Ignition of Solid Fuels and the Modelling of Forest Fires

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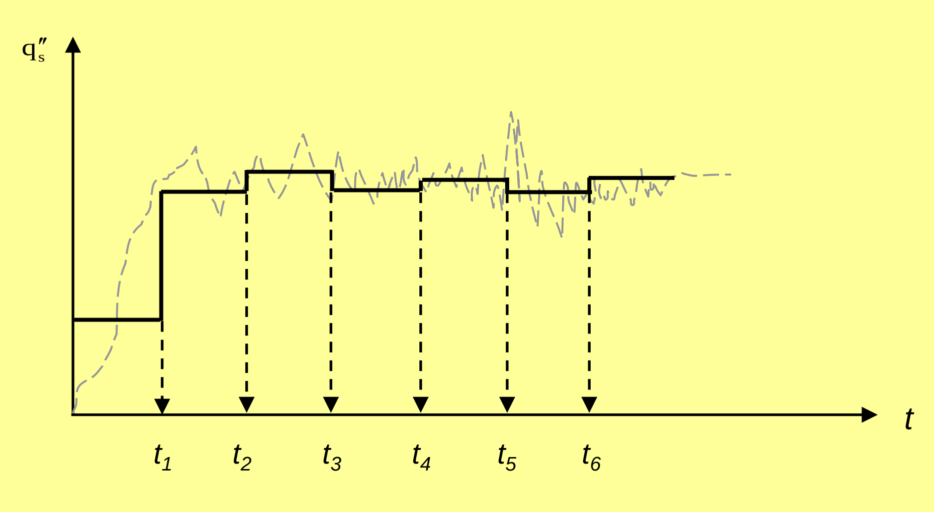
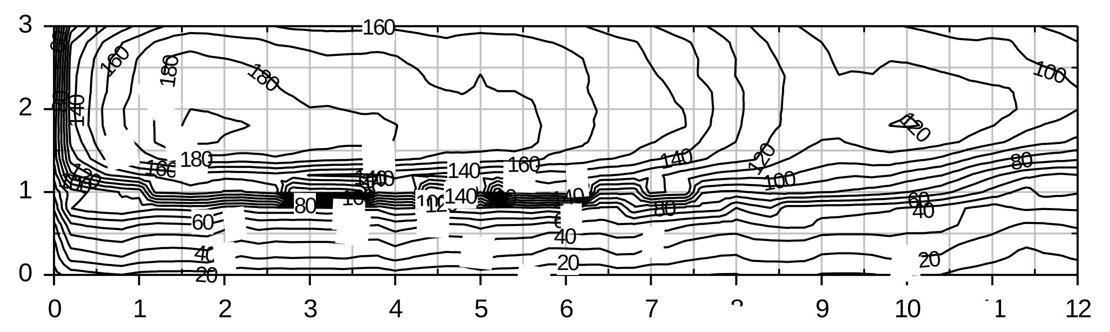
Modelling of Forest Fires

- A very complex problem

Type	Time Scale (s)		
Combustion	0.0001 – 0.01		
Fuel particles	-		
Fuel complex	-		
Flames	0.1 – 30		
Radiation	0.1 – 30		
			0.01 – 0.1
			0.1 – 10
			1 – 1,000
			1 – 10,000
			1 – 100



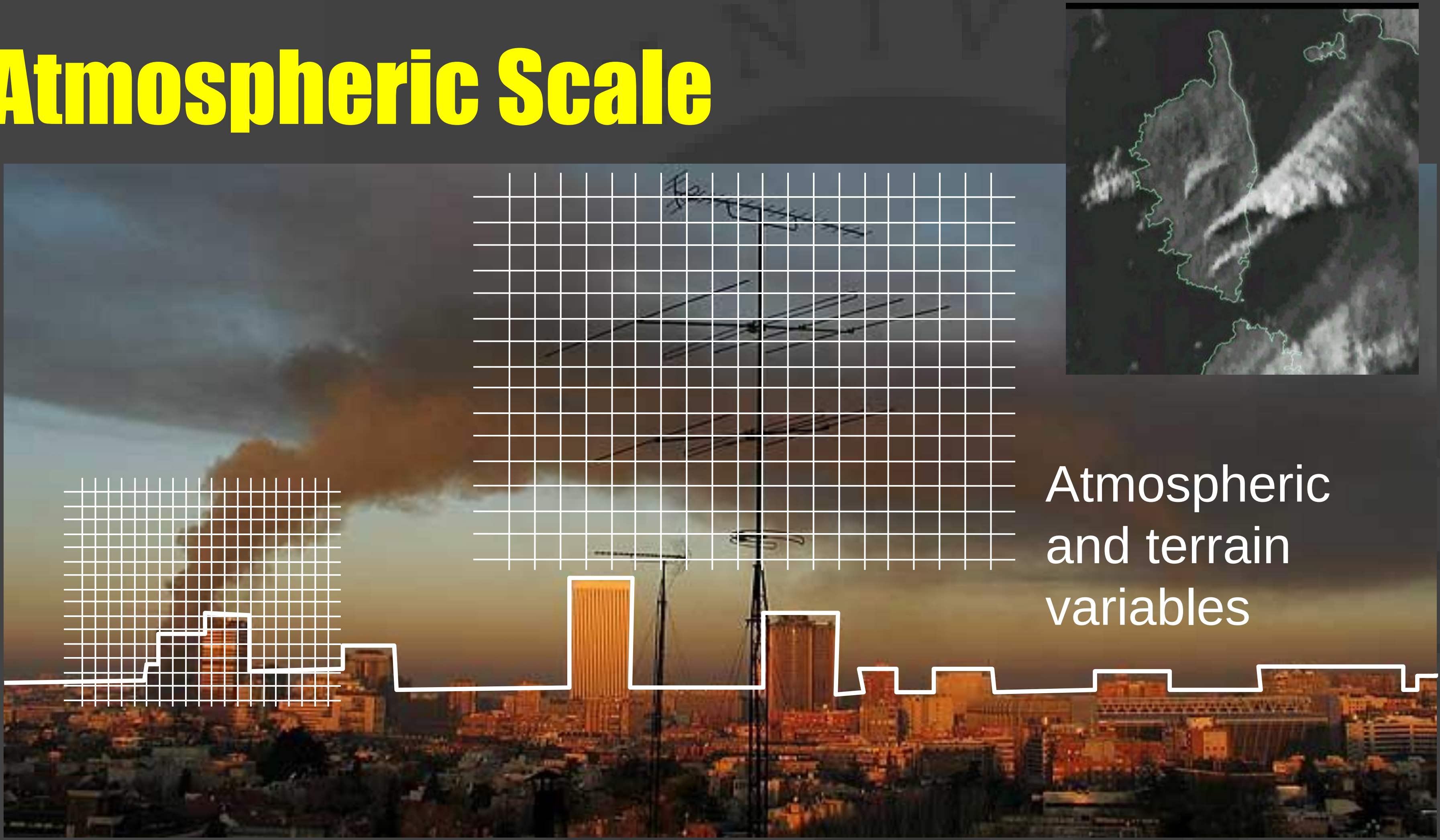


Sullivan, A., "A Review of Wildland Fire Spread Modelling, 1990-Present, 1: Physical and Quasi-Physical Models", arXiv:0706.3074v1[physics.geo-ph] (2007).

