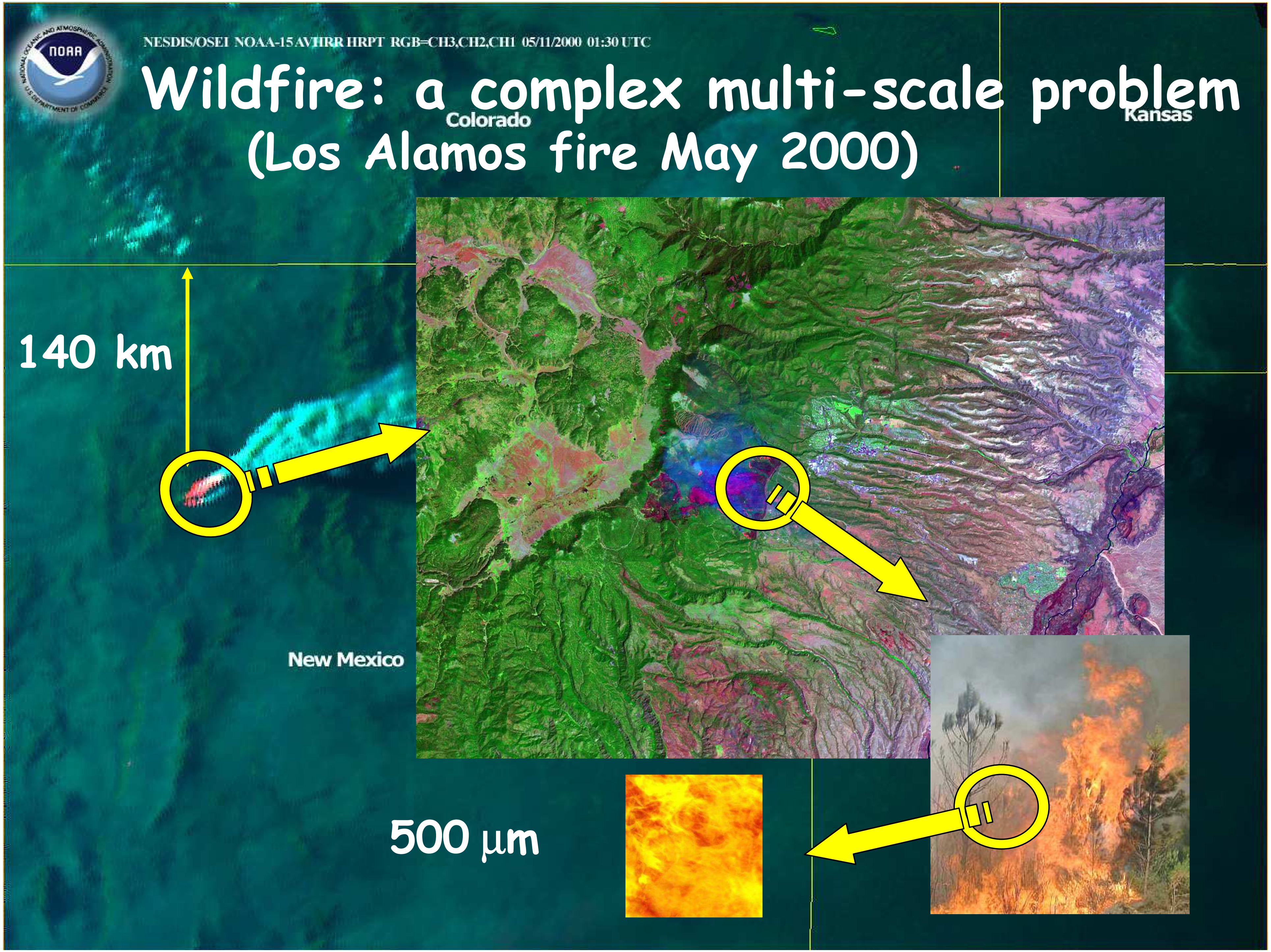
Physics & Wildfires modeling

Dominique MORVAN
Aix-Marseille University / UMR CNRS 7340 M2P2
dominique.morvan@univ-amu.fr

Wildfire: a complex multi-scale problem

(Los Alamos fire May 2000)



Wildfires: some physical characteristics (I)

Flames:

- Turbulente,
- Very bright and sooty,
- Intense radiation,
- Soot production,

Wildfires: some physical characteristics (II)

Rate of spread R (m/s): 0.1-1.5 m/s

Byram formula:

Fire line intensity I (kW/m): $I = M_{burn} \times \Delta H$

USA, Australia: 100 000 kW/m

Europe: 10 000 kW/m

M_{burn}: Solid fuel consumption rate (kg/m/s)

η : Combustion efficiency

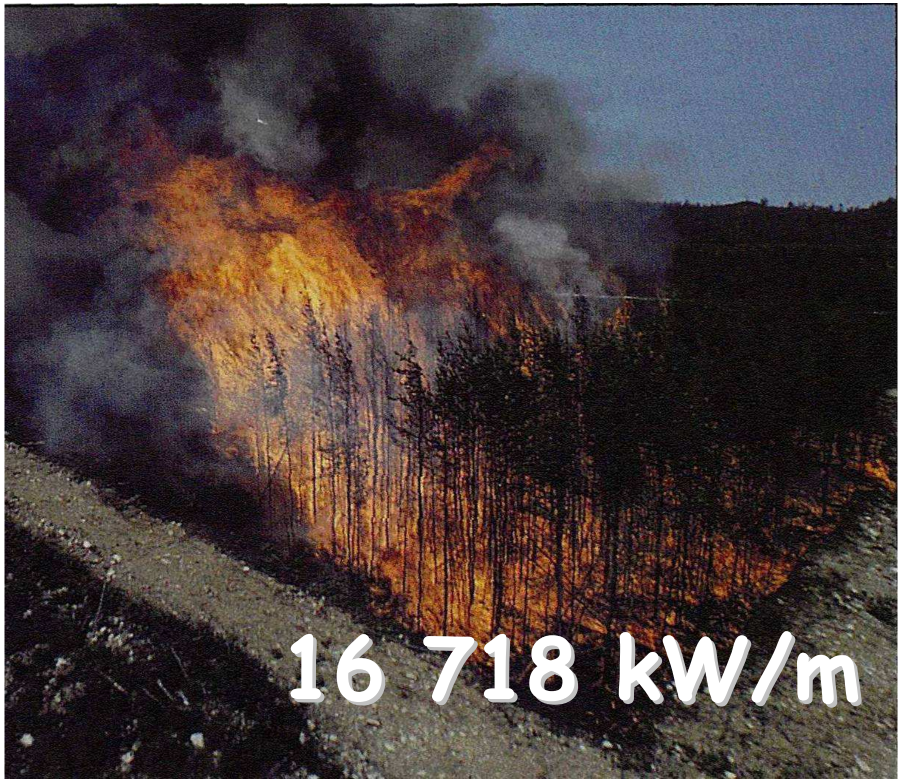
M_{fuel}: Dry solid fuel load (kg/m^2)

ΔH: Heat of combustion (~18 700 kJ/kg)

H_f: Flame height (m)

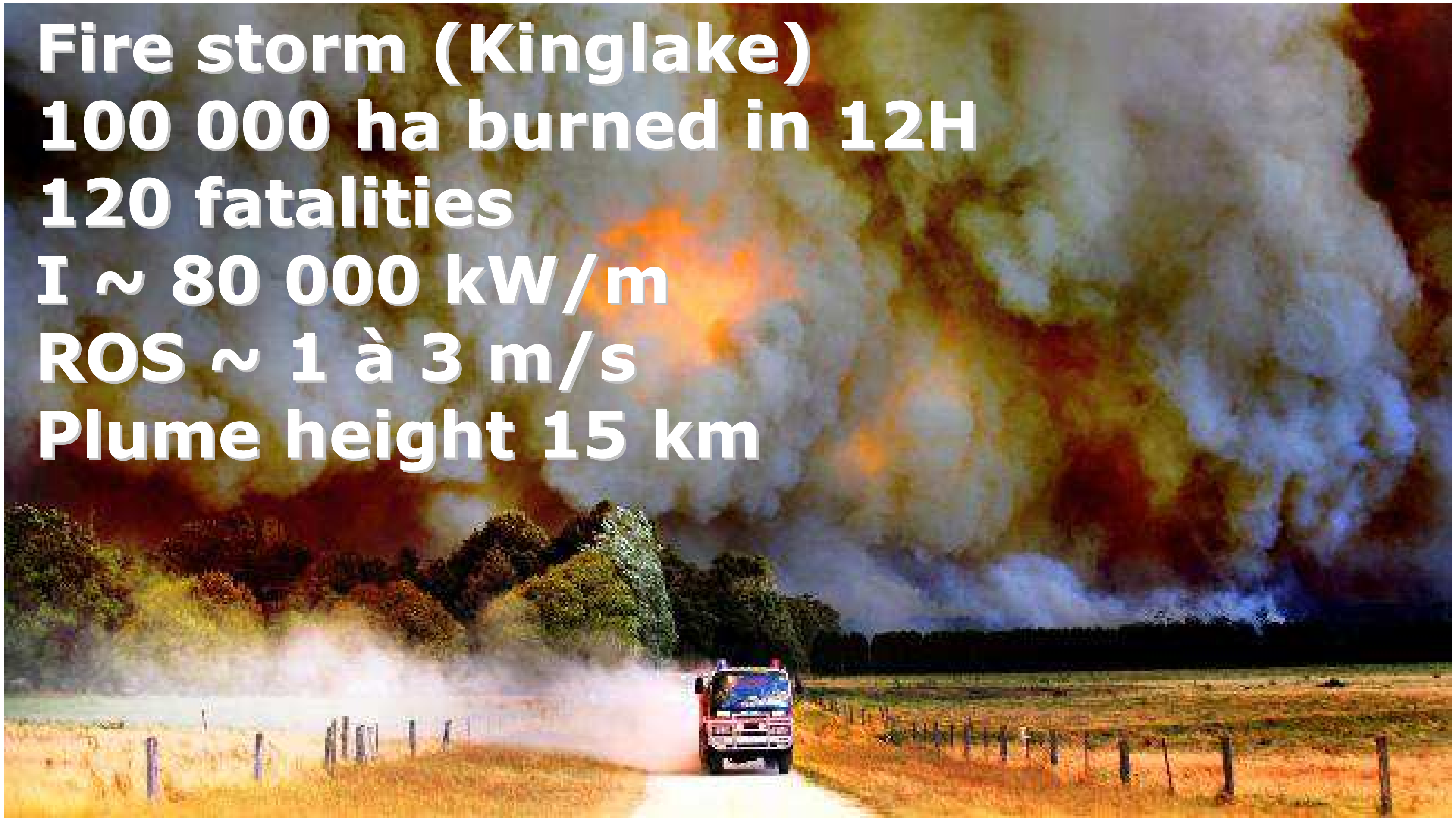
$$\boxed{I = \eta \, M_{fuel} \times \Delta H \times R \sim 300 \times H_f^2}$$

Fire intensity scales…



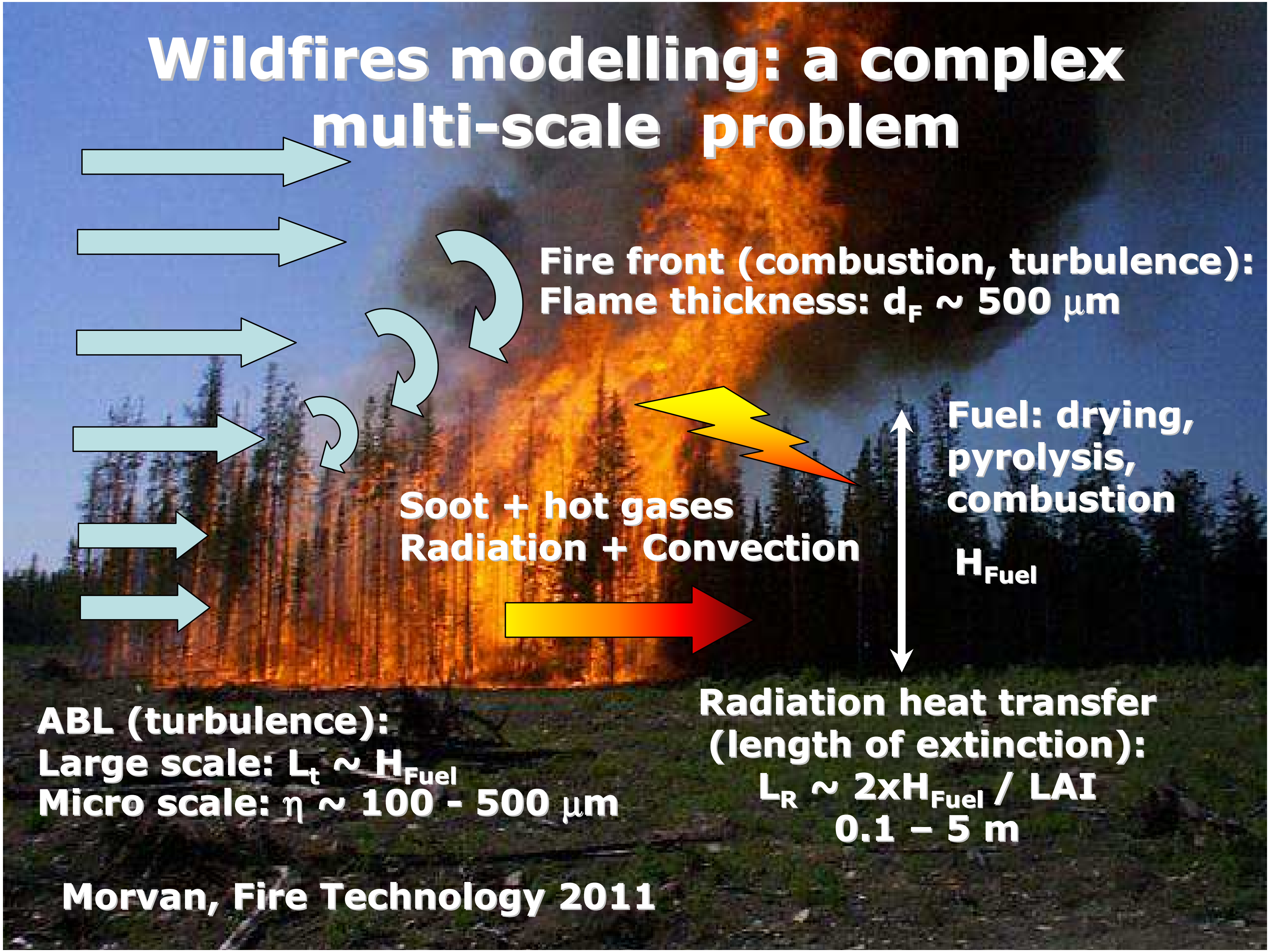
Efficiency limit: 2000 kW/m (terrestrial), 7000 kW/m (aerial)

Black Saturday (07/02/2009) Victoria district (Australia)



Fire storm (Kinglake)
100 000 ha burned in 12H
120 fatalities
I ~ 80 000 kW/m
ROS ~ 1 à 3 m/s
Plume height 15 km

Wildfires modelling: a complex multi-scale problem



Fire front (combustion, turbulence):
Flame thickness: $d_F \sim 500\ \mu m$

Fuel: drying,
pyrolysis,
combustion

H_{Fuel}

Soot + hot gases
Radiation + Convection

ABL (turbulence):
Large scale: $L_t \sim H_{Fuel}$
Micro scale: $\eta \sim 100$ - $500\ \mu m$

Radiation heat transfer
(length of extinction):
$L_R \sim 2xH_{Fuel}$ / LAI
0.1 – 5 m

Morvan, Fire Technology 2011

An other mecanism of fire propagation : firebrands

Distance travelled by a firebrand > 2400 m (source: SALTUS) !

