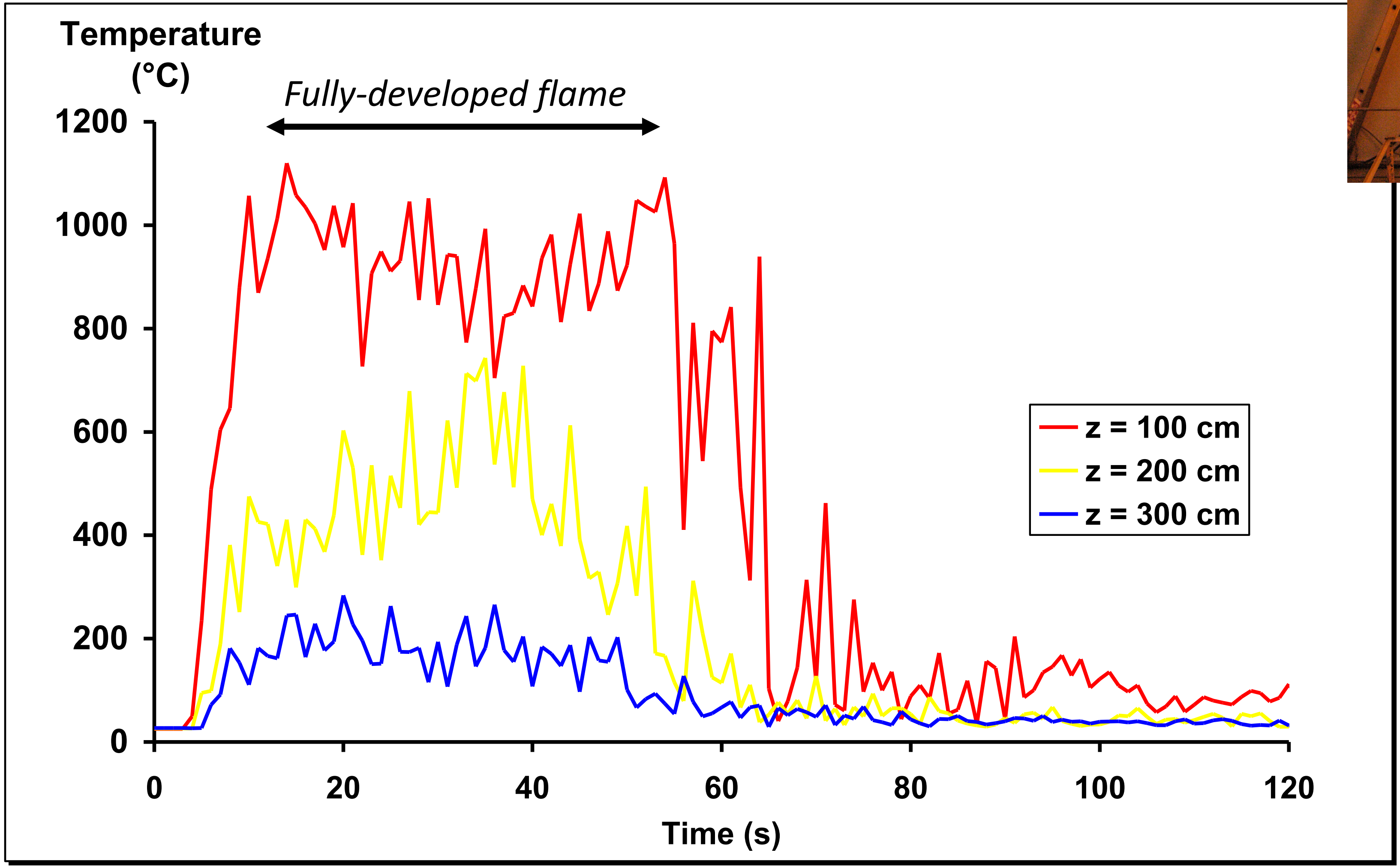
Local, instantaneous values fluctuate a lot

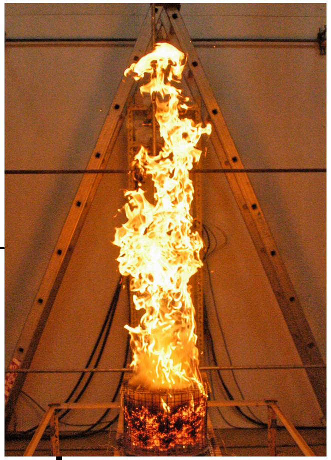
Average temperature decreases above the persistent flame, and radially