Compatibility

- Resolving all length and time scales in a single model is impossible
- It is necessary to develop sub-grid/filtering models
- Sub-grid/filtering models need to be “compatible” with the outputs of the primary model

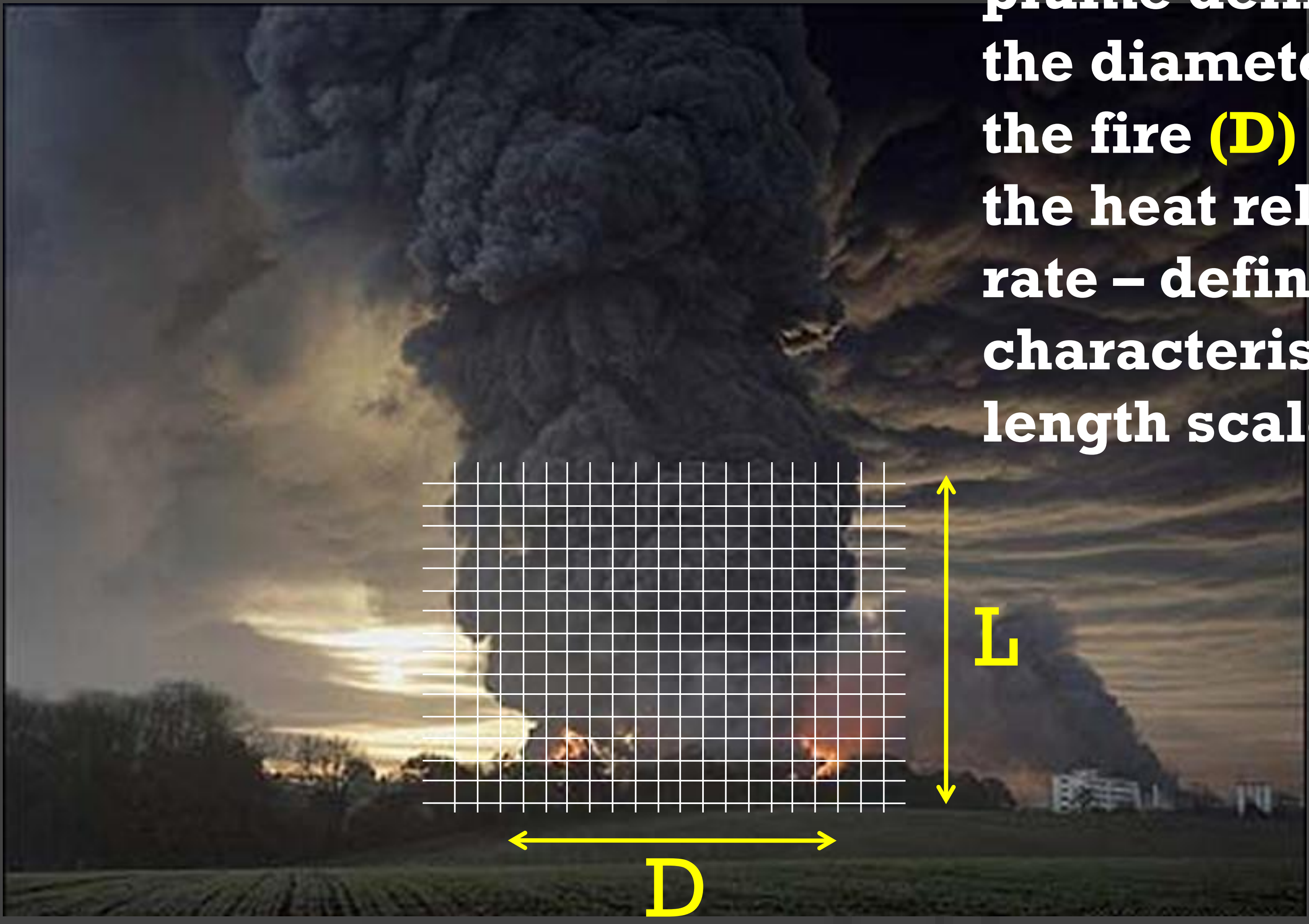
Atmospheric Scale



- Dispersion
- The fire is treated as a heat source

The Plume

- Strength of the plume defined by the diameter of the fire (D) and the heat release rate – defines the characteristic length scale (L)



Compatibility

- Energy/species can be introduced within a defined volume as a source term and allowed to disperse

Classic Scaling Approach

- **Focuses on proper modelling of buoyant entrainment**

$$\rho u \frac{\partial u}{\partial x} \approx \frac{\rho_\infty u_b^{\,2}}{D}$$

Inertia Buoyancy

$$\rho g \approx \rho_\infty g \quad \Rightarrow \quad u_b = \sqrt{gD}$$

$$\rho Cp\, u \frac{\partial T}{\partial x} \approx \frac{\rho_\infty Cp_\infty u_b T_\infty}{D}$$