Factors affecting the behaviour of forest fires: the fire triangle

Topography
- Flat or slopes
- Aspect

Weather
- Wind
- Temperature
- Relative Humidity
- Precipitation

Fuel
- Fine or Heavy
- Arrangement & continuity
- Fuel Moisture

Atmosphere/wildfire interaction

Unstable

Neutral or stable


Rudy Trujillo/USFS


U.S. Fish and Wildlife Service

$$\frac{dT}{dz} < DATG$$

$$\frac{dT}{dz} \geq DATG$$

DATG: dry adiabatic temperature gradient

$$DATG = -\frac{g}{c_p} \approx -10\ K/km$$

Wildfires modeling (Weber 1991, Sullivan 2009 …)

- **Statistical models (empirical),**

  ➡ Mc Arthur (1966) $R=f(f_i)$

- **Semi-empirirical models,**

  ➡ Rothermel (1972) $R= \xi I_r / \rho \Delta h_i$

- **Physical models (radiative, full physics),**

➡ Albini (1985), De Mestre (1989),
Balbi, Santoni & al (1998), Siméoni & al (2001)
$R = q / \rho |dh/dx|$

➡ Grishin (1985), Larini, Morvan, Porterie & al (1996)
Clark & al (1996), Lin & al (1997),
Sero-Guillaume & al (2002), Rehm & al (2003), Mandel & al (2004), Mell & al (2005), Mahalingam (2008), Filippi & al (2009) …

Semi-empirical Rothermel's model de (BEHAVE, FARSITE)

Fuel:

Excelsior

Pine needles

$R = \xi \, Ir \, / \, (\rho_s \, \alpha_s \, \Delta hi)$, $\xi = (192+7.894 \, \sigma_s)^{-1} \exp[(0.792+3.760 \, \sigma_s^{1/2})(\alpha_s - 0.1)]$

$\rho_s \, \alpha_s$: Fuel density and fuel volume fraction

Ir : Heat of combustion

$\Delta hi = C_p \, [T_i - T_a]$ Enthalpy of ignition

σ_s : Surface area / Volume ratio of solid fuel particles

Semi-empirical Rothermel's model de (BEHAVE, FARSITE)

$R = R_0\,[1 + \phi_w + \phi_s\,]$

$\phi_w = C_w\,U_w^{Bw}\,[\alpha_s / \alpha_s^{\,0}]^{-Ew}$ (wind effect)

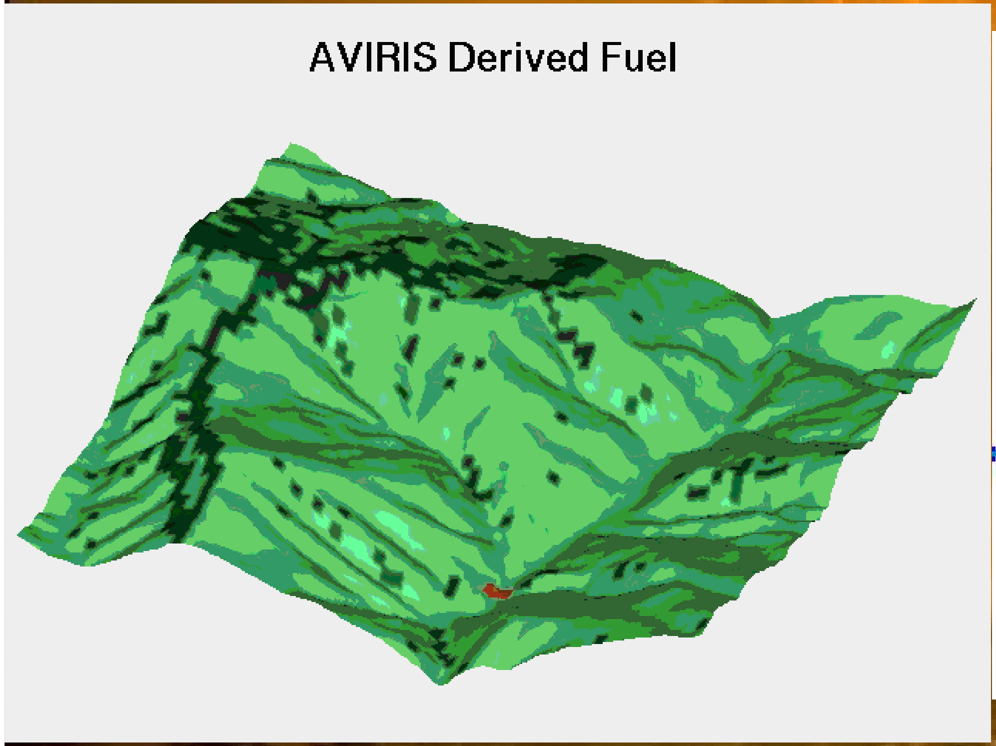
$\phi_s = 5.275\,\alpha_s^{-0.3}\,tg^2(\varphi)$ (slope effect)

$C_w\,,\,B_w\,,\,E_w = f\,(\sigma_s)\,,\,B_w = 0.0132\,\sigma_s^{0.54}$

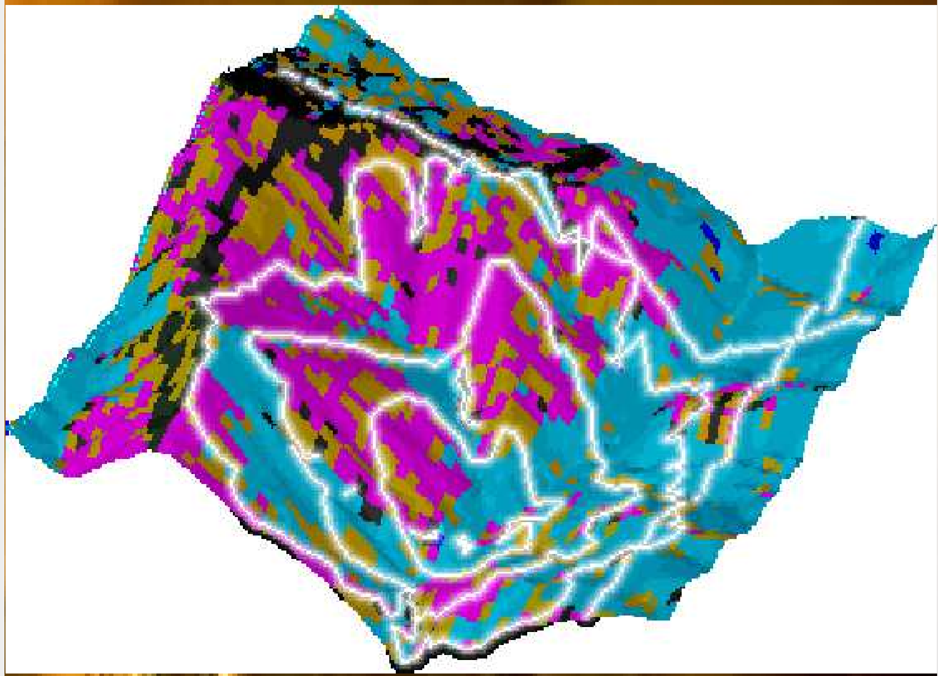
$B_w = 0.4\;(\sigma_s = 666\ m^{-1})$

$B_w = 1.6\;(\sigma_s = 7596\ m^{-1})$

Malibu fire (22/10/1996)



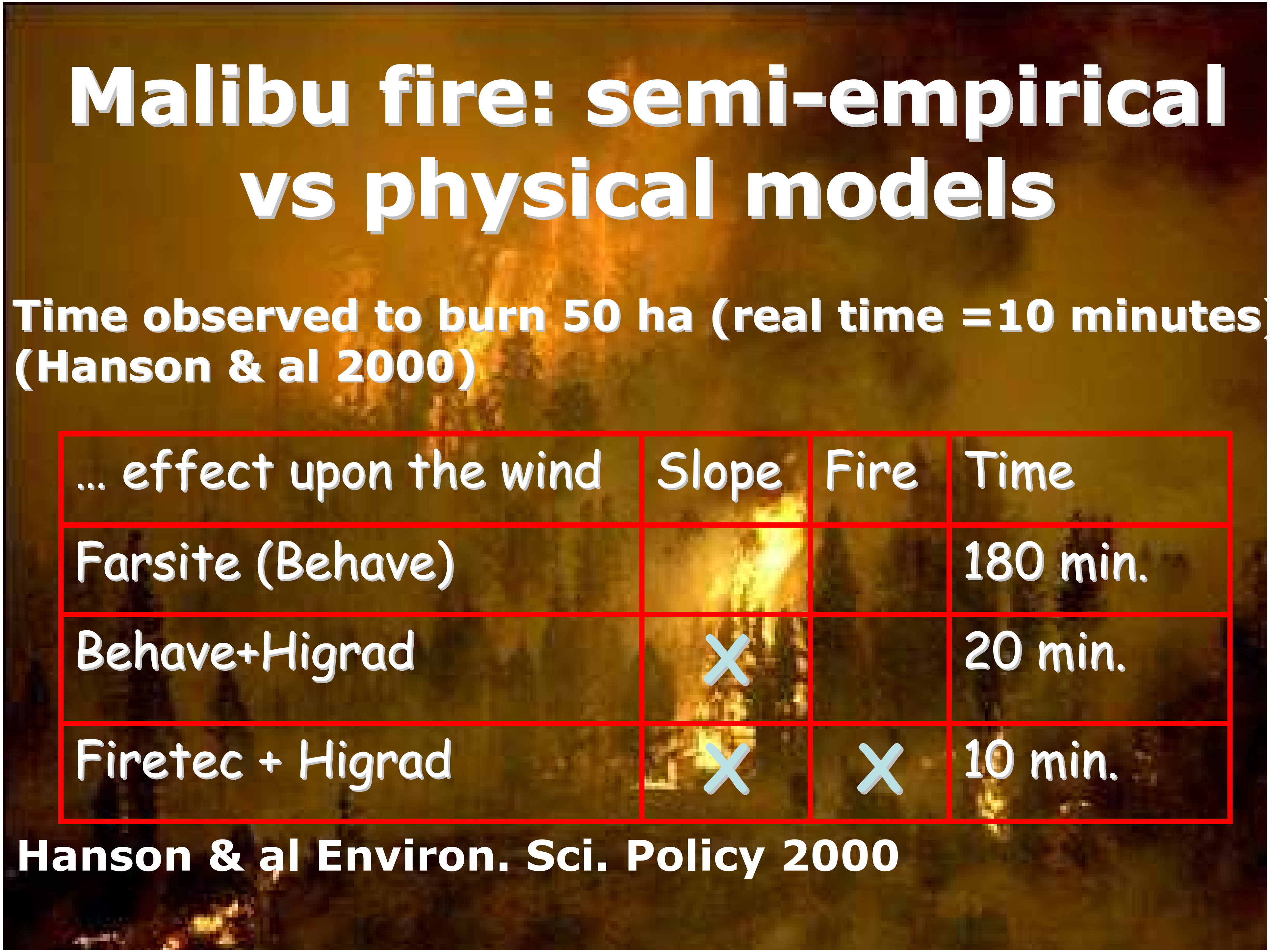
HIGRAD-FIRETEC



FARSITE

Hanson & al Environ. Sci. Policy 2000

Malibu fire: semi-empirical vs physical models

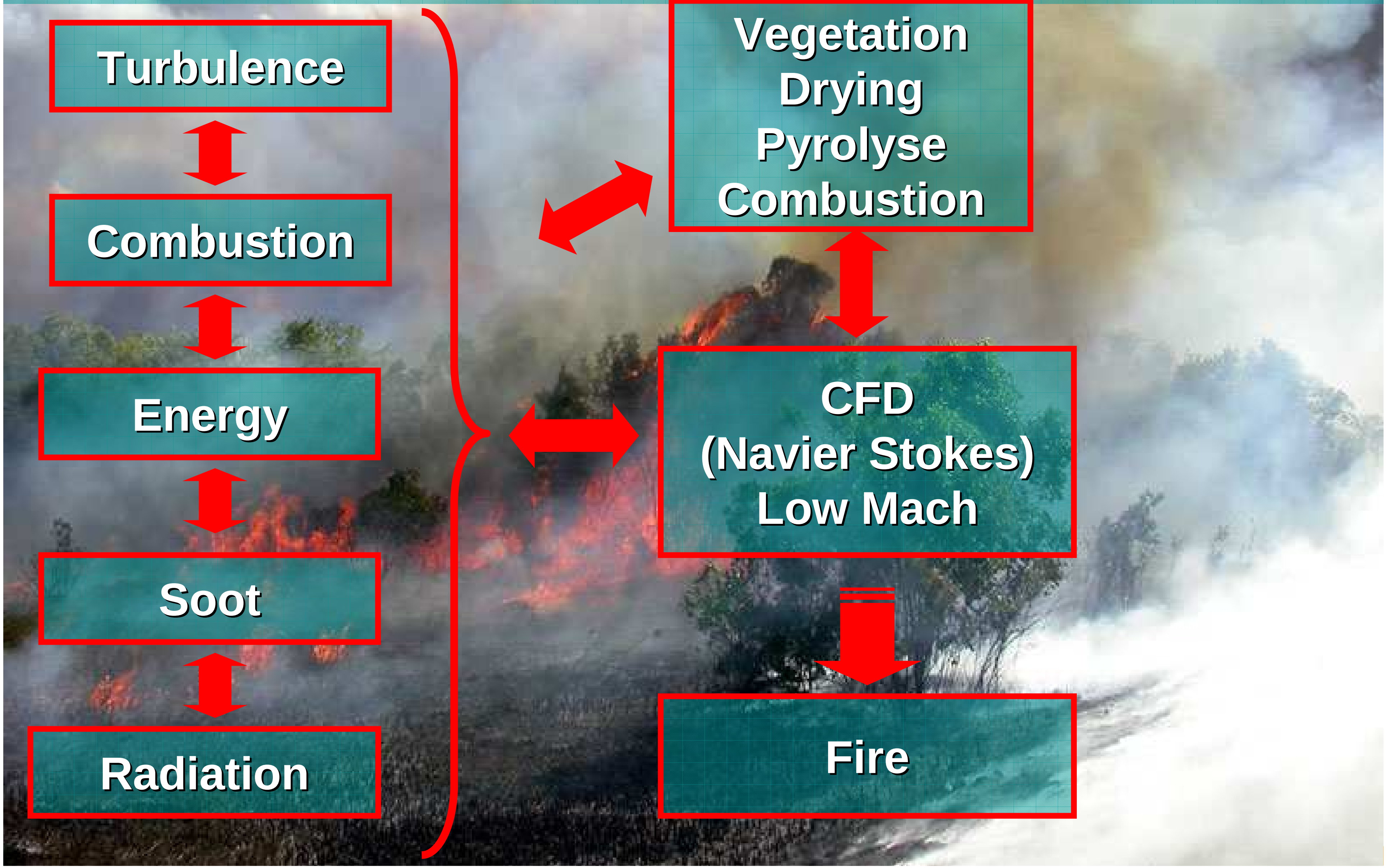


Time observed to burn 50 ha (real time =10 minutes
(Hanson & al 2000)

... effect upon the wind	Slope	Fire	Time
Farsite (Behave)			180 min.
Behave+Higrad	X		20 min.
Firetec + Higrad	X	X	10 min.