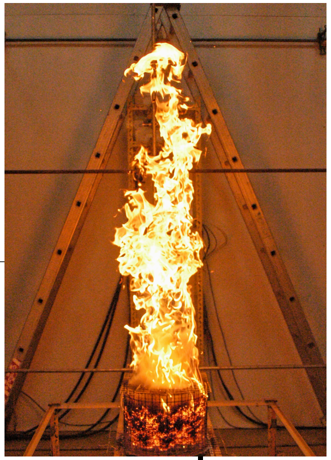


Basic fire processes

Flame - temperature

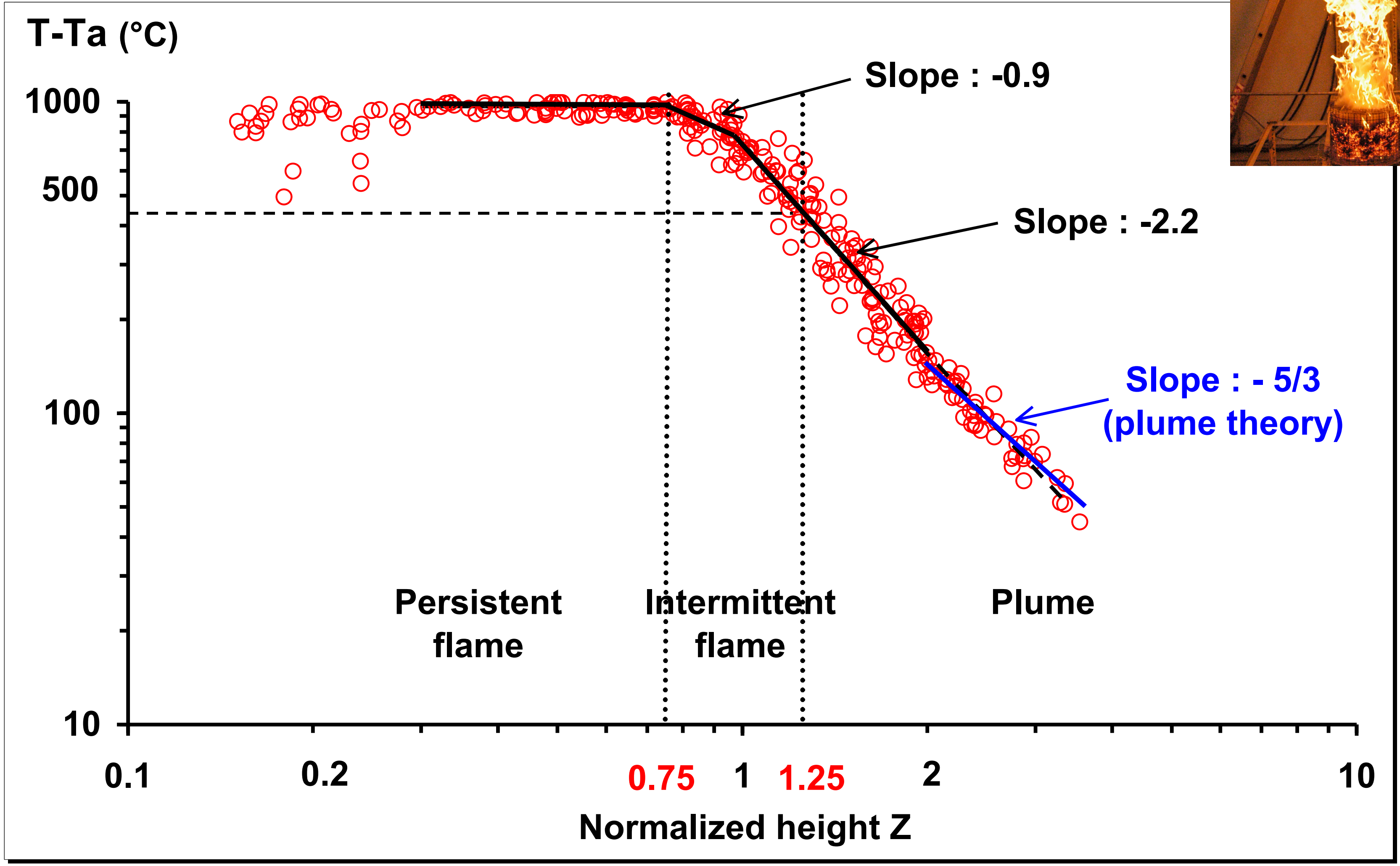






Flame - temperature