$$\dot{Q}''' = \frac{\dot{Q}}{D^3}$$

Energy
Release Rate

$$Q^* = \frac{\dot{Q}_0}{\rho_\infty T_\infty Cp_\infty (gD)^{1/2} D^2}$$

Use of Q*

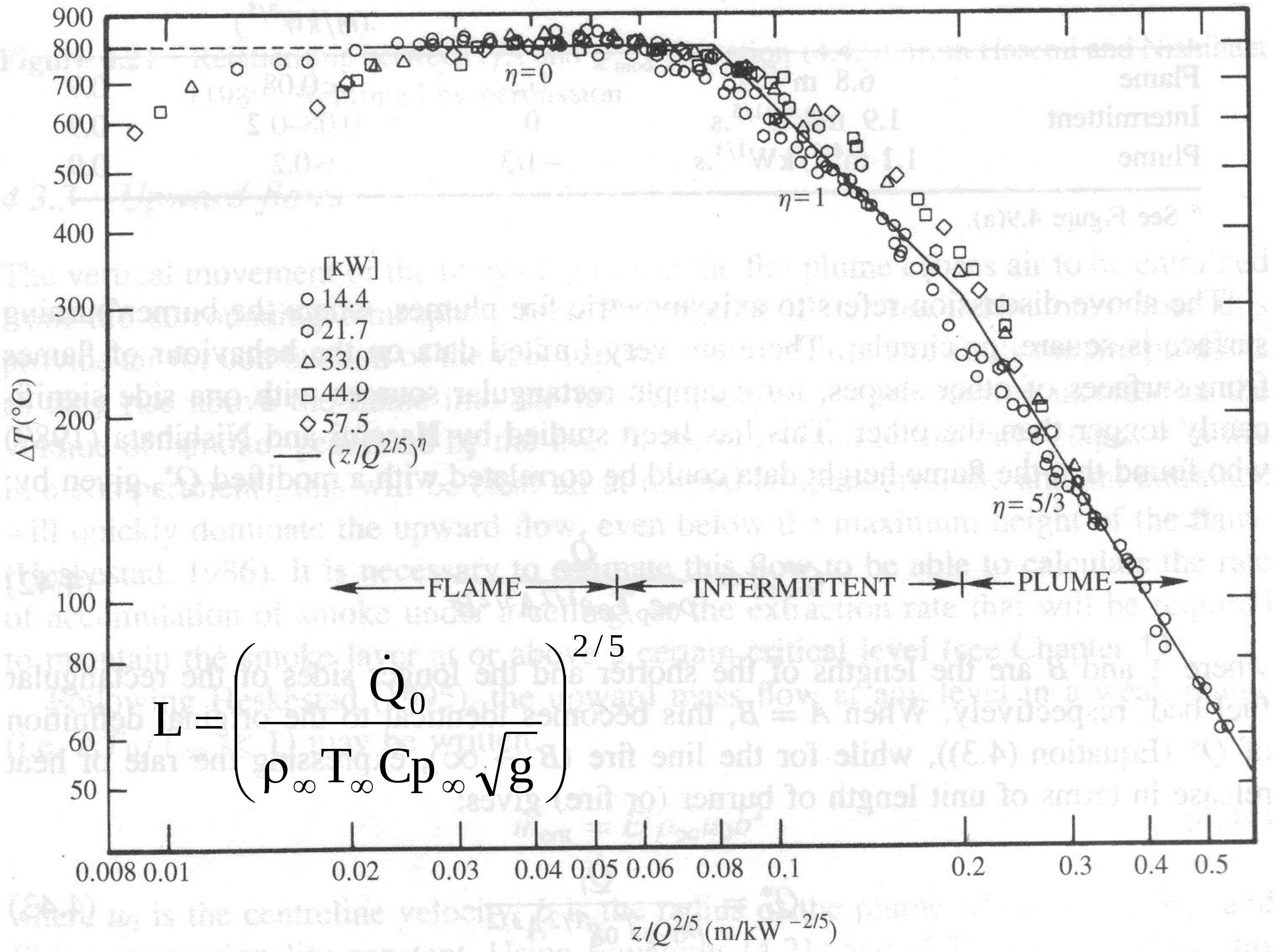
$$Q^* = \frac{\dot{Q}_0}{\rho_\infty T_\infty Cp_\infty (gD)^{1/2} D^2}$$

- Obtain a characteristic length scale

- If Q*=1

$$L = \left(\frac{\dot{Q}_0}{\rho_\infty T_\infty Cp_\infty \sqrt{g}} \right)^{2/5}$$

- Temperature and velocity fields can be presented as a function of a scaled length: Incorporates the Heat Release Rate Dependency



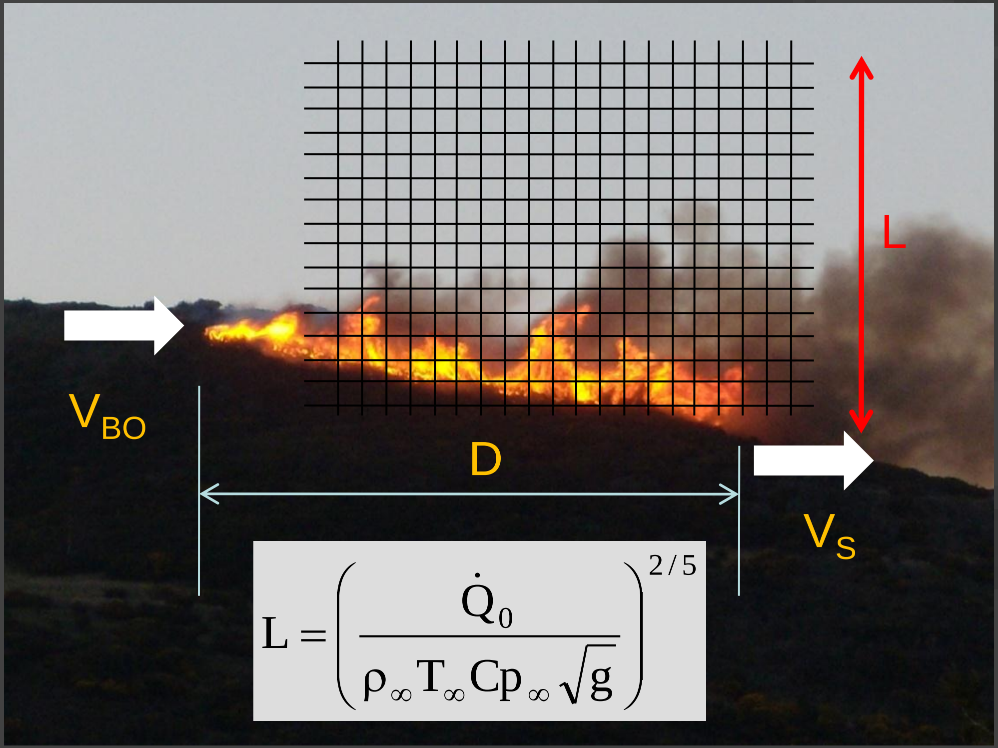
$$L = \left(\frac{\dot{Q}_0}{\rho_\infty T_\infty C p_\infty \sqrt{g}}\right)^{2/5}$$

Compatibility

- In a stationary fire compatibility between the “entrainment region” and the “dispersion region” can be achieved by a sub grid model that defines the fire as a heat release rate (source term) over a well defined “volume” (characteristic length scales (D,L))

Flame Spread

- **Forest fires spread – thus spread rates are necessary**
  - Flame spread rates can be defined in an empirical way and incorporated to “atmospheric type” models – compatible
  - To maintain the characteristic length scale “burn-out” rates are necessary too - compatible