Hanson & al Environ. Sci. Policy 2000

Simulating wildfire behaviour using a physical model : multiphase approach



Turbulence

Combustion

Energy

Soot

Radiation

Vegetation
Drying
Pyrolyse
Combustion

CFD
(Navier Stokes)
Low Mach

Fire

ABL/canopy interaction

Leaf Area Density

$$a_L = LAD = \frac{\alpha_s \sigma_s}{2}$$

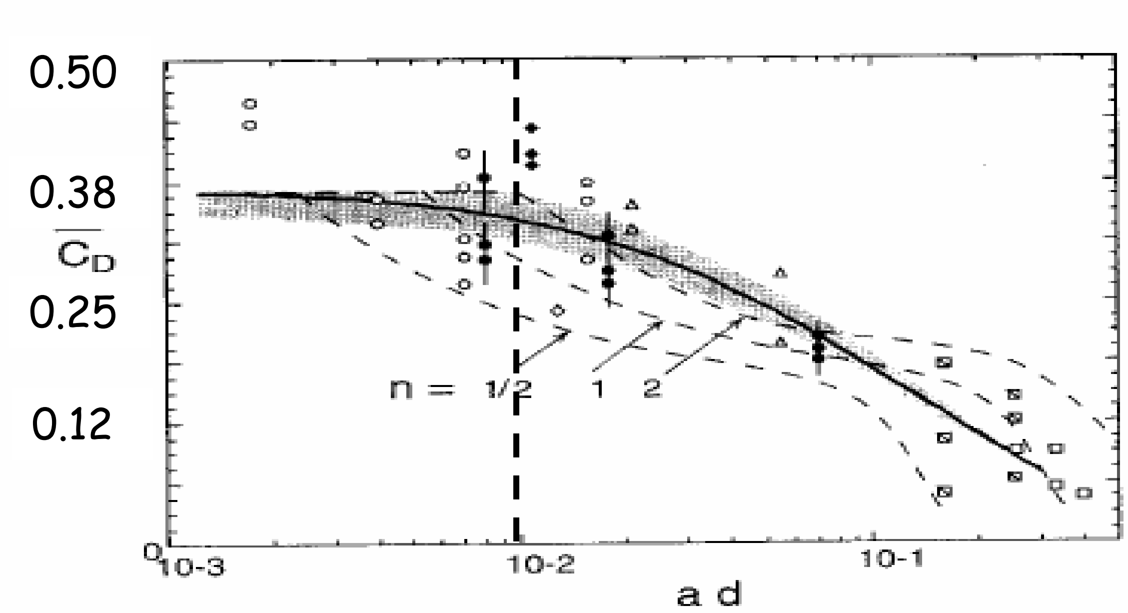
$$\frac{\partial}{\partial t}\left(\rho\langle u_i\rangle\right) + \frac{\partial}{\partial x_j}\left(\rho\langle u_i\rangle\langle u_j\rangle\right) = \frac{\partial\langle\sigma_{ij}\rangle}{\partial x_i} + \frac{\partial\tau_{ij}}{\partial x_i} - a_L C_D \rho\left|\langle u\rangle\right|\langle u_i\rangle$$

$$\frac{\partial\langle u'w'\rangle}{\partial z} = -C_D \times LAD \times \langle u\rangle^2 \Rightarrow C_D = 0.1 - 0.4$$

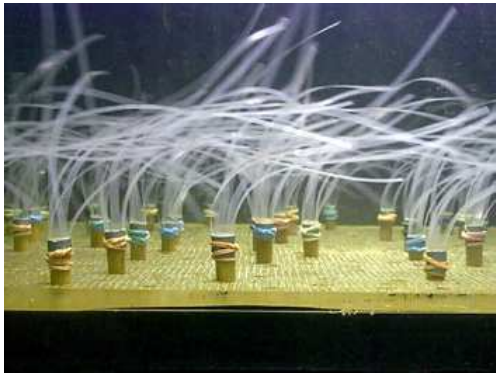
$$\frac{D\rho K}{Dt} = \frac{\partial}{\partial x_j}\left[\frac{\mu_{eff}}{\sigma_k}\frac{\partial K}{\partial x_j}\right] + \rho P - \rho\varepsilon + a_L C_D \rho\left[\langle U\rangle^3 - 4\langle U\rangle K\right]$$

Drag coefficient in a sea grass

(C_D défini à partir de la LAD (Leaf Area Density))



$$ad = \frac{4\alpha_s}{\pi}$$



- If ad < 0.01 $\langle C_D \rangle = C_D (R_e)$ (~ single particle)
- If ad > 0.01 $\langle C_D \rangle = f(ad)$ (wake interaction)
- Typical values: ad ~ α_s ~ 10^{-3}- 10^{-2} → $C_D = 0.38$

(Water Resources Research Vol.35(2) pp.479-489 (1999), H.M. Nepf)

Energy balance in the solid phase

$$\alpha_{s,p}\,\rho_{s,p}C_{s,p}\frac{dT_{s,p}}{\mathrm{dt}}=h_{conv}\underbrace{\alpha_{s,p}\sigma_{s,p}\left(T-T_{s,p}\right)}_{\text{Convection} \sim \text{linear}}+\underbrace{\frac{\alpha_{s,p}\sigma_{s,p}}{4}\left(J-4\sigma T_{s,p}^{4}\right)}_{\text{Radiation non-linear}}-\sum_{\alpha}M_{s,\alpha}h_{s,\alpha}$$

Convection
~ linear

Radiation
non-linear

Turbulence/Radiation Interaction

Optically thin fluctuation approximation (OPFA)

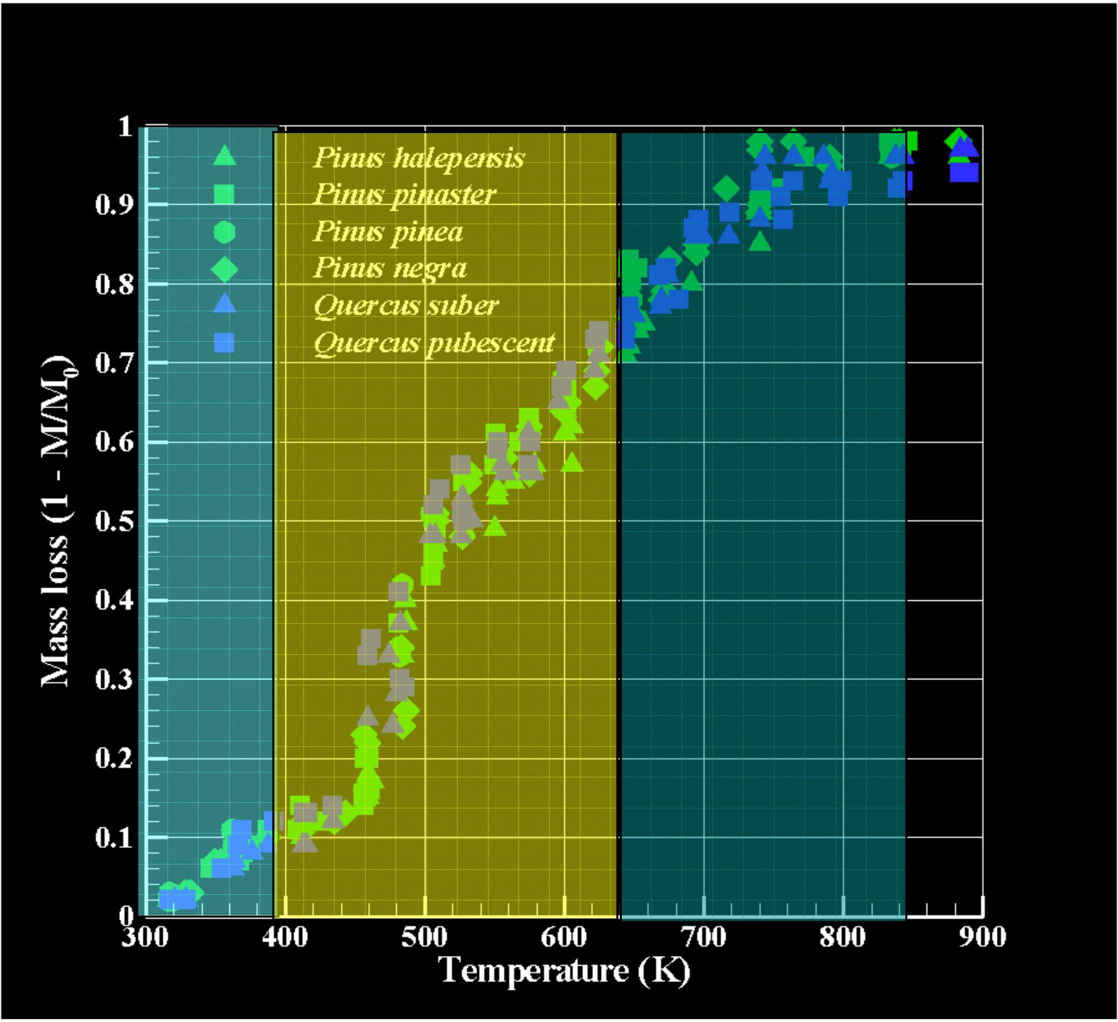
$$\frac{d\alpha_G \bar{I}}{\mathrm{ds}} = \alpha_G \left(\frac{\overline{\sigma \sigma_a T^4}}{\pi} - \overline{\sigma_a}\,\bar{I} \right) + \frac{\sigma_S \alpha_S}{4} \left(\frac{\sigma T_S^4}{\pi} - \bar{I} \right)$$

$$\overline{\sigma_a T^4} \approx \overline{\sigma_a}\,\bar{T}^4 \left[1 + 6\frac{\overline{T'^2}}{\bar{T}^2} + 4\frac{\overline{\sigma_a' T'}}{\overline{\sigma_a}\,\bar{T}} \right] = \overline{\sigma_a}\,\bar{T}^4 \left[1 + 6\frac{\overline{T'^2}}{\bar{T}^2} + 4\frac{\overline{T'^2}}{\overline{\sigma_a}\,\bar{T}} \frac{\partial \sigma_a}{\partial T} \right]$$

$$\frac{\partial \sigma_a}{\partial T} = 1862 \times \alpha_{soot} \qquad \overline{T'^2} = \theta$$

$$\frac{D\bar{\rho}\theta}{Dt} = \frac{\partial}{\partial x_j} \left(\frac{\mu_{eff}}{\mathrm{Pr}_T} \frac{\partial \theta}{\partial x_j} \right) + 2P_\theta - 2\varepsilon_\theta \qquad P_\theta = \frac{\mu_T}{\mathrm{Pr}_T} \left(\frac{\partial \bar{T}}{\partial x_j} \right)^2 \qquad \varepsilon_\theta = \rho \frac{\theta}{2 \times R} \times \frac{\varepsilon}{K}$$

Thermal analysis of Mediteranean vegetation samples (INRA-Avignon)



Drying

Pyrolysis

Combustion

Mass balance in the solid phase

Water & dry solid fuel

$$\frac{d\left(\alpha_{s,p}\ \rho_{s,p}\mathrm{Y}_{\mathrm{s,p}}^{\mathrm{h2o}}\right)}{\mathrm{dt}} = -\omega_{vap}^{s}$$

$$\frac{d\left(\alpha_{s,p}\ \rho_{s,p}\mathrm{Y}_{\mathrm{s,p}}^{\mathrm{i}}\right)}{\mathrm{dt}} = -\omega_{pyr}^{s}$$

Charcoal

$$\frac{d\left(\alpha_{s,p}\ \rho_{s,p}\mathrm{Y}_{\mathrm{s,p}}^{\mathrm{char}}\right)}{\mathrm{dt}} = \left(\upsilon_{char} - \upsilon_{soot}\right)\omega_{pyr}^{s} - \left(\frac{\upsilon_{ash}}{\upsilon_{char}} + 1\right)\omega_{char}^{s}$$

Mass balance in the solid phase

Global mass balance

$$\frac{d\left(\alpha_{s,p}\ \rho_{\mathrm{s,p}}\right)}{\mathrm{dt}} = -\sum_{\alpha} M_{s,p,\alpha}$$

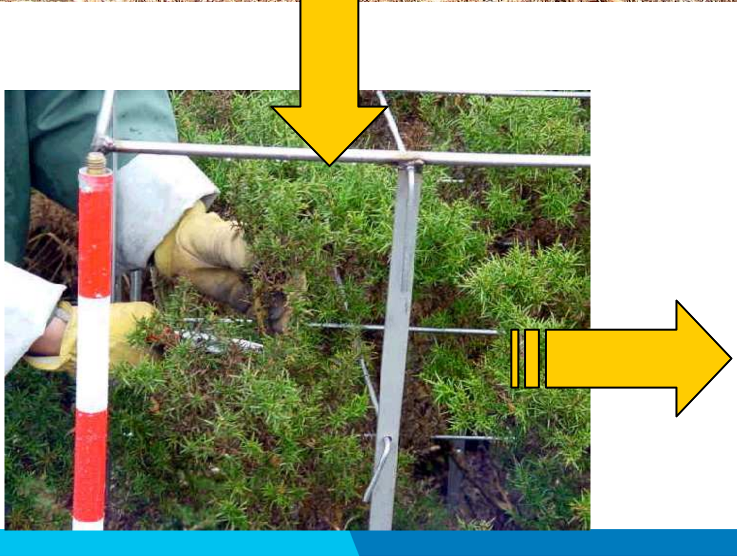
Volume balance

$$\frac{d\alpha_{s,p}}{\mathrm{dt}} = -\frac{1}{\rho_{\mathrm{s,p}}}\,\omega^{s}_{char}$$

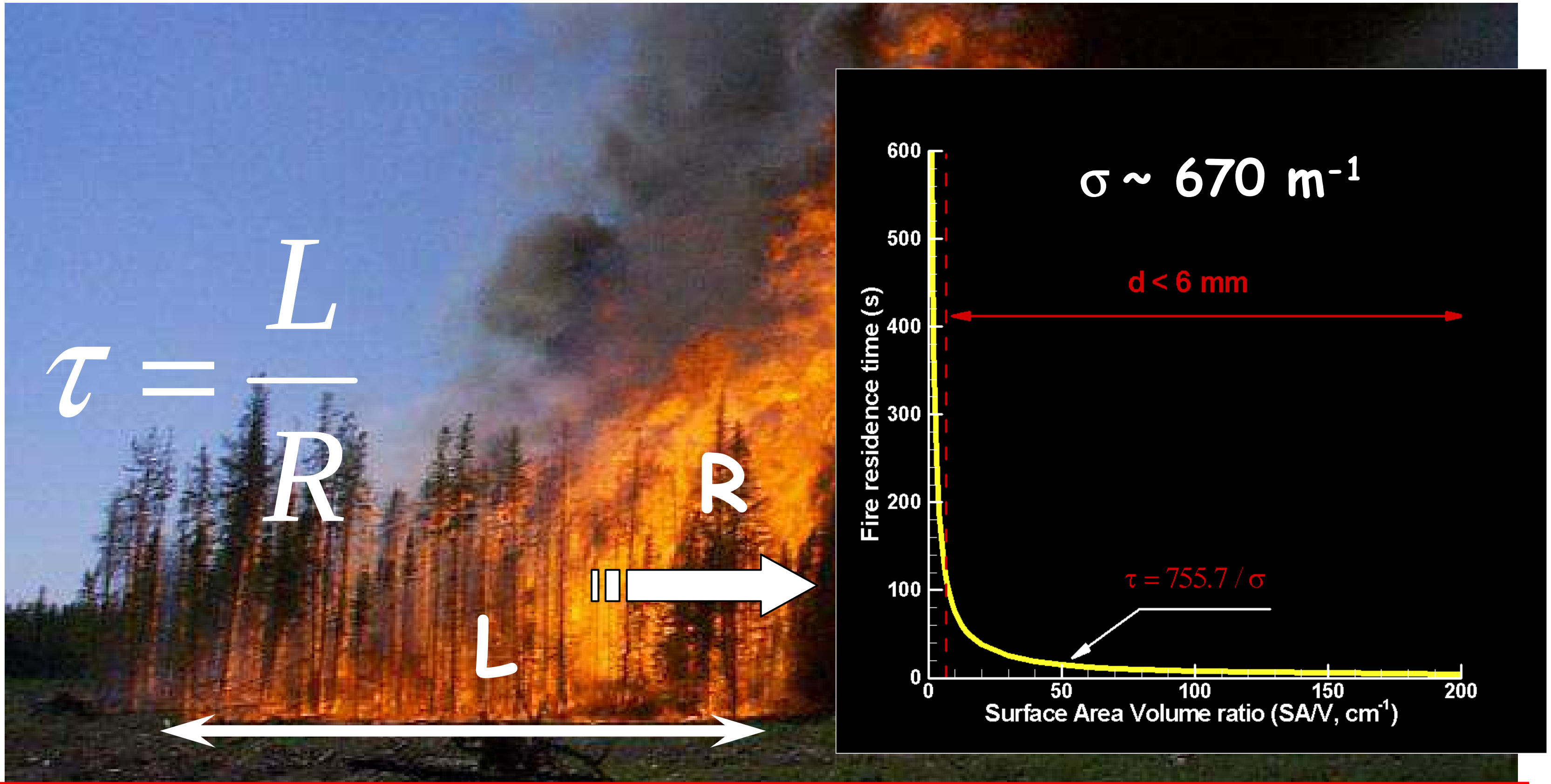
Physical description of the vegetation layer