Vertical profile of time-averaged temperature

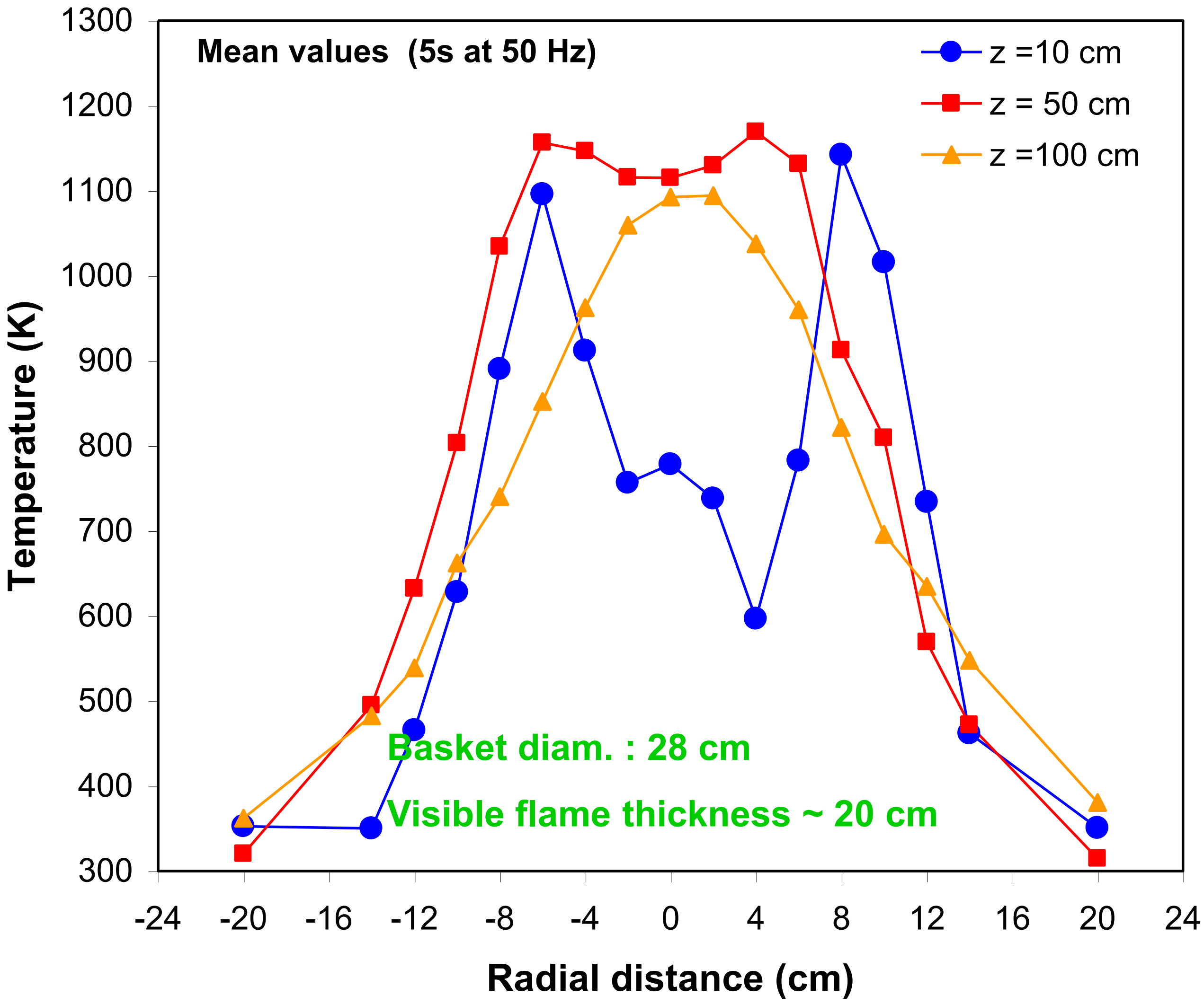


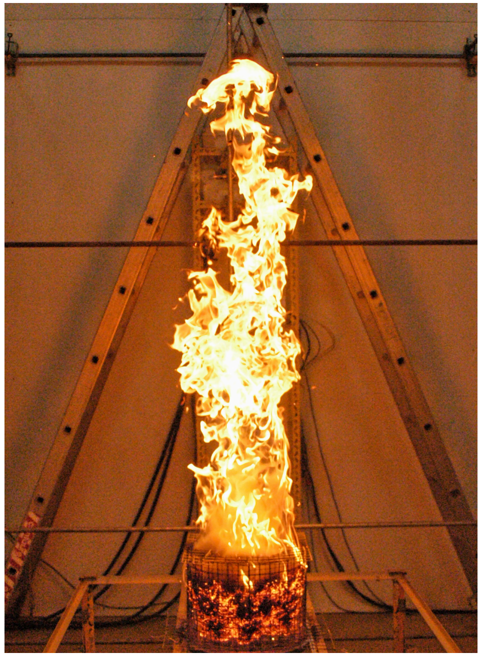
$Z = \frac{z}{H}$ *H* is mean flame height