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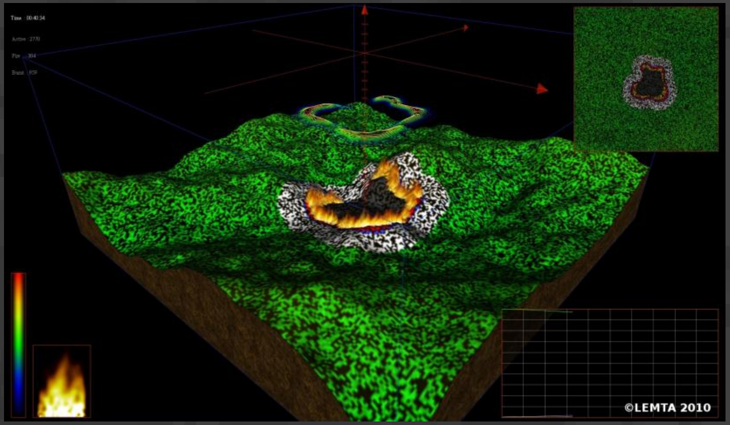
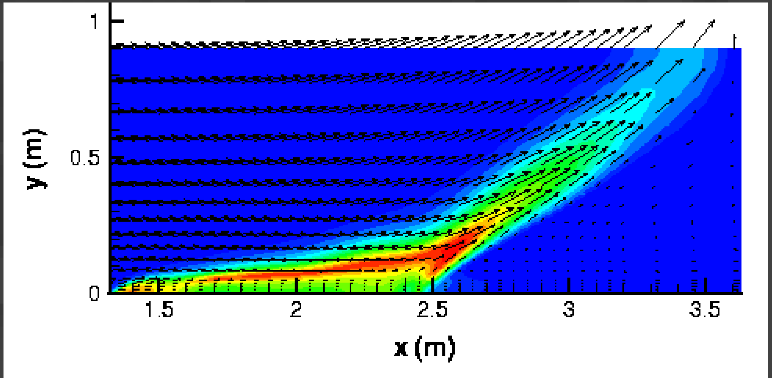
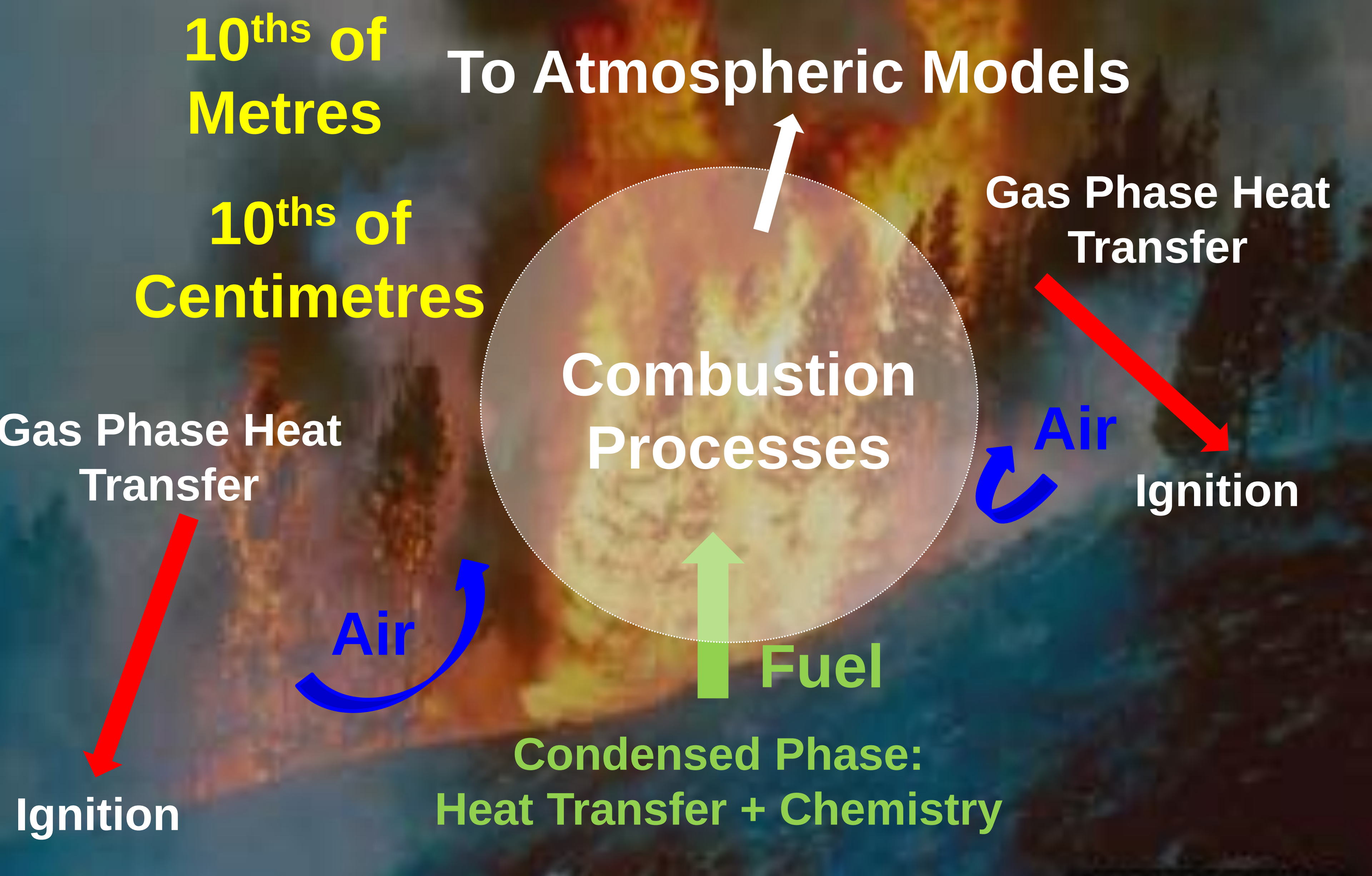




Limitations

- Flame Spread rates depend on many variables (vegetation type, density, humidity, slope, wind, etc.)
- Burn-out rates depend on many variables (vegetation type, humidity, fuel load, density, wind, etc.)
- Mixture of fuel and environmental variables

Flame Spread: Sequence of Ignitions



10ths of Metres

To Atmospheric Models

10ths of Centimetres

Gas Phase Heat Transfer

Combustion Processes

Gas Phase Heat Transfer

Air

Ignition

Air

Fuel

Ignition

Condensed Phase:
Heat Transfer + Chemistry

Incompatible

Fuel Degradation (μm, s)

↓

Gas Phase Chemistry (nm, ms)

↓

Soot Production (μm, ms)

↓

Radiative Losses (cm, ns)

↓

Flame Temperature (cm, s)