Physical properties

- Density
- Volume fraction
- Surface Area/Volume (SA/V)
- Fuel moisture content (FMC)



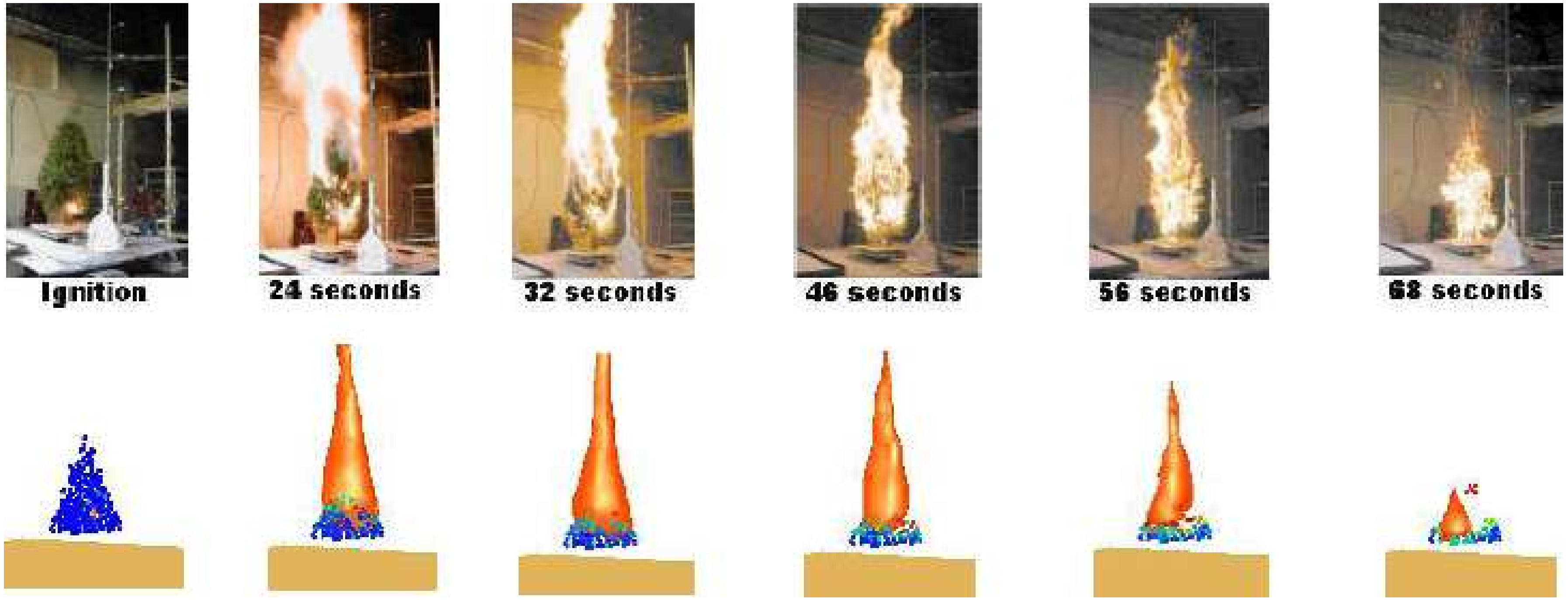
Fire residence time



$$\tau = \frac{L}{R}$$

σ (m^{-1})	600	2000	5000	10000	20000
τ (s)	125	37	15	7	3

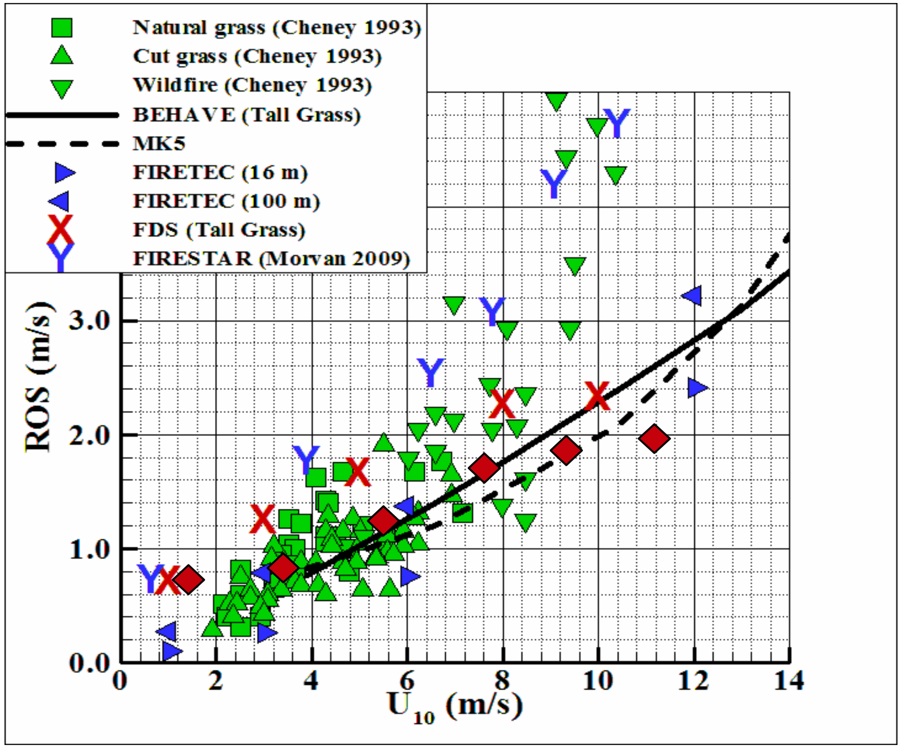
New tools for simulating wildfires
WFDS: Wildland Fire Dynamic Simulator



Mell & al Combust. Flame 2009
US Foret Services Pacific Wildland Fire Sciences Lab. (Seatle)
NIST National Fire Research Lab. (Gaithersburg)

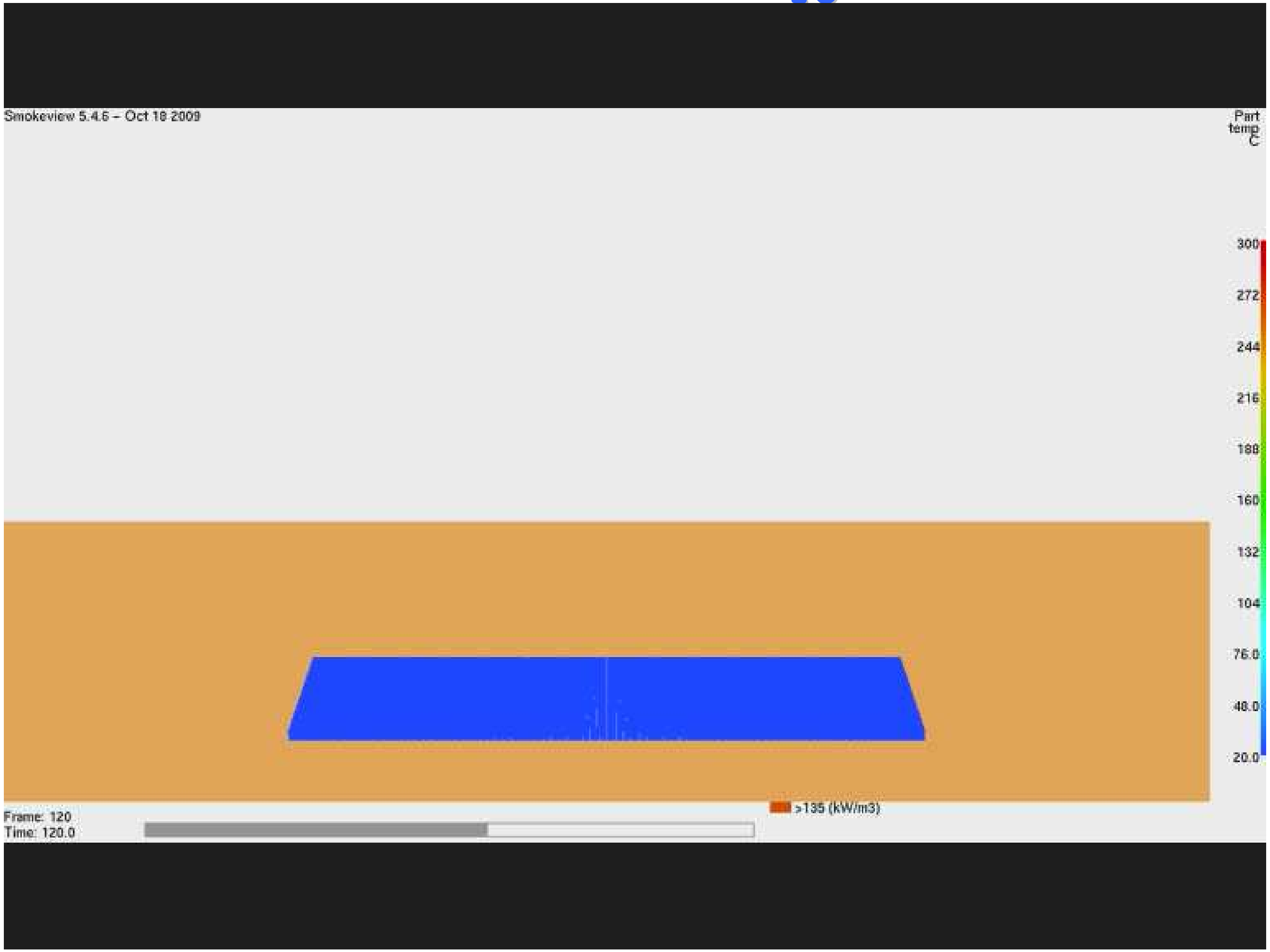
Large scale experimental fires (grassland, CSIRO, Australia)