Basic fire processes

Flame - temperature

Radial profile of time averaged temperature



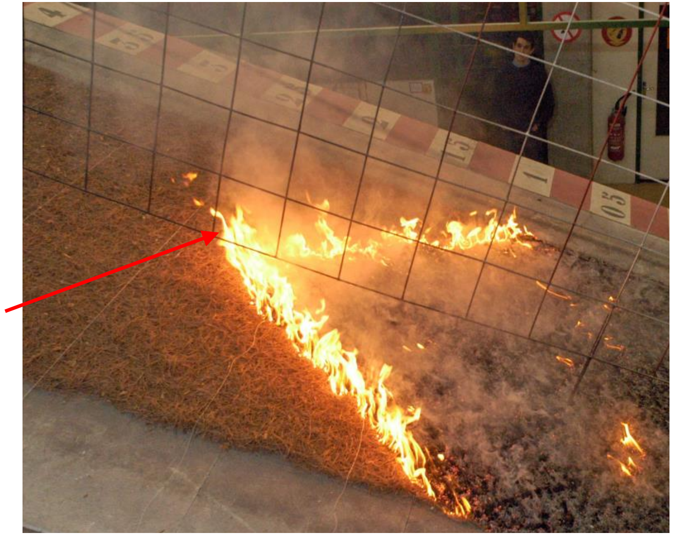


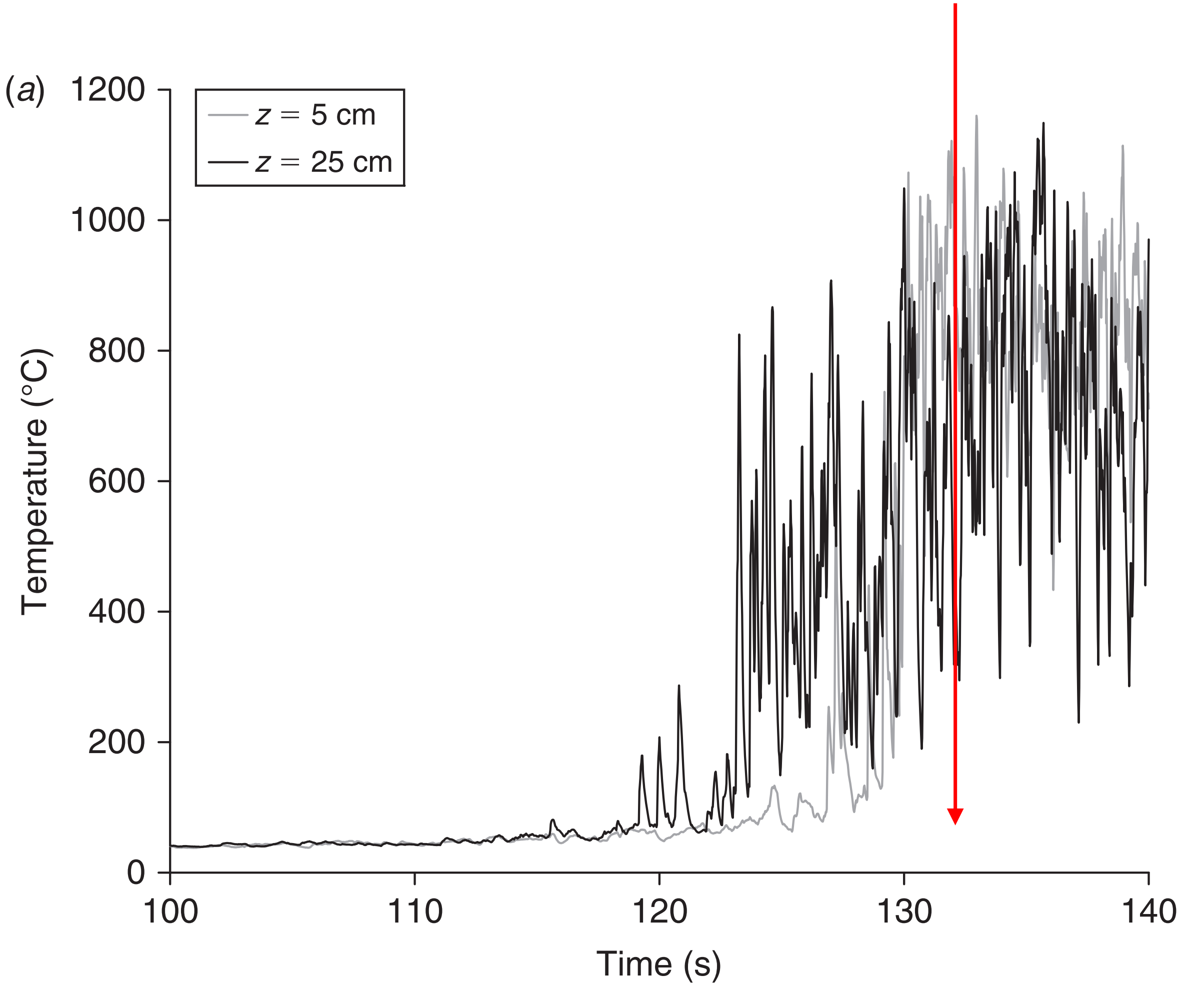
Basic fire processes

Flame - temperature

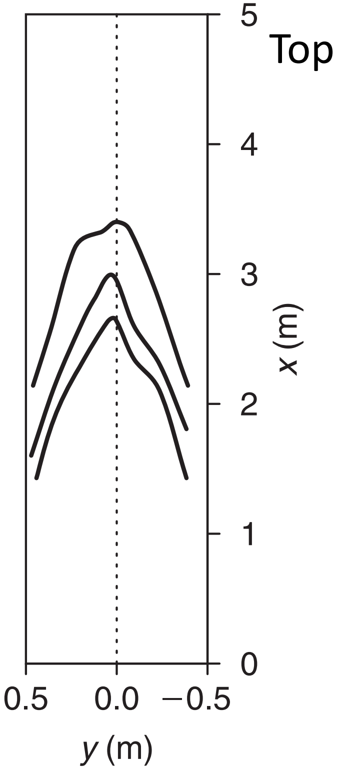
Temperature recordings in a spreading fire

Head fire (flame) reaches the thermocouple





30°, 1 m (test #44)