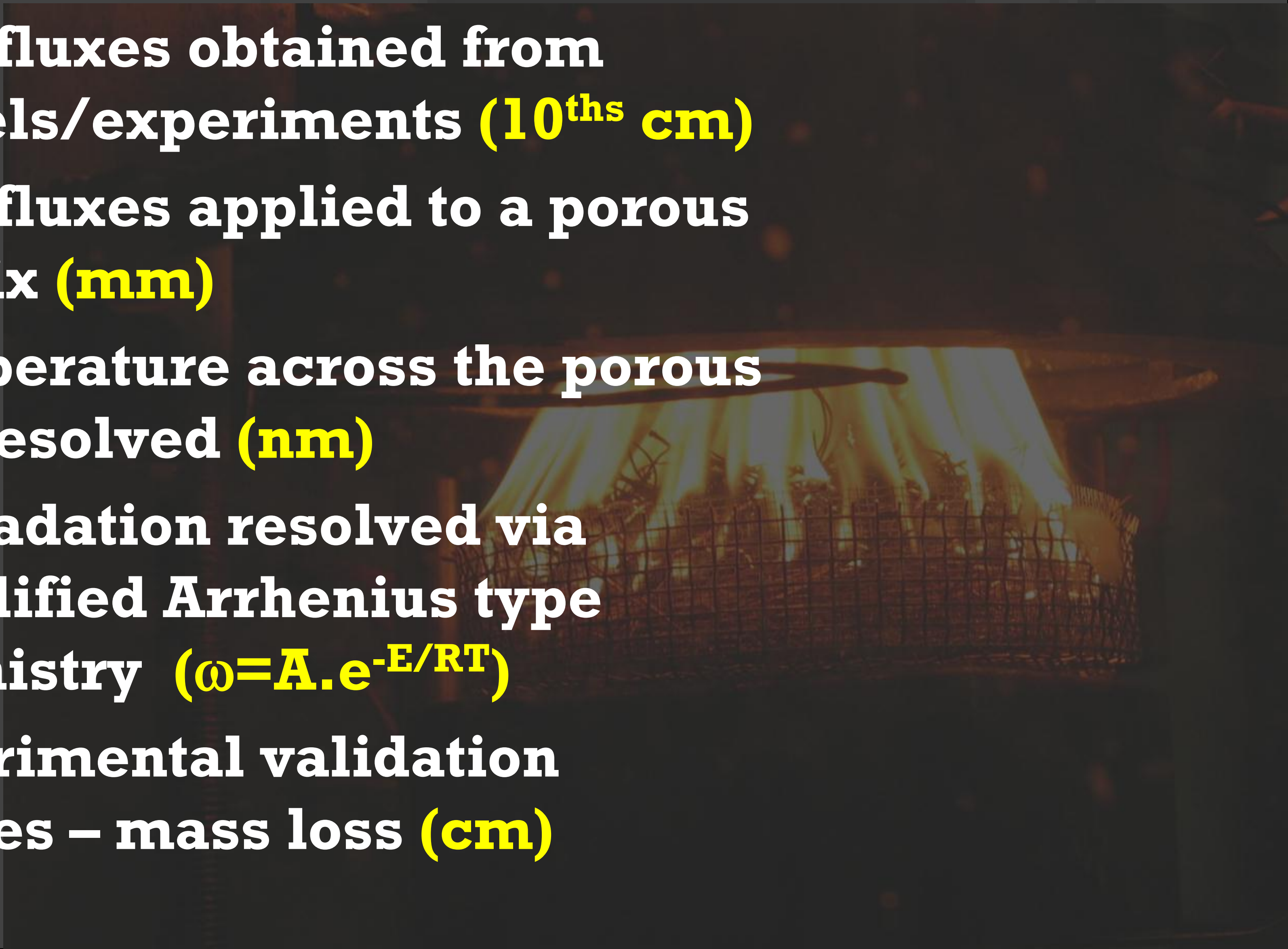
↓

Radiative Heat Transfer (cm, ns)

Resolution

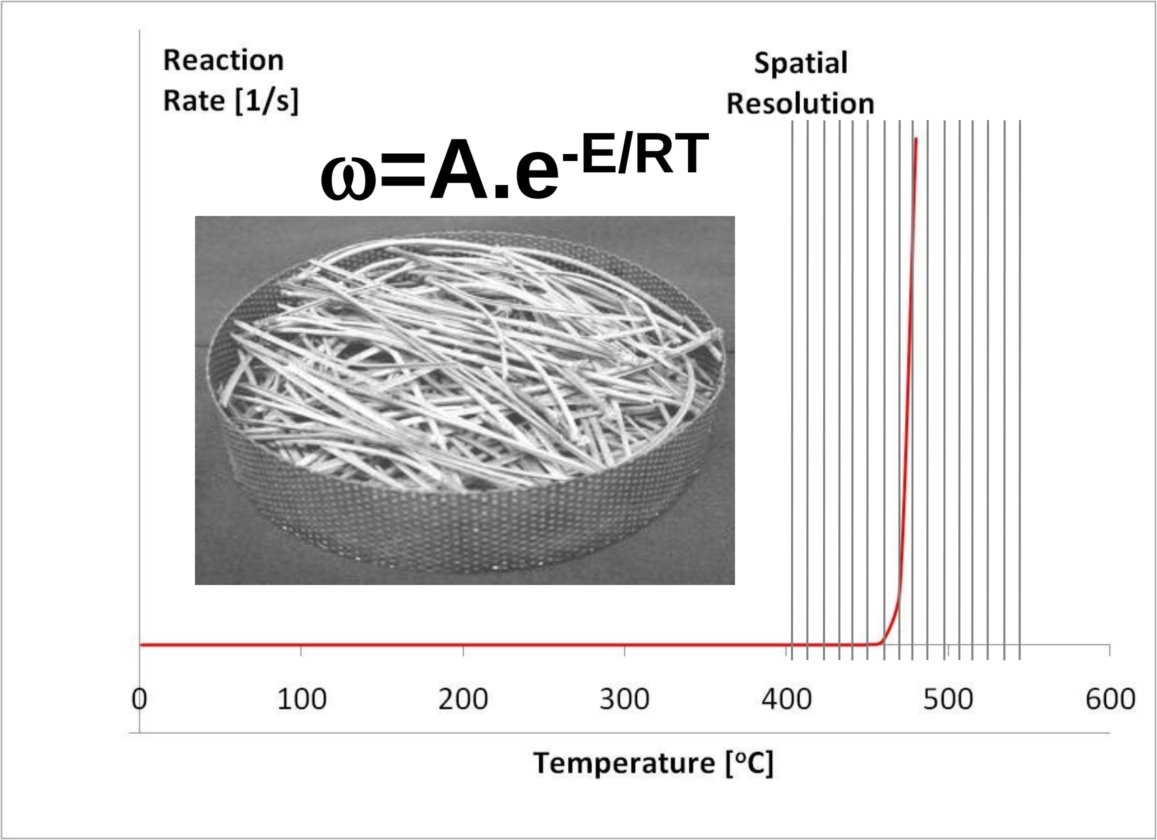
- To resolve ignition it is necessary to resolve the fasters time scales and the smallest length scales (nm, ns)
- Result needs to be fed into an combustion model (10ths cm, sec resolution)– Incompatible
- Computational cost unacceptable – Precision unnecessary

Incompatibility



- Heat fluxes obtained from models/experiments **(10$^{\text{ths}}$ cm)**
- Heat fluxes applied to a porous matrix **(mm)**
- Temperature across the porous bed resolved **(nm)**
- Degradation resolved via simplified Arrhenius type chemistry **($\omega = A.e^{-E/RT}$)**
- Experimental validation studies – mass loss **(cm)**

Why nm Resolution?