Plot: 20 m x 50 m (+ safety band)
Mesh > 20 Millions cells



Cheney & al Int. J. Wildland Fire 1998
Morvan & al Fire Safety Journal 2009

Fire in grassland: 3D simulation (WFDS) Plot: 50m x 20m U_{10} = 1 m/s

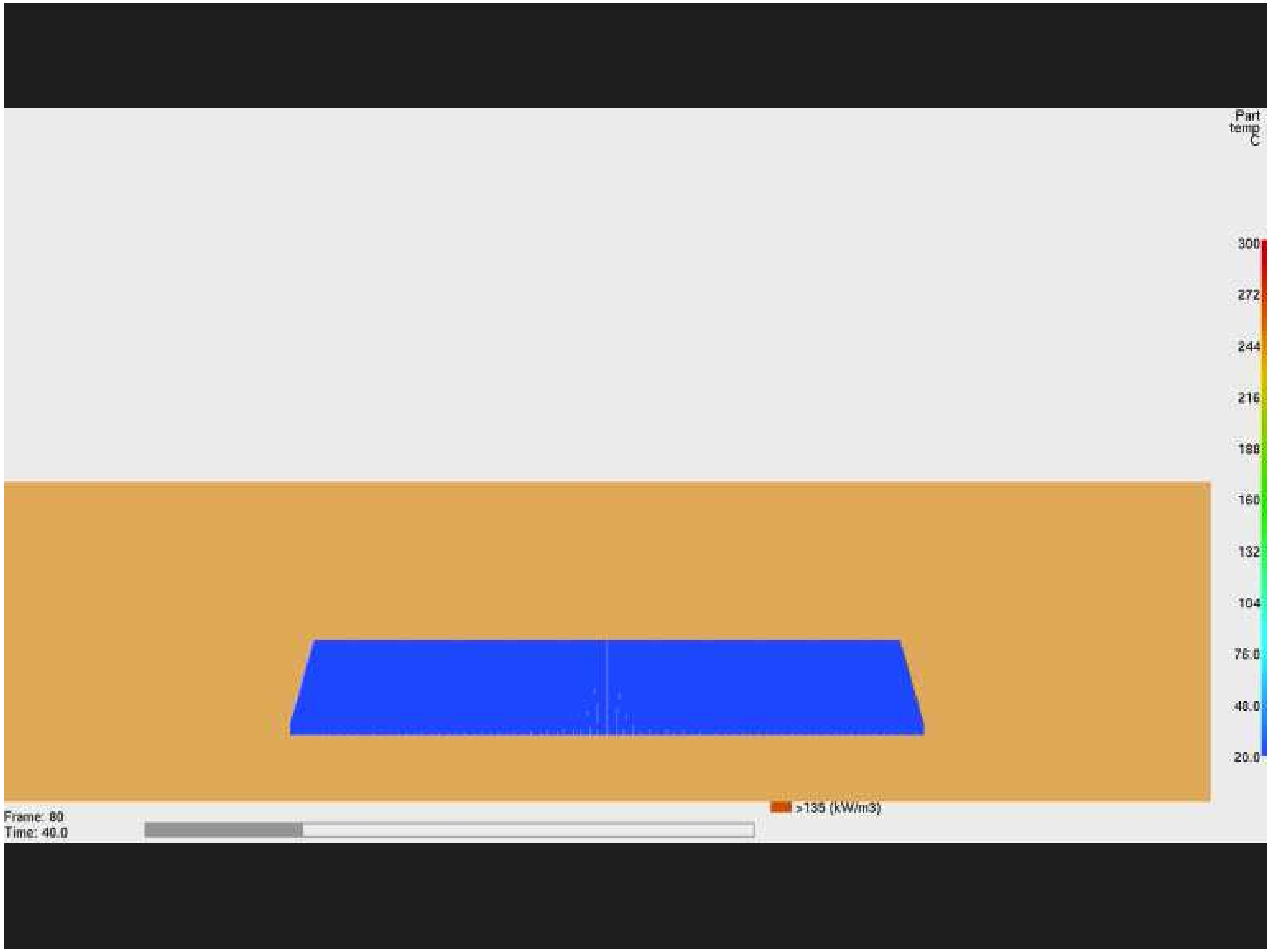


Smokeview 5.4.6 – Oct 18 2009

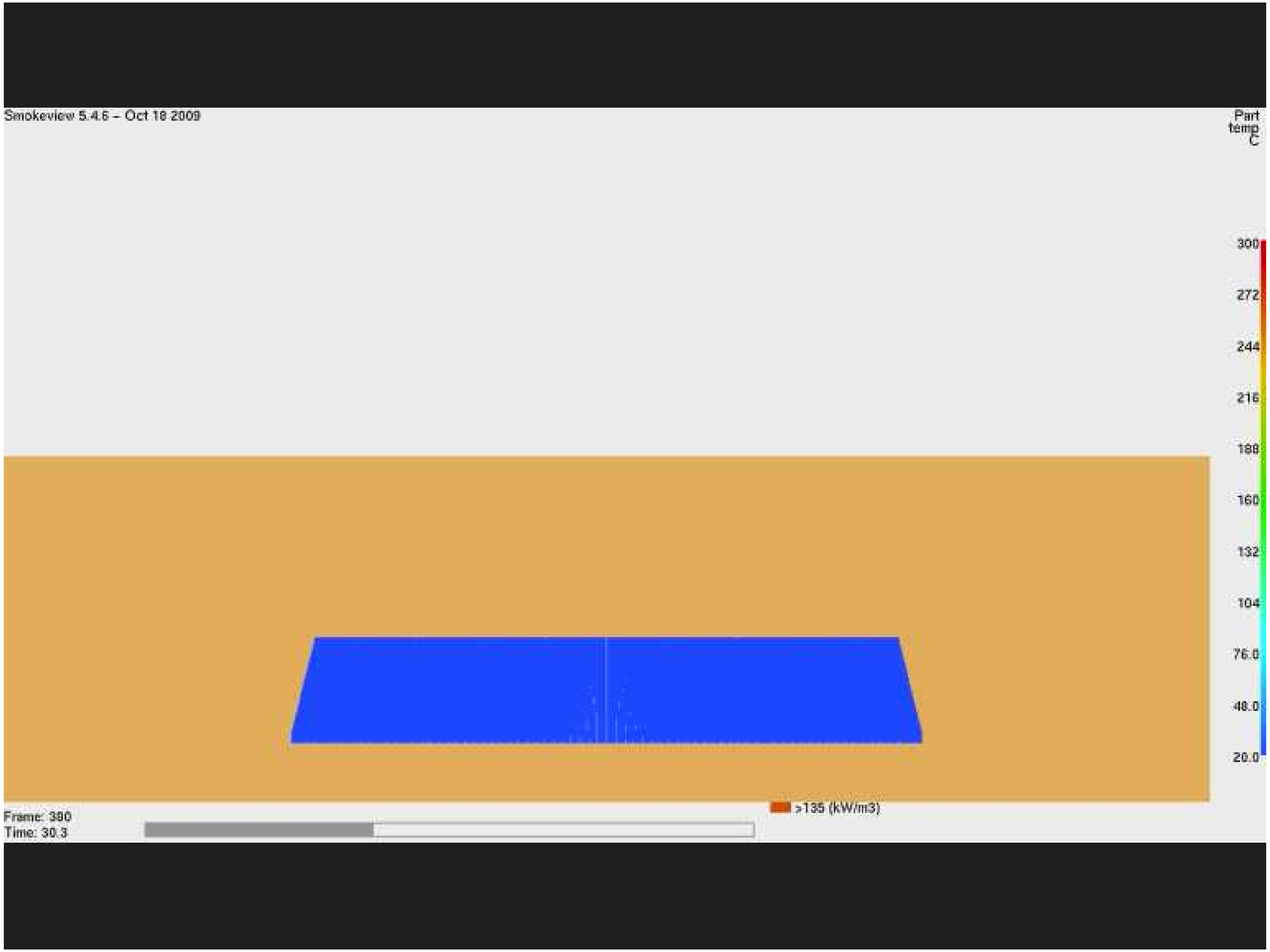
Frame: 120
Time: 120.0

Fire in grassland: 3D simulation (WFDS)

Plot: 50m x 20m U_{10} = 3 m/s

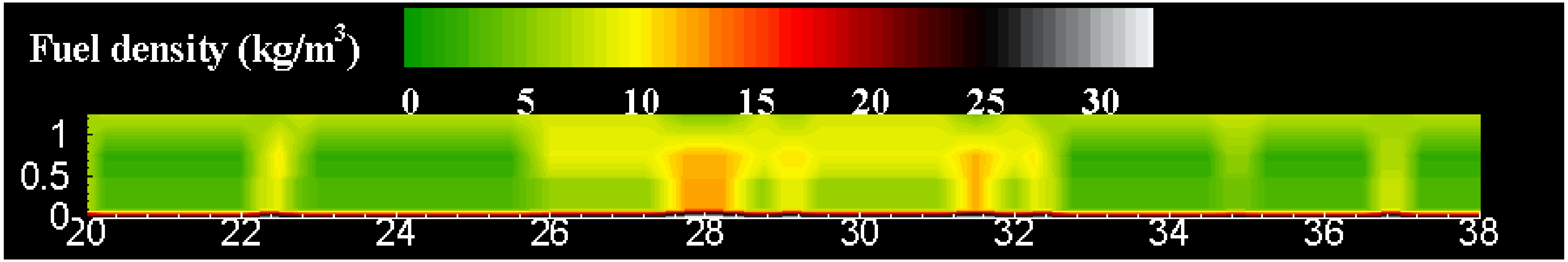


Fire in grassland: 3D simulation (WFDS)
Plot: 50m x 20m U_{10} = 10 m/s



Experimental fire in shrubland
(EU Firestar project,Galicia-Spain)

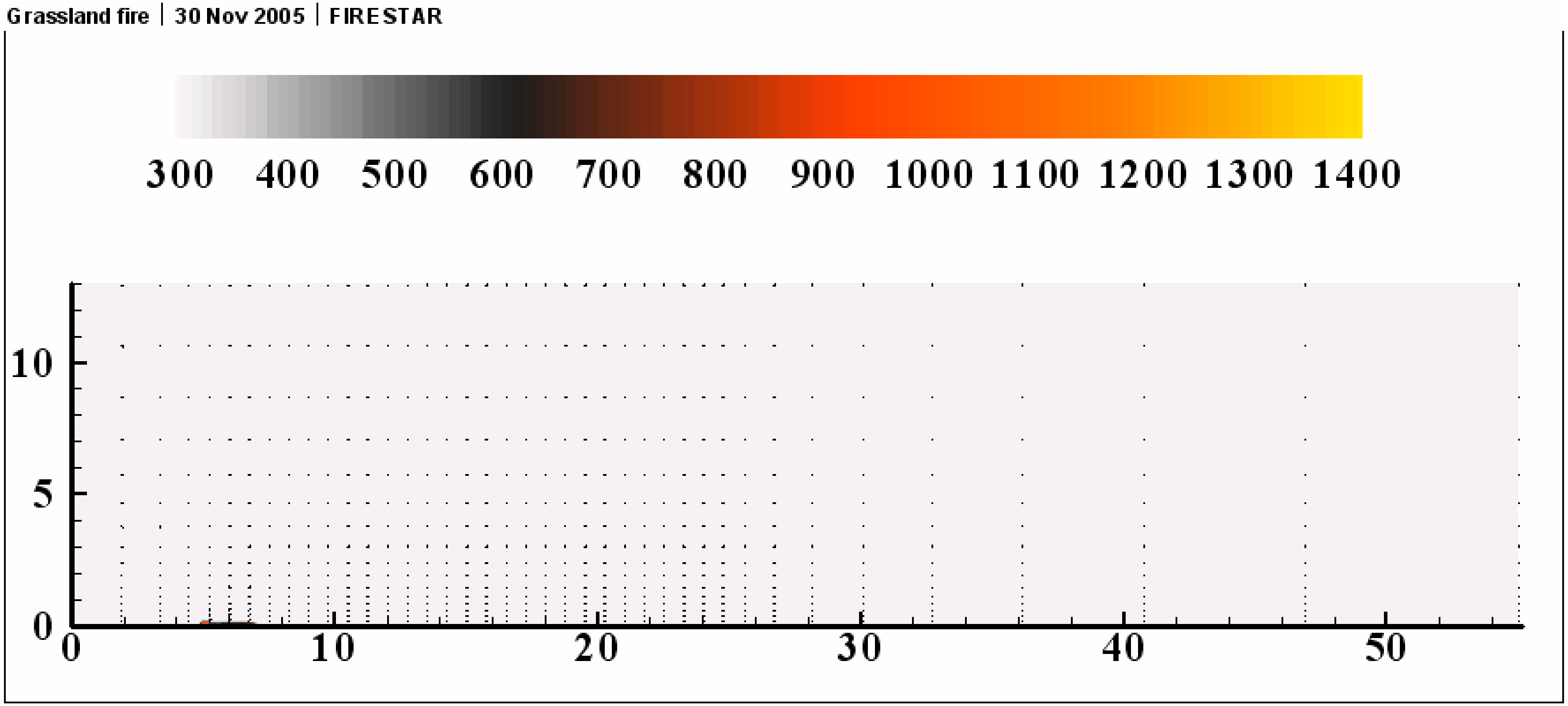
Experimental fire in shrubland
(EU Firestar project,Galicia-Spain)



- **Fuel: *Ulex (Europaeus, Minor),***
- **Fuel families=14**
- **FMC:**

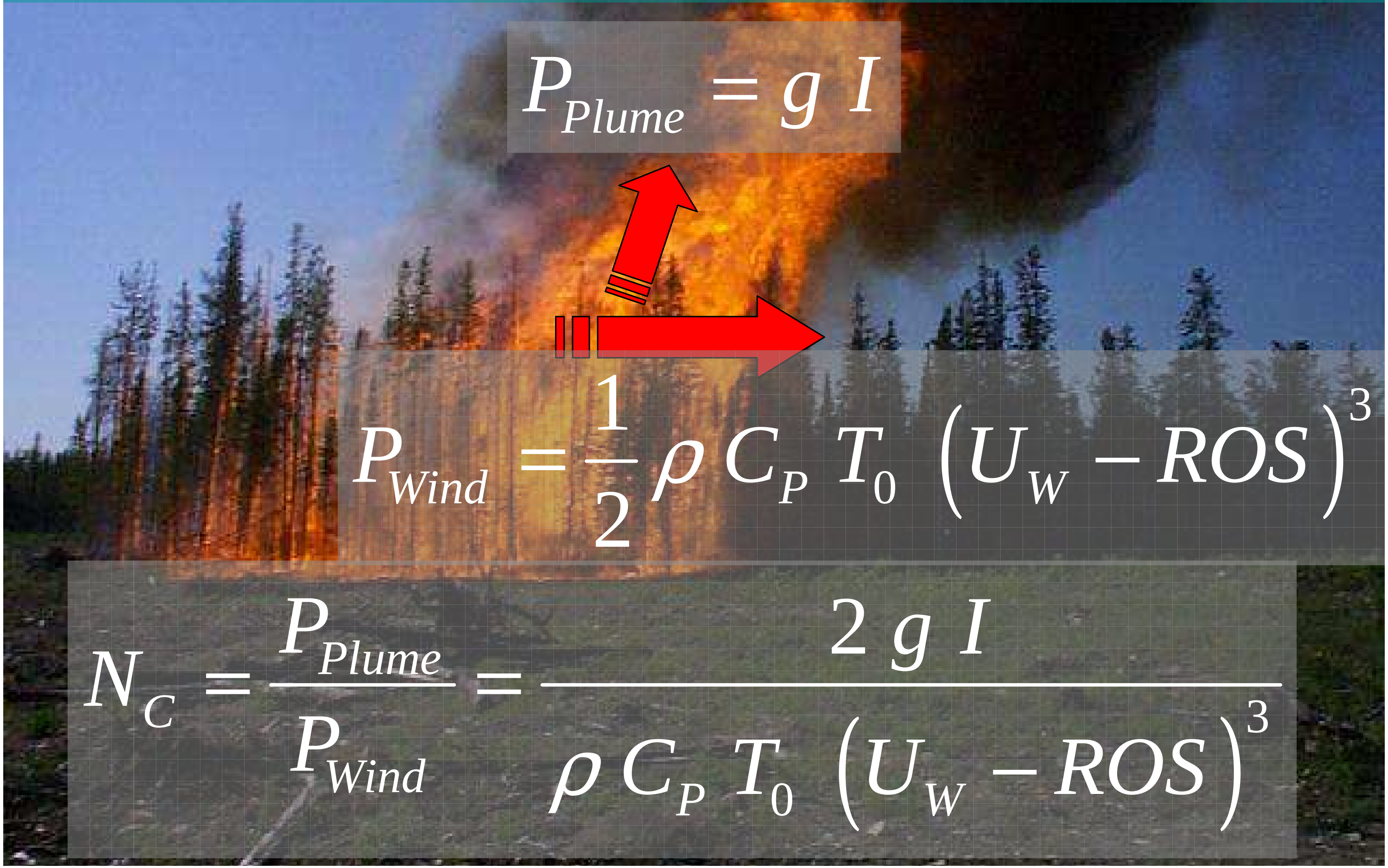
  108-150 % (vivant), 10-32% (mort)
- **Fuel depth = 1.25 m,**
- **Wind : 5.7 m/s (z=10 m),**
- **Slope : 5°**

Experimental fire in shrubland
(EU Firestar project,Galicia-Spain)



- **Experiment: ROS = 0.273 m/s**
- **Simulation : ROS = 0.248 m/s**

Wildfire propagation regimes
Convective Byram number

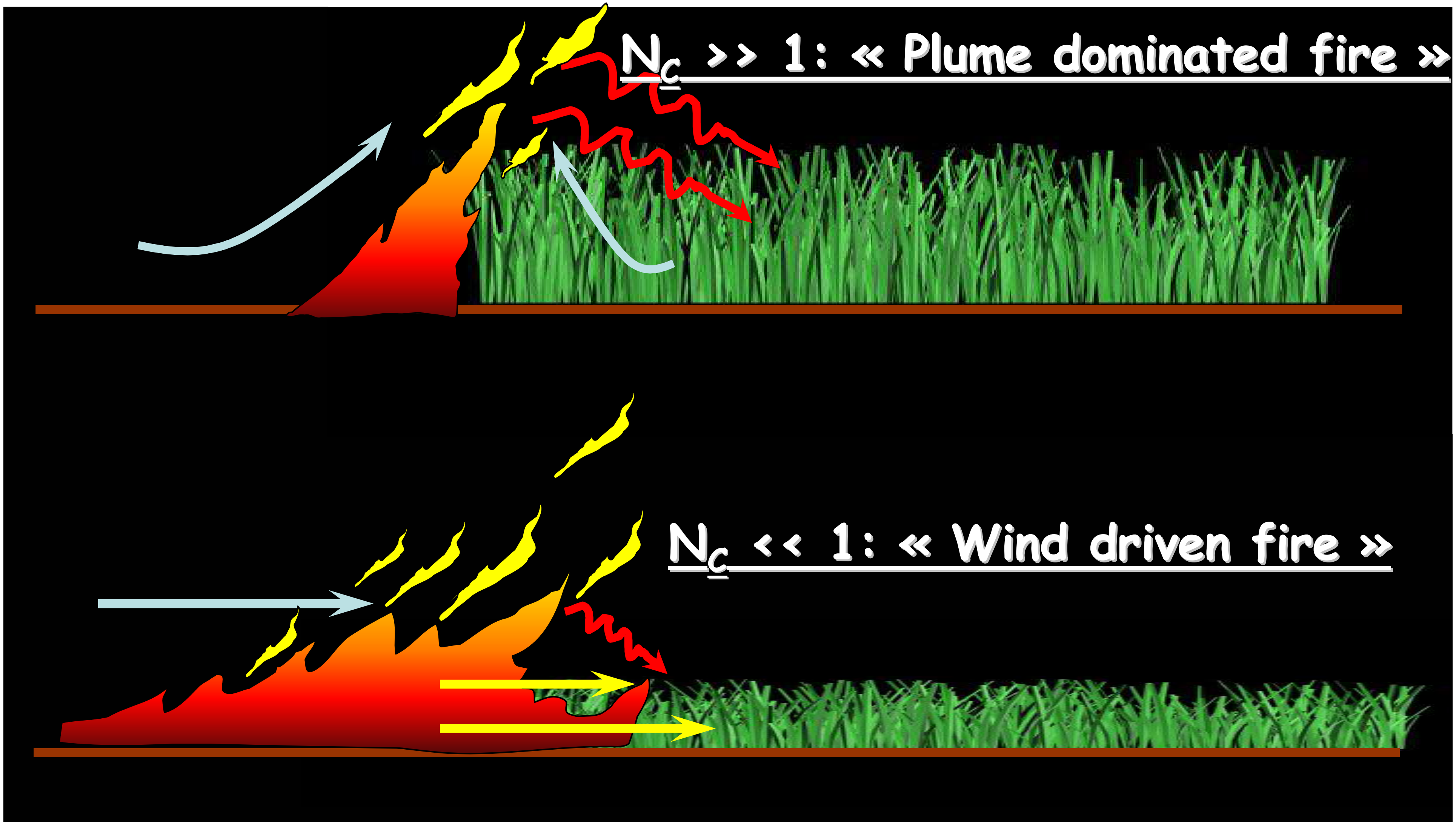


$$P_{Plume} = g\, I$$

$$P_{Wind} = \frac{1}{2}\rho\, C_P\, T_0\, \left(U_W - ROS\right)^3$$

$$N_C = \frac{P_{Plume}}{P_{Wind}} = \frac{2\, g\, I}{\rho\, C_P\, T_0\, \left(U_W - ROS\right)^3}$$