Top view of fire lines

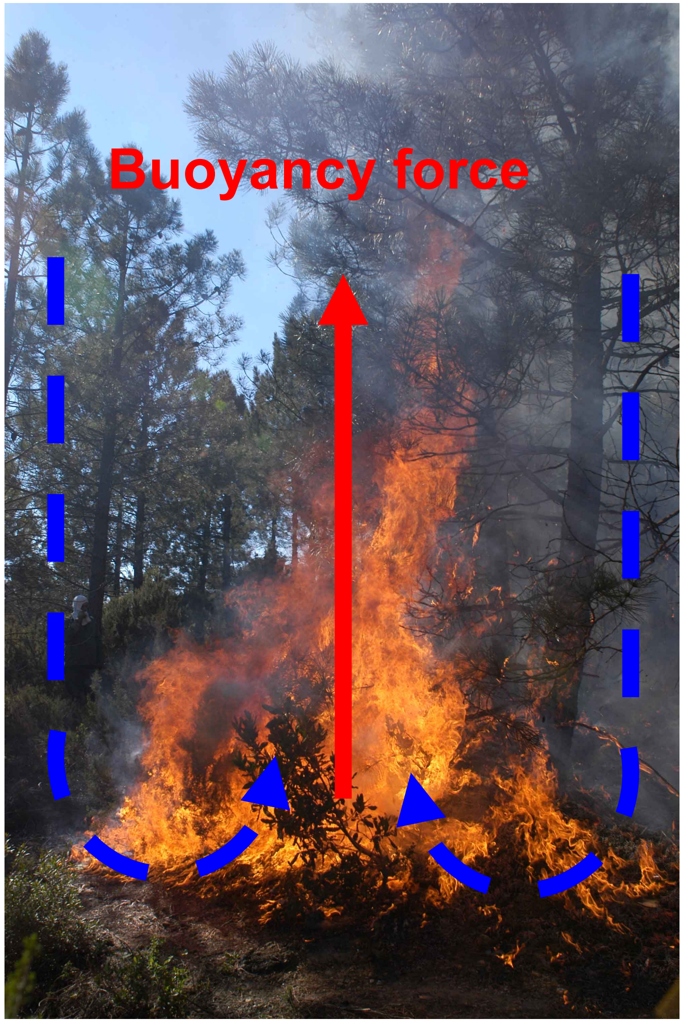
Basic fire processes

Buoyancy and fire-induced flow

Hot air is much less dense than fresh air (ambient *a*), generating a buoyancy force :

$F = g\ (\rho_a - \rho)$, g is gravity and ρ is density
(F expressed as forced per unit volume of air)

Rising hot air and gas must be replaced by fresh air



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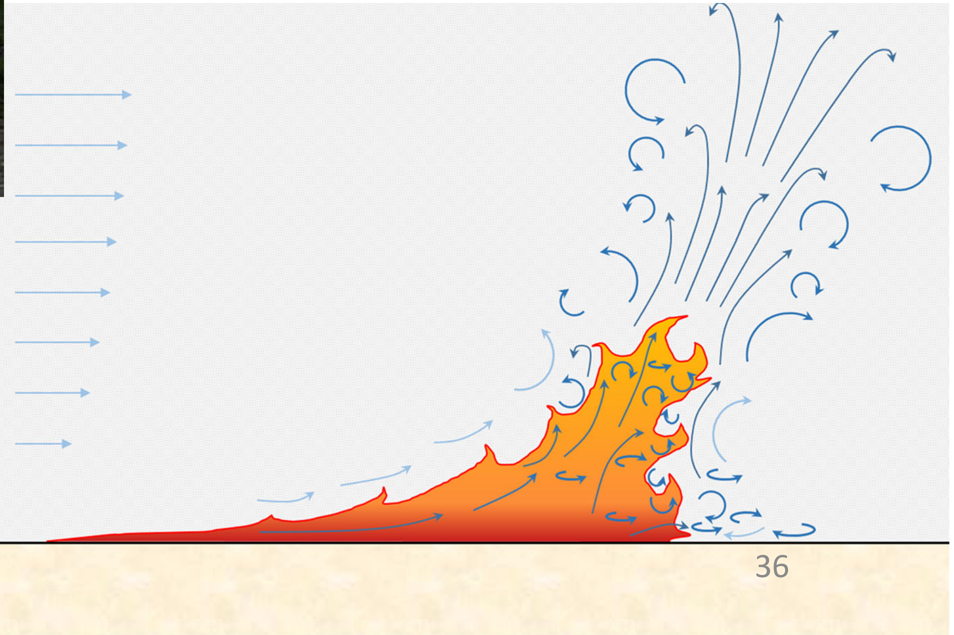
Fire-induced downdraft