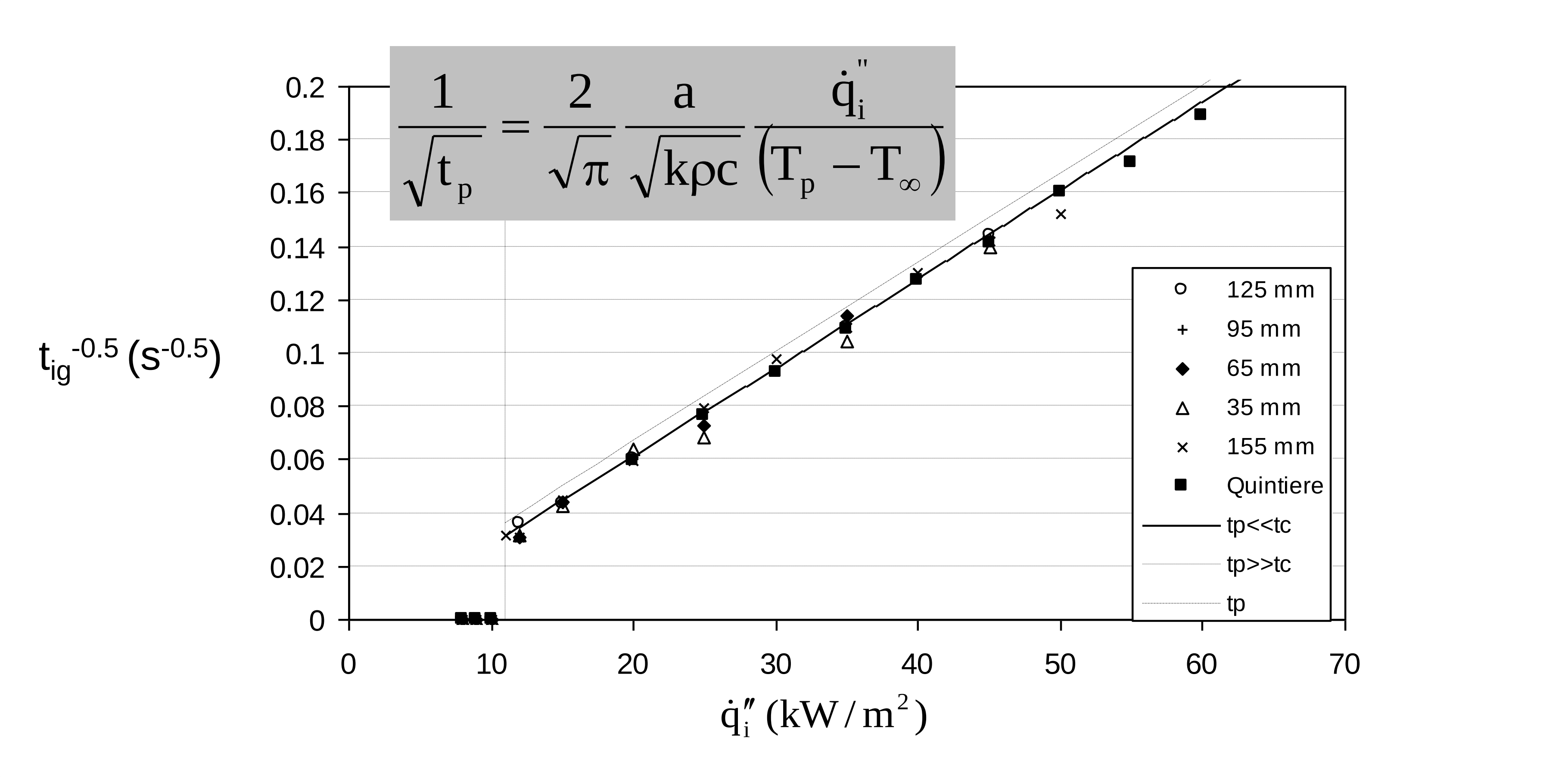
- Adequate resolution of the degradation chemistry requires resolving temperature gradients within the fuel thickness

Compatible Solution

- **Ideal Scenario:**
  - Input is the gas phase heat flux
  - Solid phase heat transfer (porous media) does not have to be resolved
  - Degradation chemistry does not have to be resolved
  - Solution: Sub-Grid model based on experimental data as an input to the model (cm/s – resolution)

Ignition Delay Time

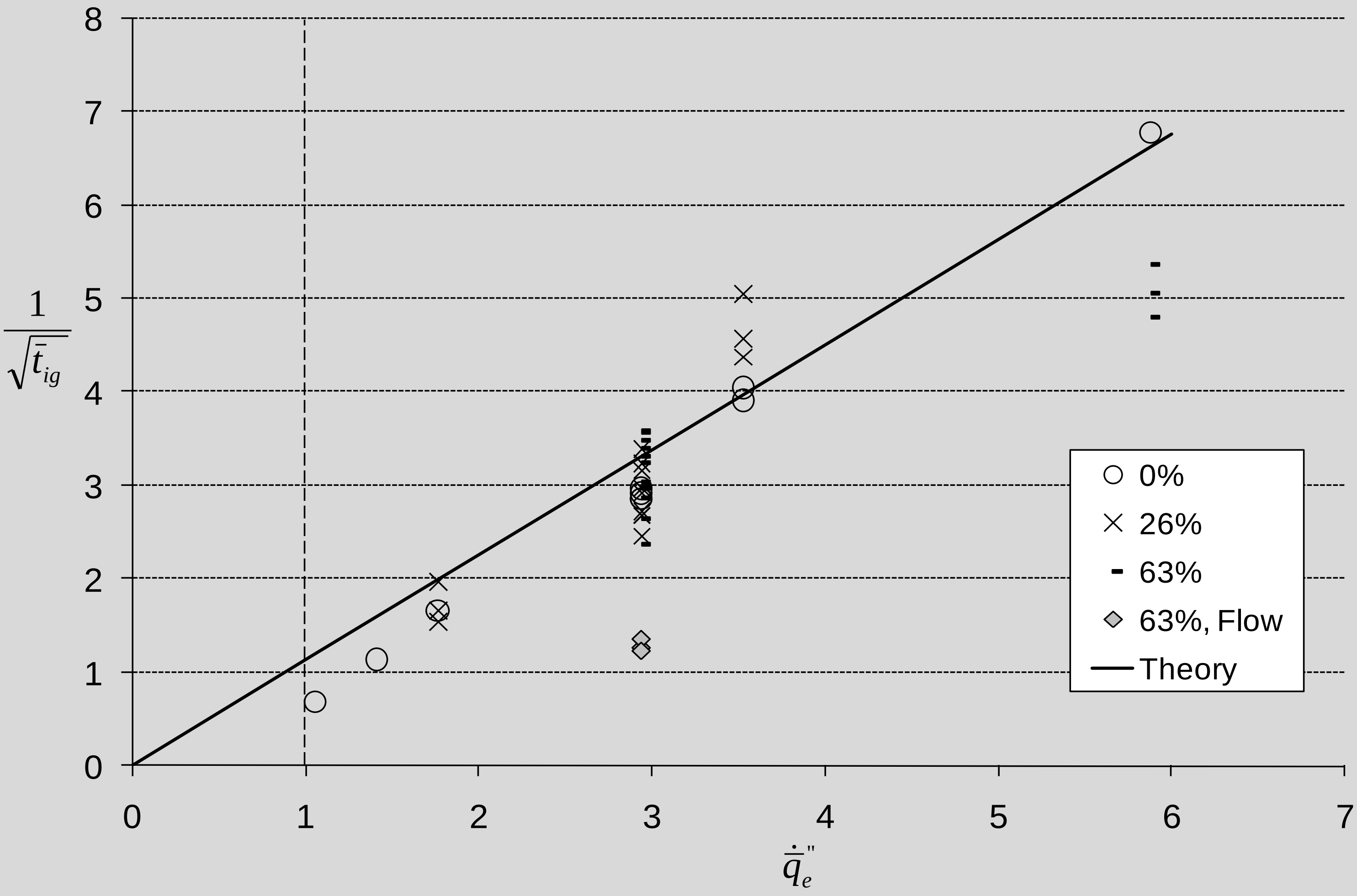
- Ignition time is linearly dependent to incident heat flux **(cm/s – Model)**