Wildfire propagation regimes

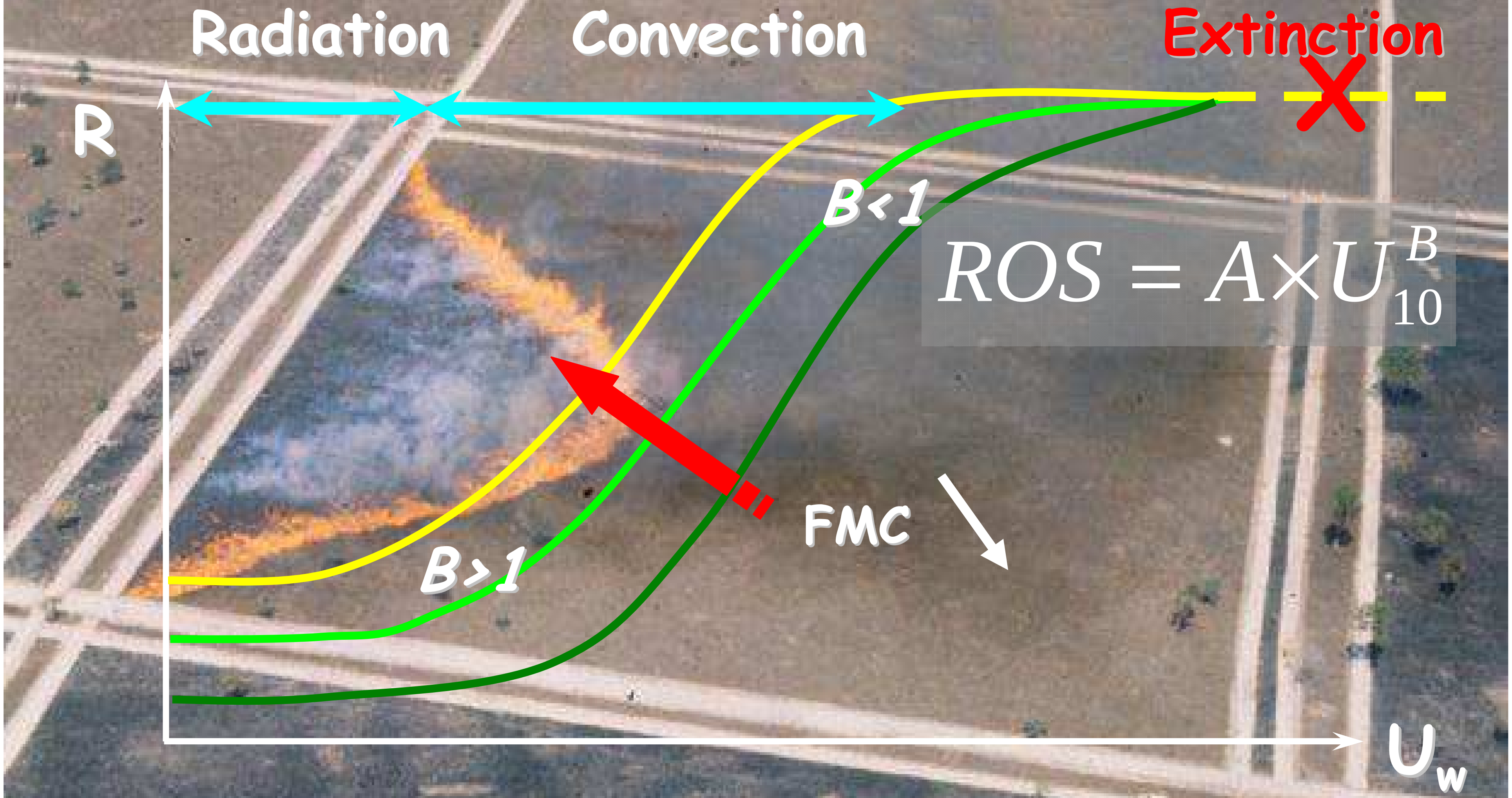


Wildfires classification

Surface fires
(wind driven)

Crown fires
(plume dominated)

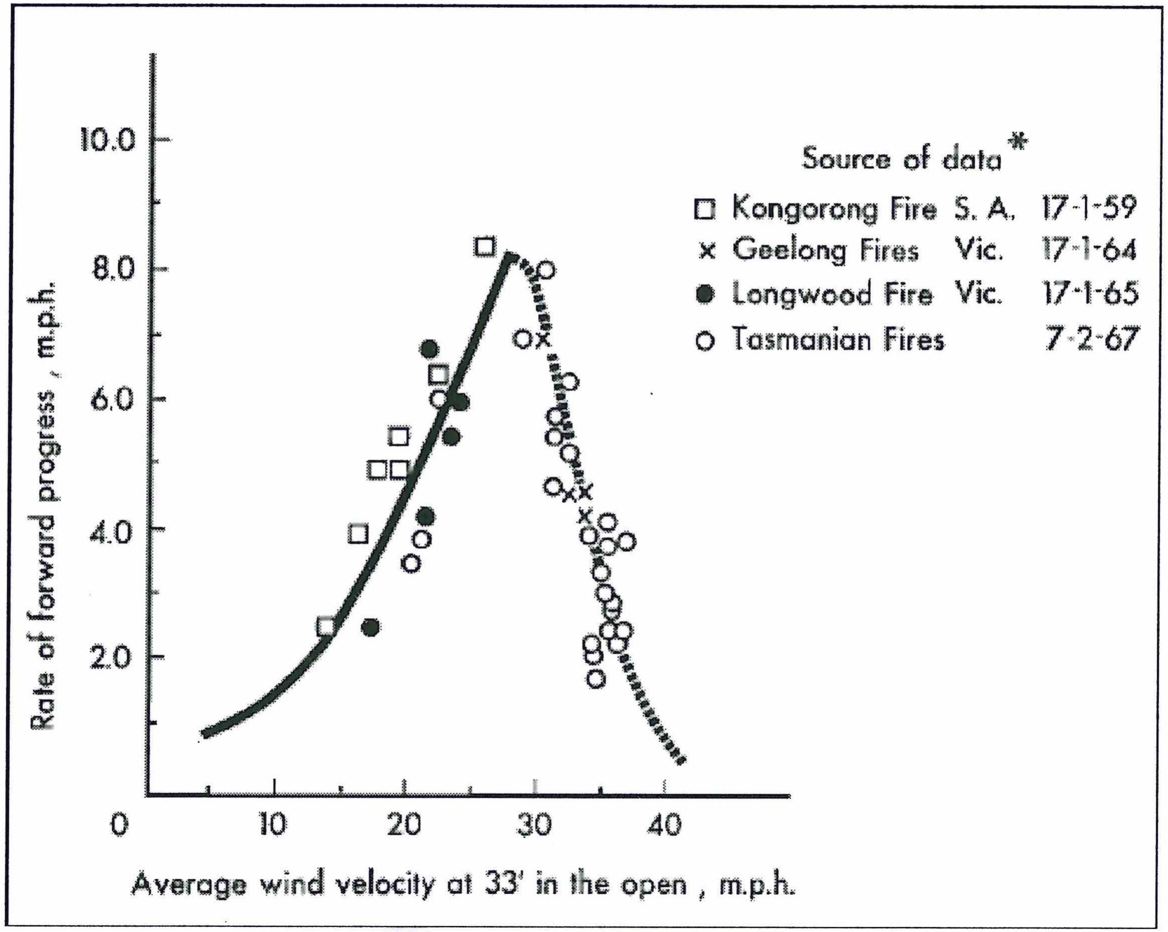
Regimes of propagation of surface fires



$$ROS = A \times U_{10}^{B}$$

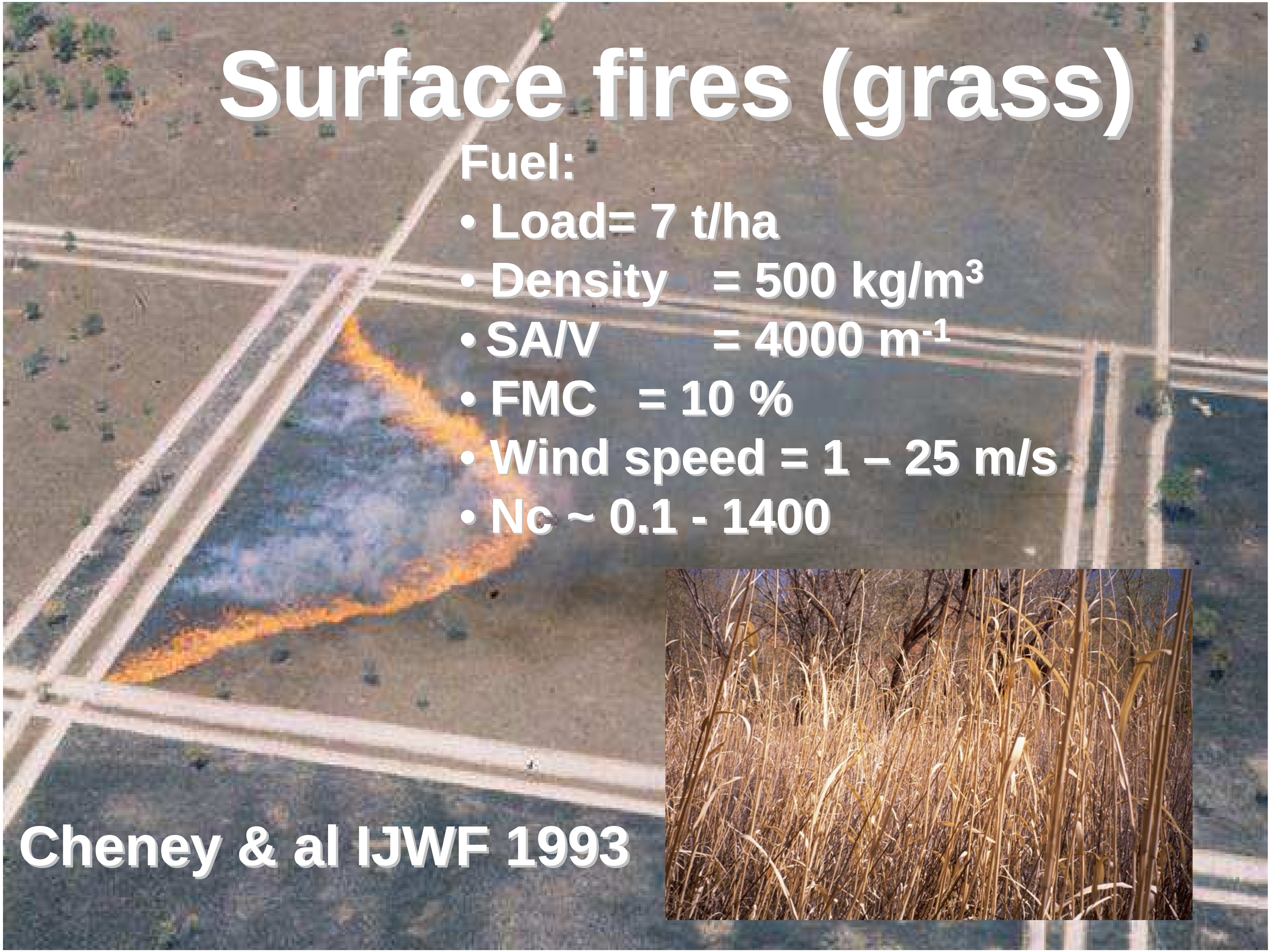
Fogarty & al Fire Tech. Transfer Note 1999

Rate of spread versus wind speed



McArthur 1969, Rothermel 1972

Surface fires (grass)