Basic fire processes

Buoyancy and wind interactions



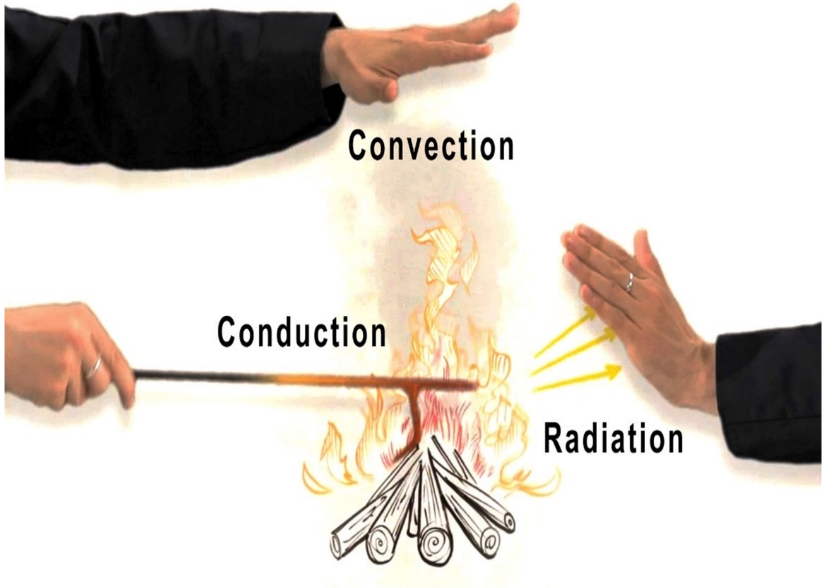
Basic fire processes

Heat transfer

The process by which heat (thermal energy) is exchanged between two objects or two parcels of matter of different temperatures

3 modes :

- conduction
- thermal radiation
- convection

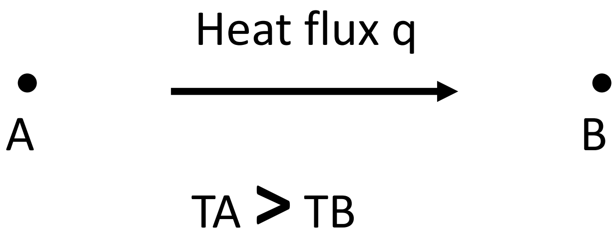


Basic fire processes

Conduction

Conduction is the transfer of heat from one molecule of matter to another by direct contact

In fires : relatively slow transfer, operating within solid fuels and soil layers



Heat flux q

A

B

TA > TB

Fourier law

$$q = -\lambda \frac{\partial T}{\partial x} \quad (\mathrm{kW/m^2})$$

Thermal conductivity λ :

- copper : 400 W/m K
- dry wood : 0.1-0.2 W / m K
- dry air : 0.02-0.03 W / m K

Basic fire processes

Thermal radiation

Thermal radiation is the transfer of heat energy by electromagnetic waves from a heat source to an absorbing material

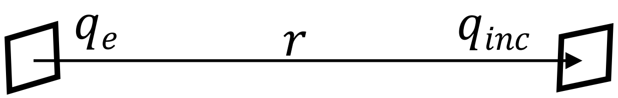
Semi-transparent bodies (the air) allow the waves to pass, so the transfer

Any body emits radiant energy due to its temperature T (Stefan-Boltzman law):

$$E_e = \varepsilon\, \sigma\, T^4$$ (Emissive power of grey bodies, W/m^2)

ε is body emissivity (=1 for a black body, 0 for a non emitting surface)
σ the Stefan-Boltzman constant

The heat flux decreases with the square of the distance to the source



(two parallel unit areas)

$$q_{inc} = \frac{q_e}{r^2} = \frac{E_e}{\pi\, r^2}$$ (W/m^2)

Any non-transparent body absorbs incident radiant energy according to

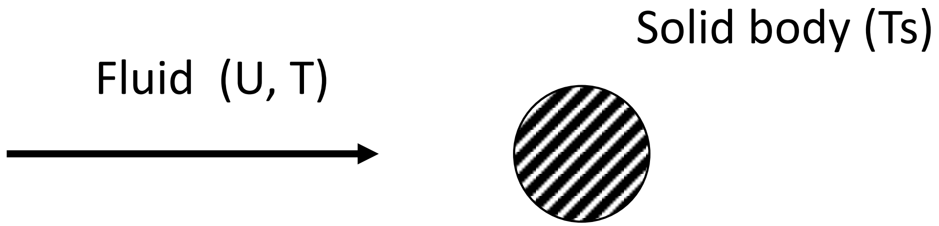
$$q_a = \alpha\, qinc$$ (absorptivity α = ε for diffuse - grey bodies)

Basic fire processes

Convection (convective heat transfer)

Convection is the transfer of heat resulting from the motion of a fluid.
In fires : the fluid is air or hot gases (flame, smoke).