$$\frac{1}{\sqrt{t_p}} = \frac{2}{\sqrt{\pi}} \frac{a}{\sqrt{k\rho c}} \frac{\dot{q}_i''}{\left(T_p - T_\infty\right)}$$

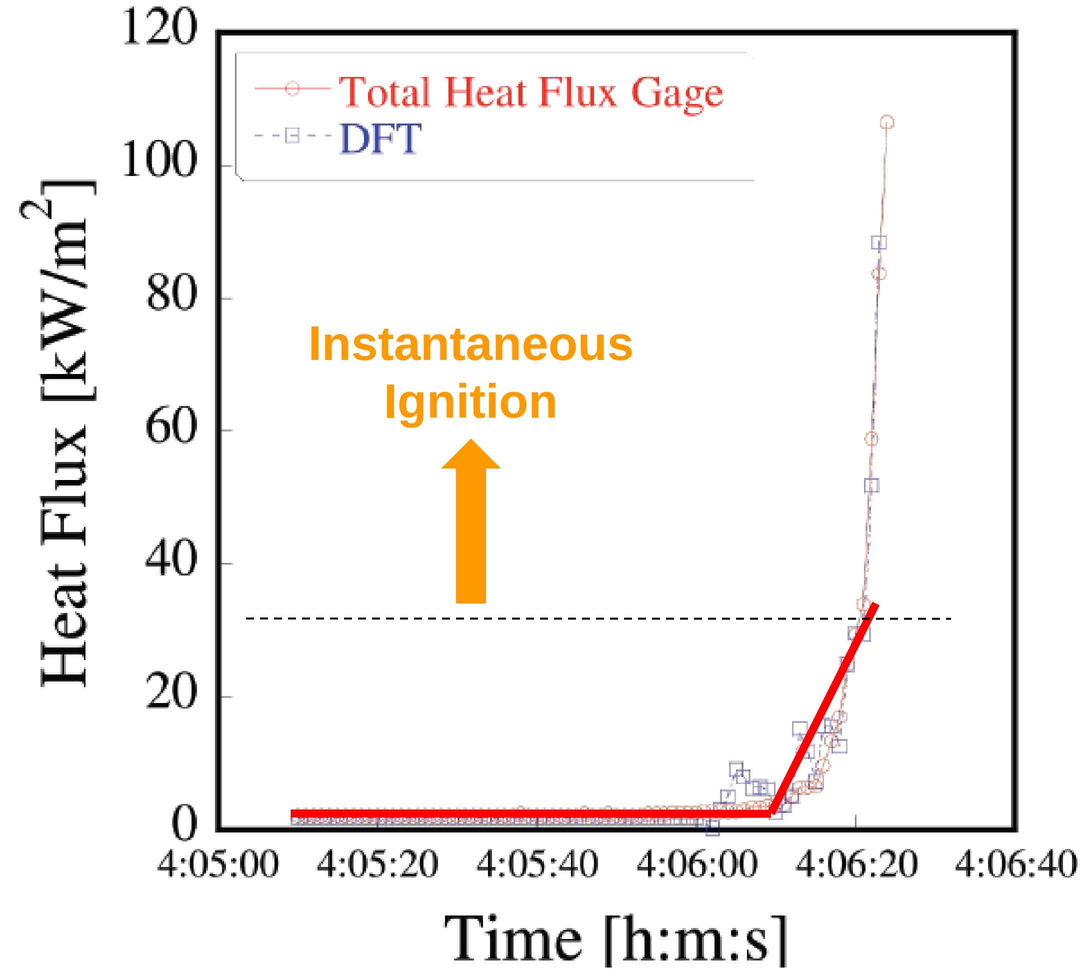
Quintiere, Fire and Materials,1983

Applicable to Forest Fire Fuels



Ignition Delay Times

- **Can be estimated as a function of the heat flux if the heat flux is a constant**



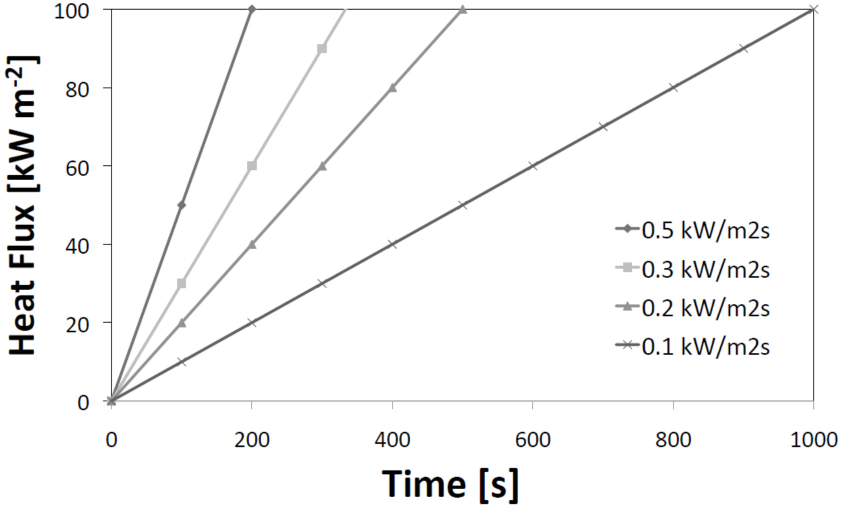
Manzello, S. L., Park, S. H., Cleary, T. G., Shields, J. R, "Developing Rapid Response Instrumentation Packages to Quantify Structure Ignition Mechanisms in Wildland-Urban Interface (WUI) Fires", Fire and Materials 2009. 11th International Conference Proceedings, San Francisco, CA, 2009, pp. 215–224.