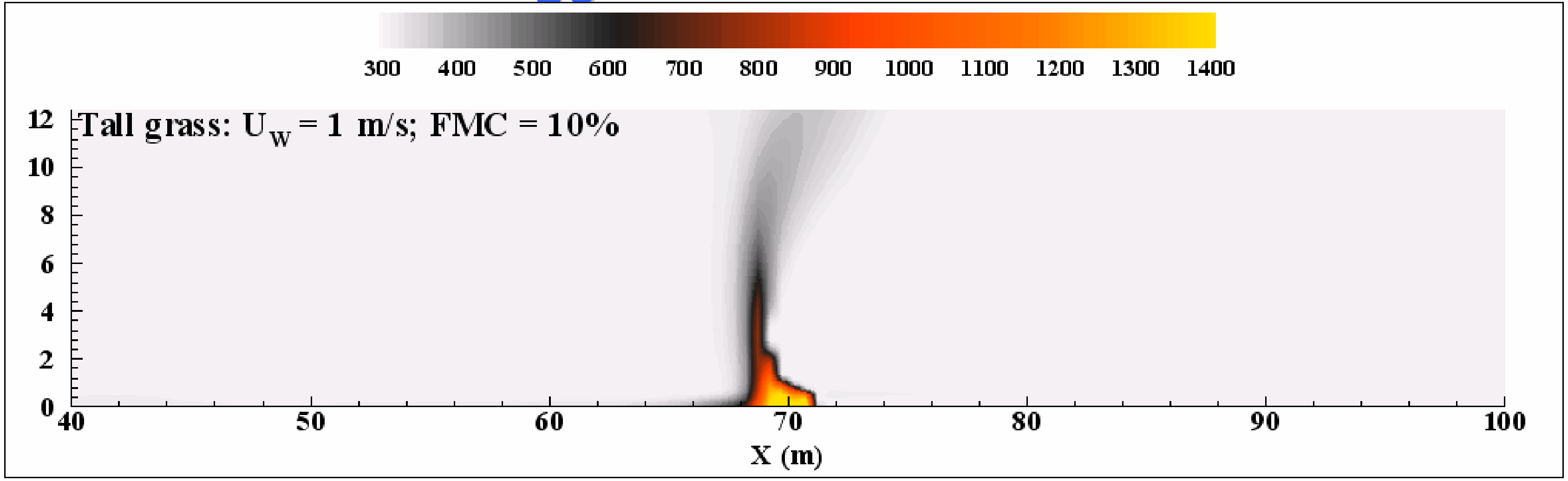


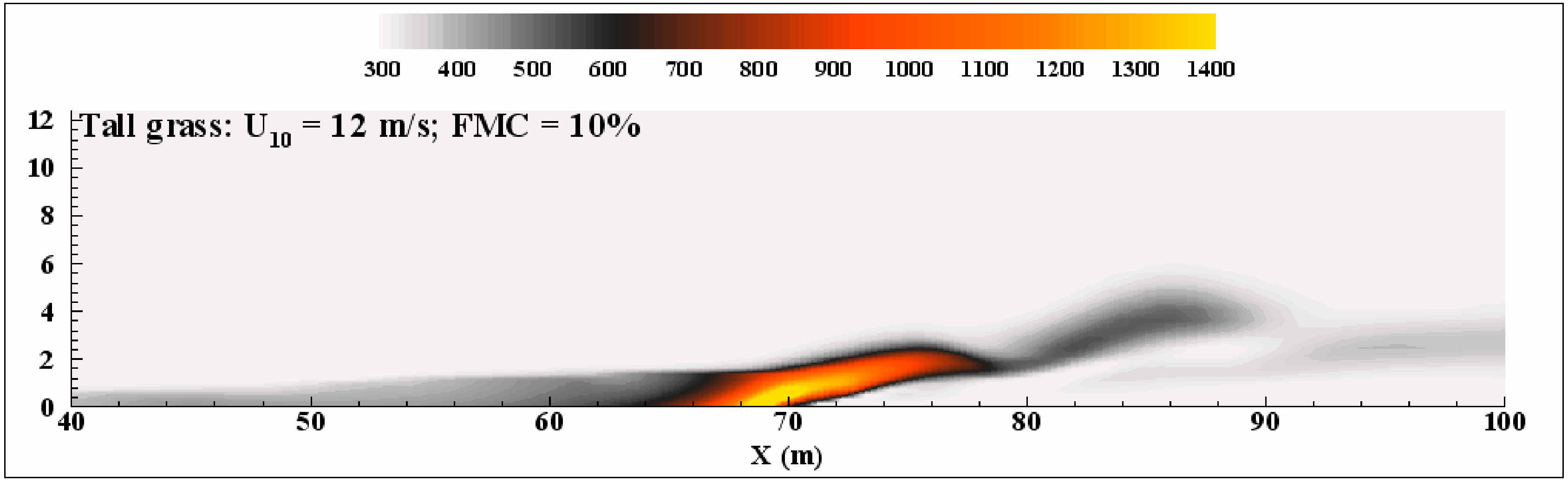
Fuel:

- Load= 7 t/ha
- Density = 500 kg/m^3
- SA/V = 4000 m^{-1}
- FMC = 10 %
- Wind speed = 1 – 25 m/s
- Nc ~ 0.1 - 1400

Cheney & al IJWF 1993

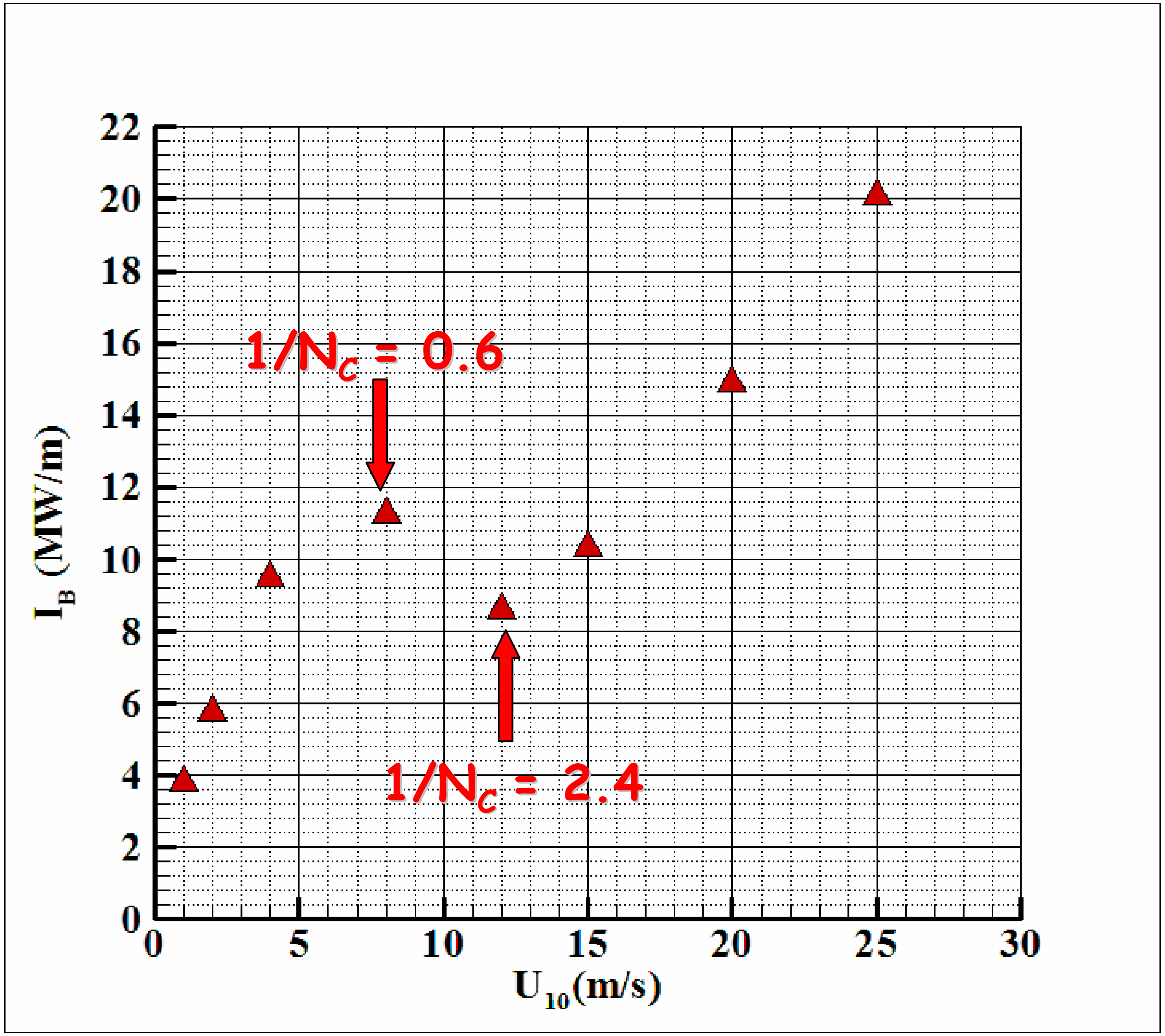
Grassland fires: temperature field for U_{10} = 1 and 12 m/s





(Morvan & al FSJ 2009, Morvan CST 2014)