The fluid transports heat and exchanges it (by conduction) with the solid body, mnamely, in fires, the fuel elements


Solid body (Ts)

Fluid (U, T)

Newton's law for convection

$$q = h\ (T - Ts)$$

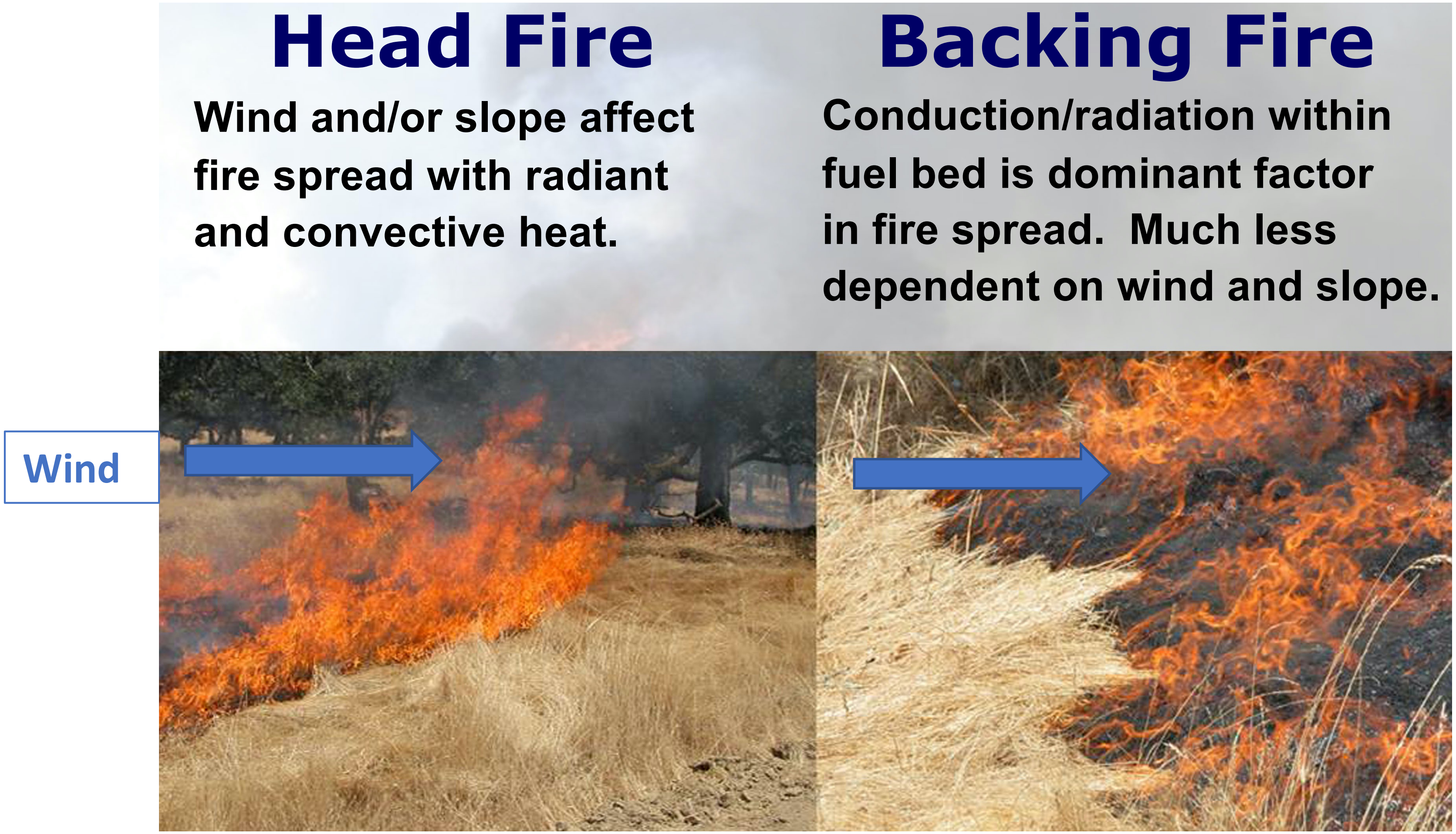
The convective heat transfer coefficient h depends on U (fluid velocity), T (fluid temperature), and other fluid properties, as well as on body geometry

This is a very efficient way of heating, especially when flame is in contact with fuel.

Note : the term *convection* is also widely used to designate the natural movement of fluid due to fluid density differences, for example above a fire ...

Basic fire processes

Dominant heat transfer in horizontal fire spread



Head Fire

Wind and/or slope affect fire spread with radiant and convective heat.

Backing Fire

Conduction/radiation within fuel bed is dominant factor in fire spread. Much less dependent on wind and slope.

Basic fire processes

Dominant heat transfer in vertical fire spread

Convection above the fire heats and may ignite tree foliage

Basic fire processes

Dominant heat transfer in glowing embers

Radiation, and conduction within charring material