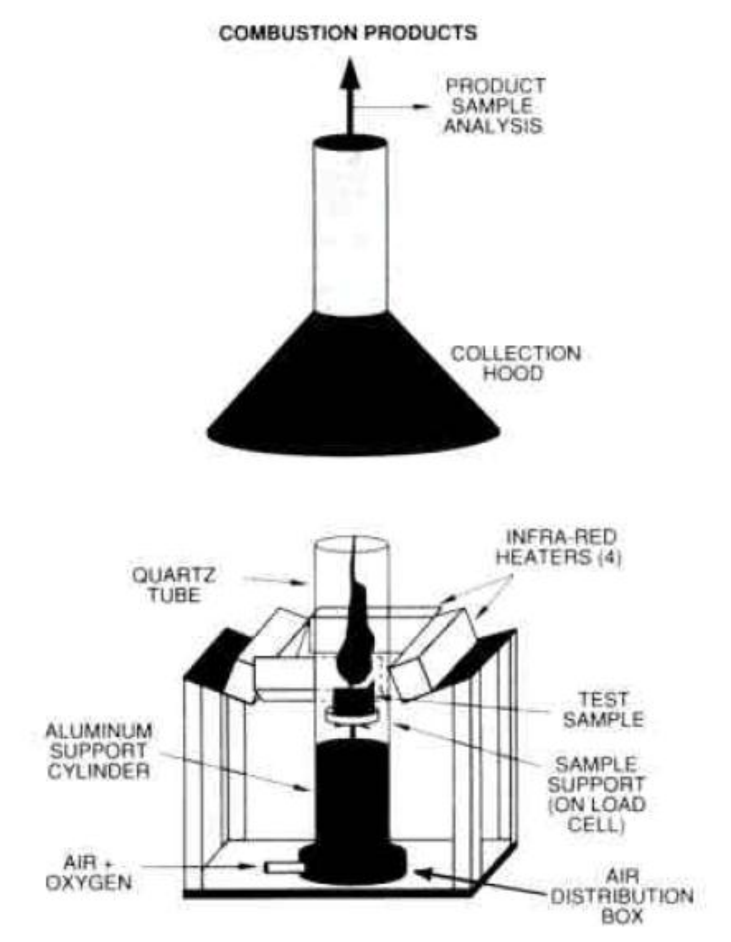
Modify Mathematical Solution

- For linear ramps integrating the expression for time to ignition over time, it can be shown that:

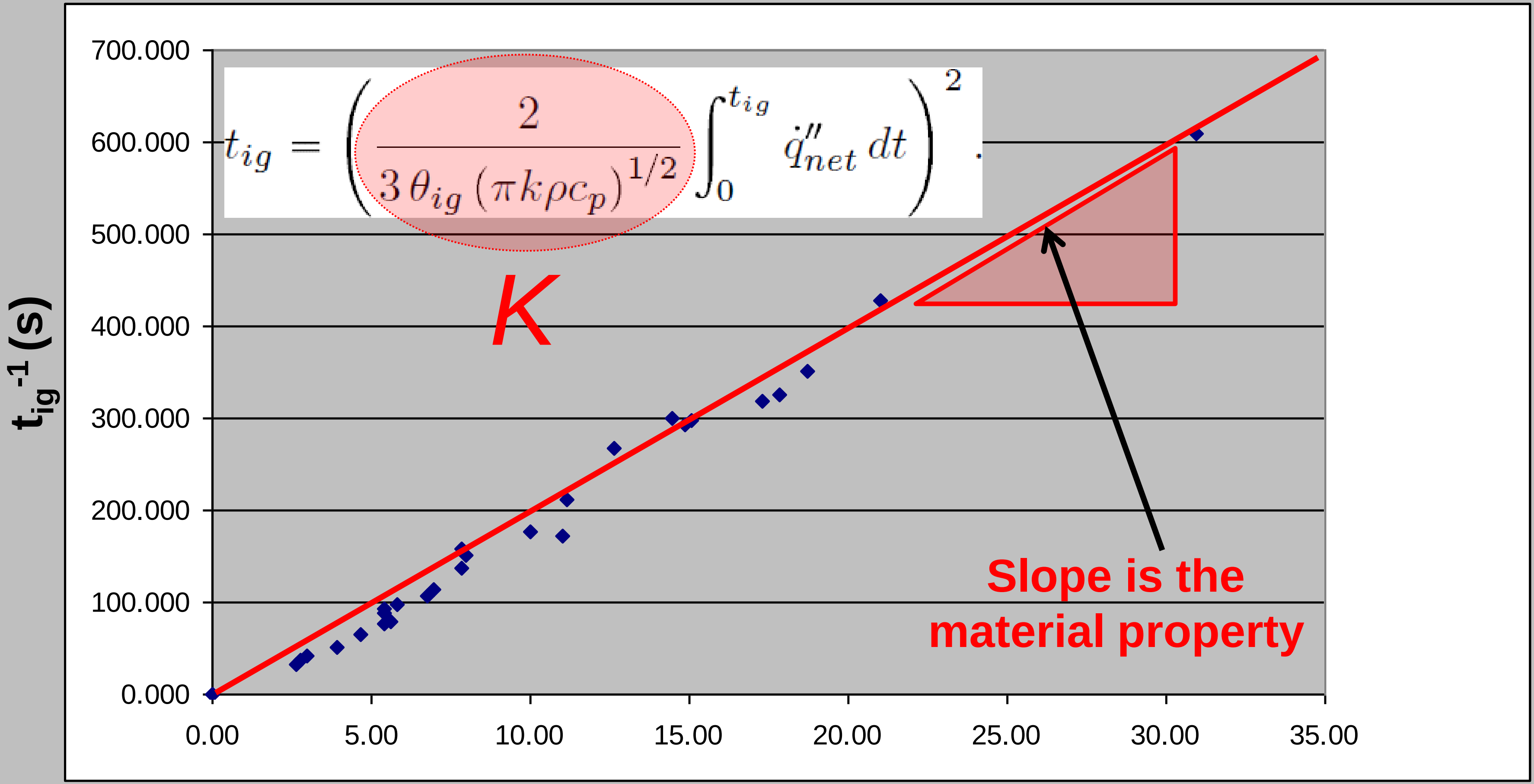
$$t_{ig} = \left(\frac{2}{3\,\theta_{ig}\,(\pi k \rho c_p)^{1/2}} \int_0^{t_{ig}} \dot{q}''_{net}\, dt \right)^2 .$$

Validation: Fire Propagation Apparatus





Results



$$t_{ig} = \left(\frac{2}{3\,\theta_{ig}\,(\pi k \rho c_p)^{1/2}} \int_0^{t_{ig}} \dot{q}''_{net}\,dt \right)^2 .$$

K

Slope is the material property

$$\left(\int_0^{t} \dot{q}''_{in}(t)\,dt \right)^2$$

Compatibility

- Combustion Model can be used to estimate the evolution of the integral heat flux to the surface as a function of time (10$^{\text{ths}}$ cm)
- "*K*"- material property (fuel type, water content, weather variables, etc.)
- Simple model provides t_{ig}
- No need to resolve porous media & solid heat transfer or degradation chemistry (nm)

Summary

- Forest fires cover an extensive range of time and length scales
- Different processes result in incompatible time and/or length scales
- For practical purposes, these need to be resolved with physically based sub-grid models that **ensure compatibility**

Thank you