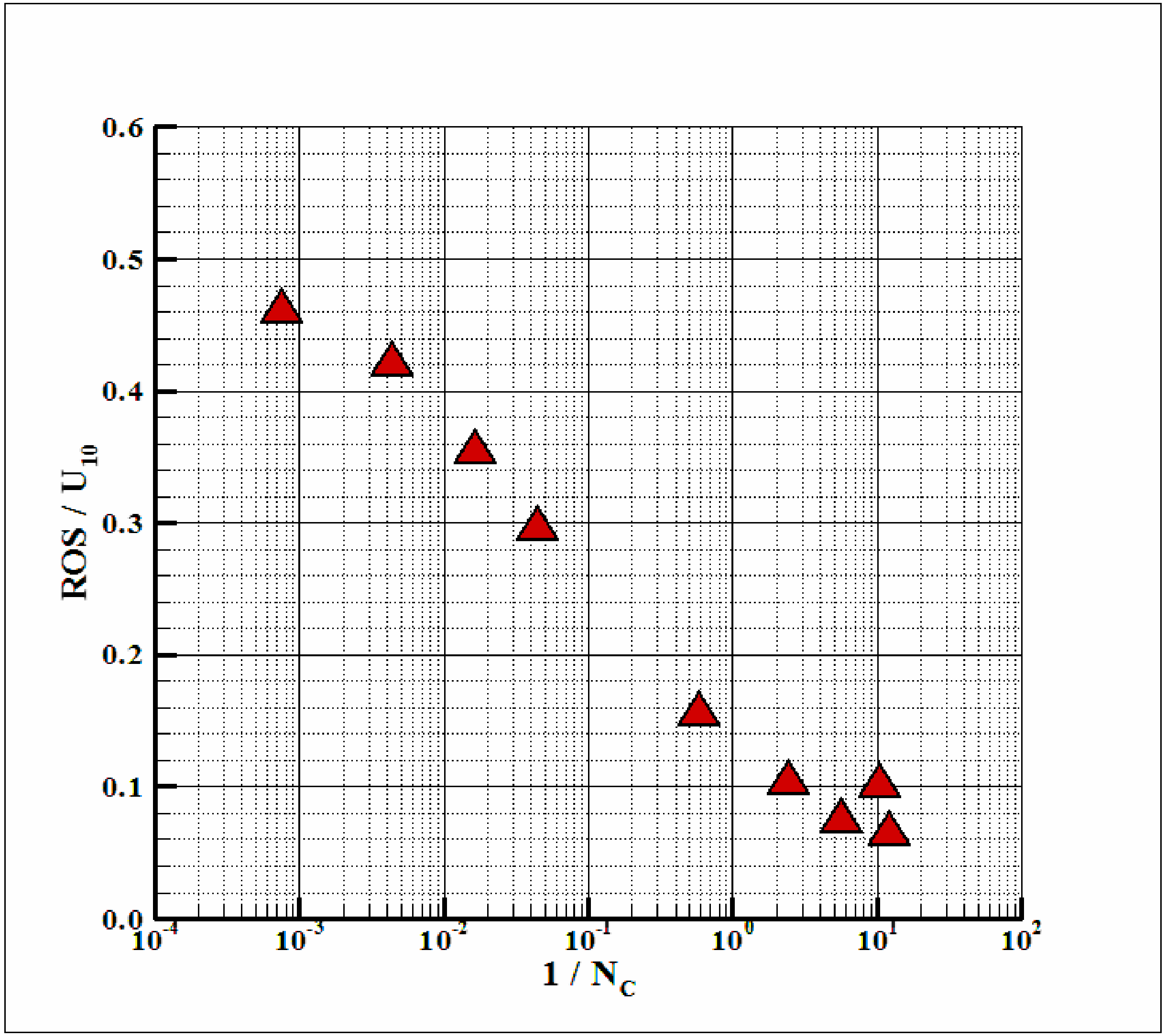
Fireline intensity versus wind speed



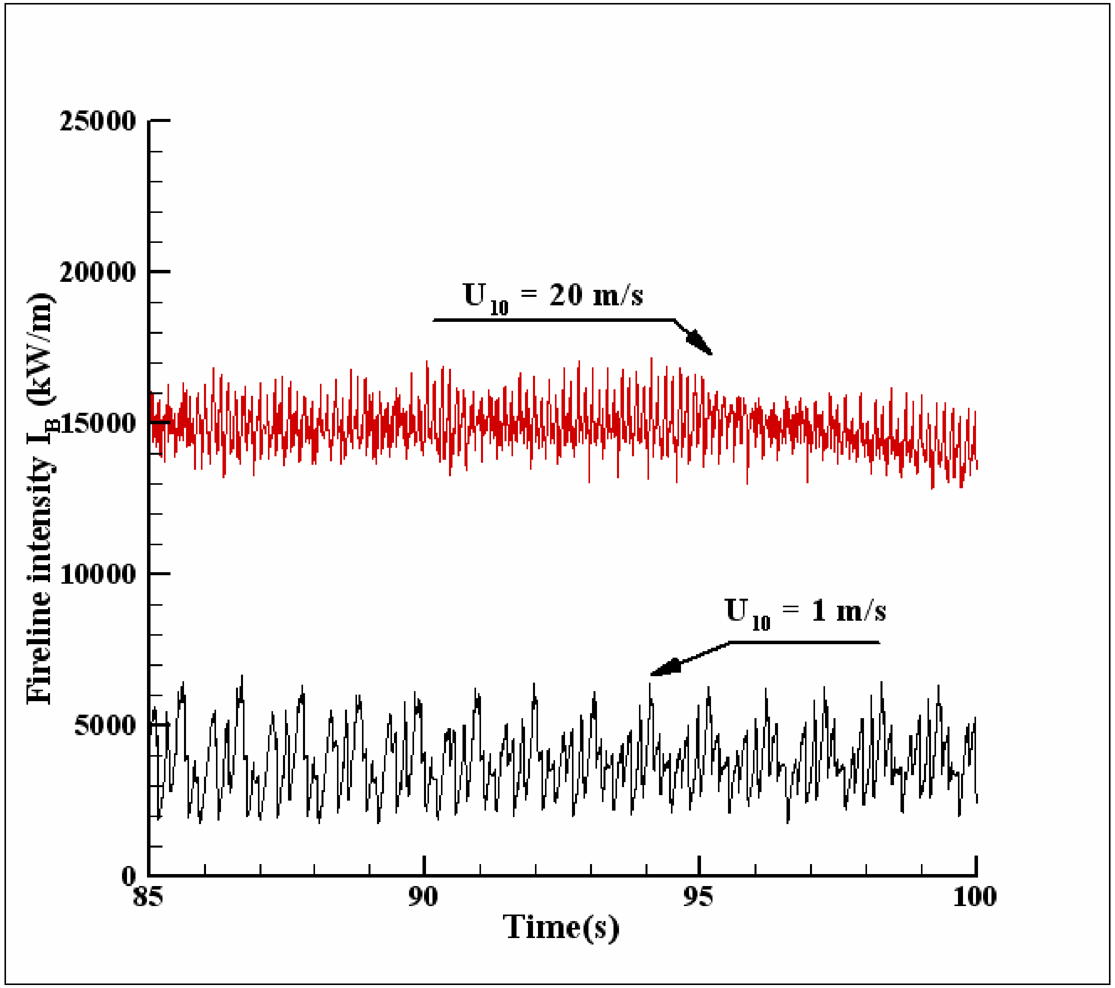
$1/N_c$ = 0.6

$1/N_c$ = 2.4

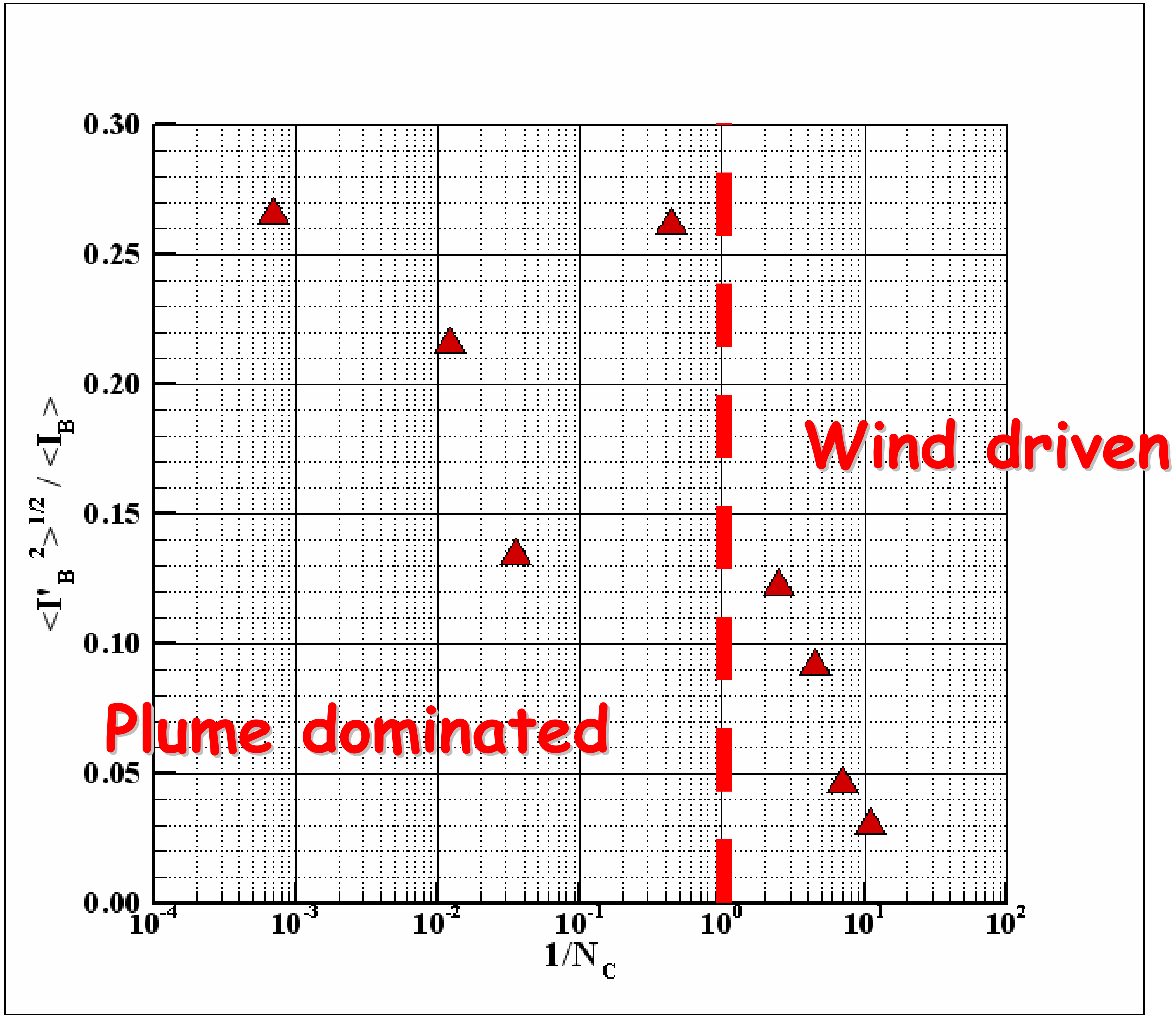
Convective Byram number / regime of propagation



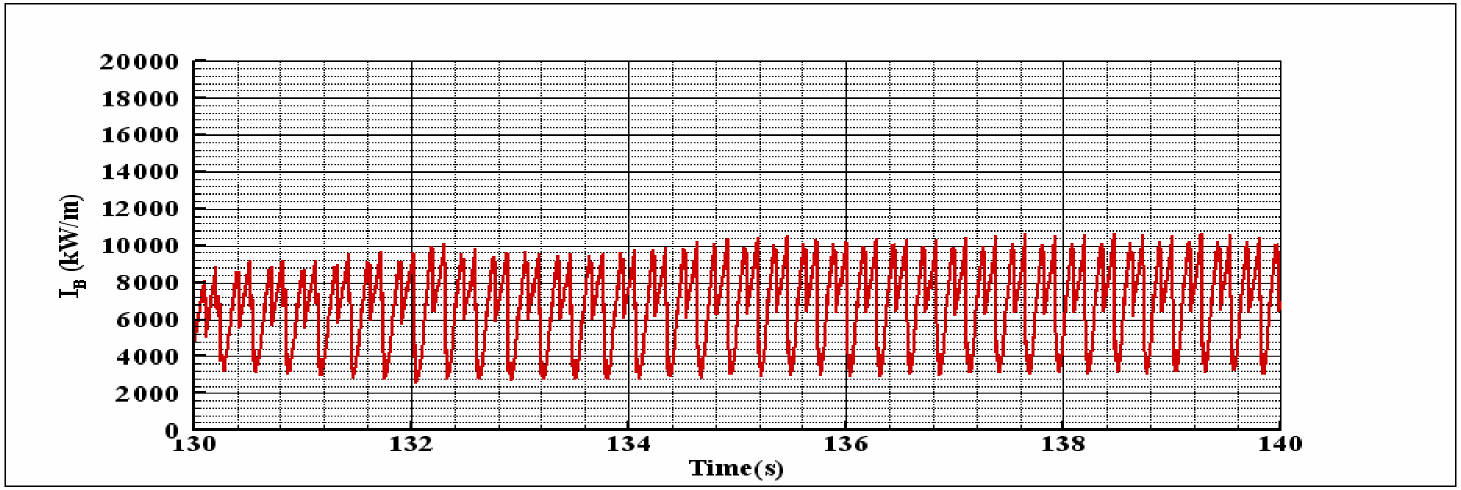
Time evolution of the fireline intensity



Fireline intensity (normalized standard deviation) versus convective Byram number

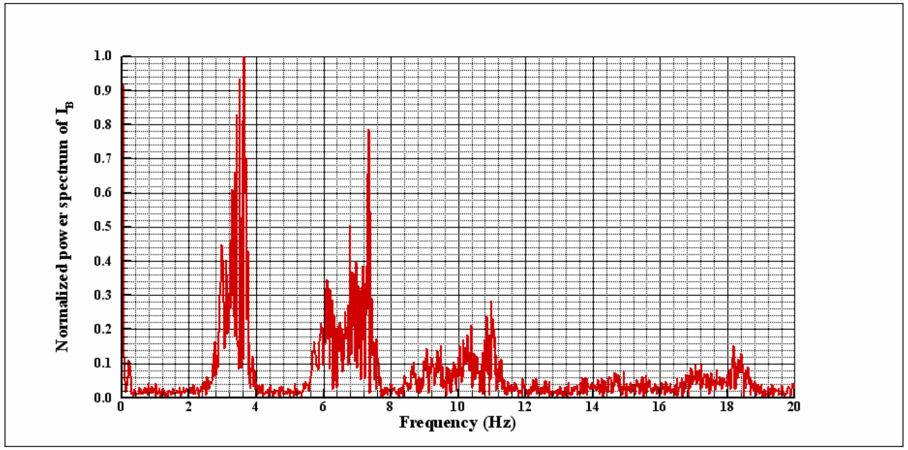


Time history and spectrum of fire intensity (U_{10} = 2 m/s)



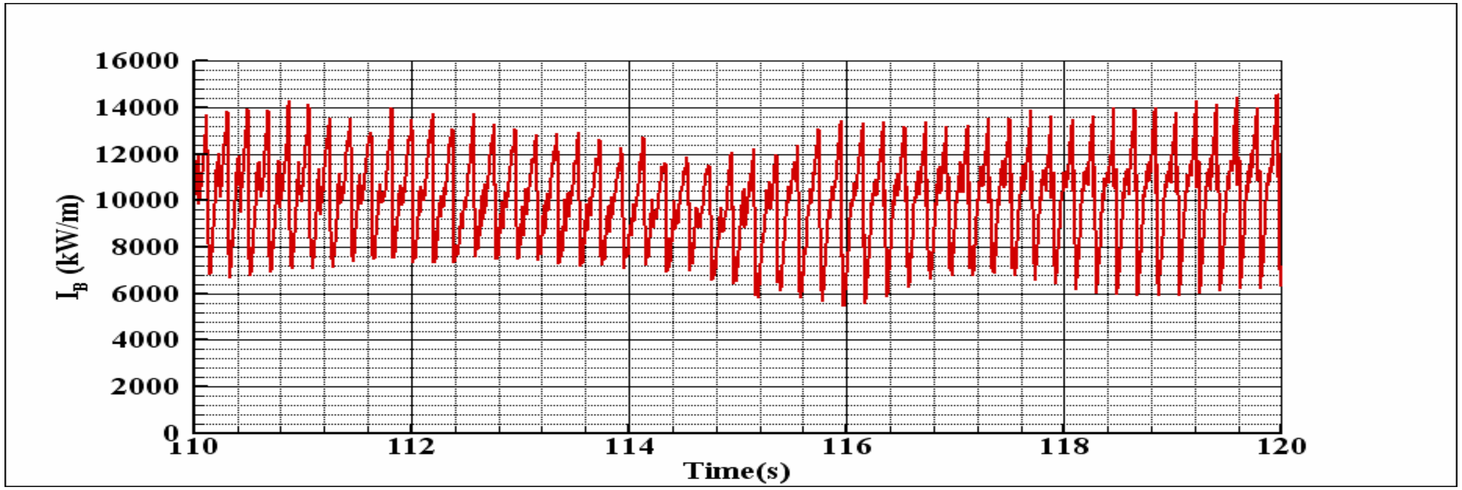
$$f_{KH} = 0.26\ Hz$$

$$f_B = 1.3\ Hz$$



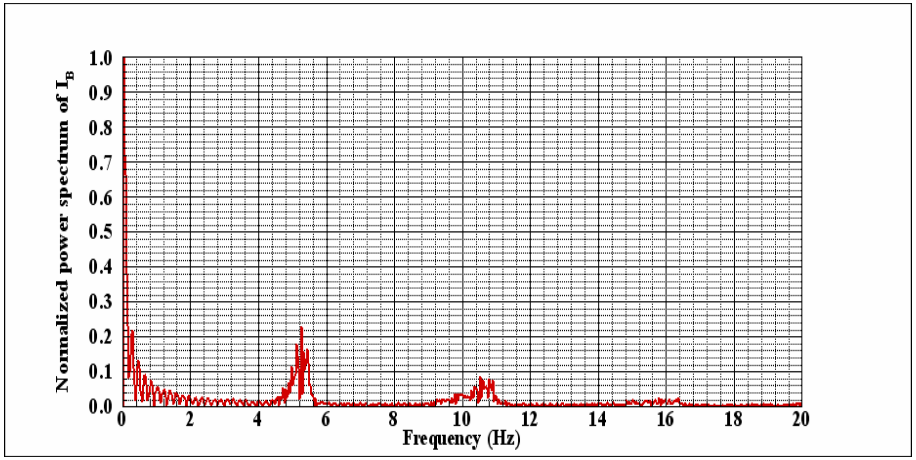
$$f = 3.4\ Hz$$

Time history and spectrum of fire intensity (U_{10} = 20 m/s)



$$f_{KH} = 2.66\ Hz$$

$$f_B = 0.66\ Hz$$

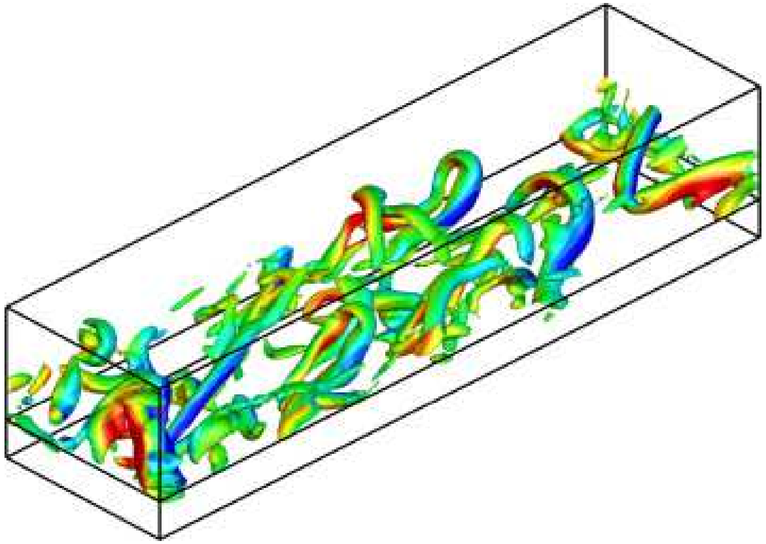


$$f = 5.5\ Hz$$

Instabilities associated with a fire front

$$S_t^{KH} = \frac{f_{KH} H_{Fuel}}{U_{10}} = 0.093$$

$$f_{KH} \nearrow \quad if \quad U_H \nearrow$$

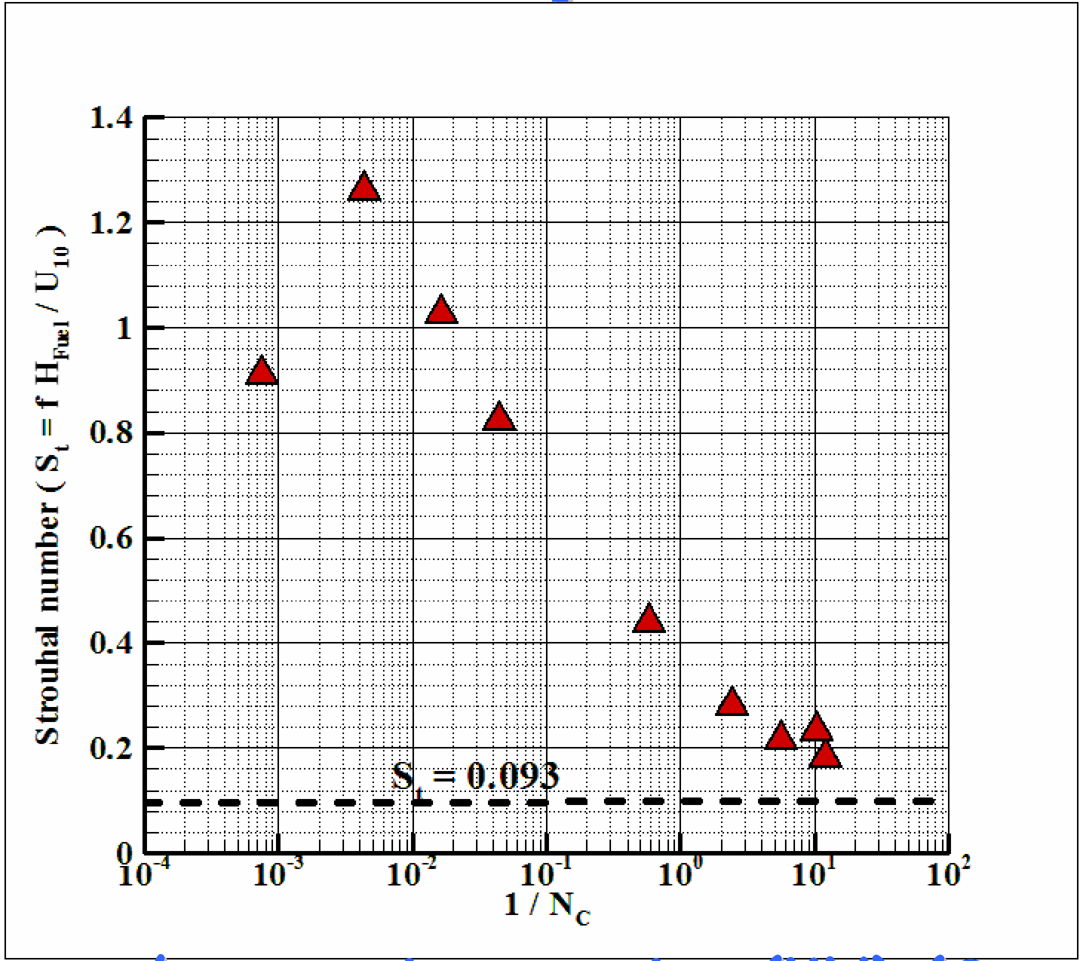


$$S_t^{B} = f_B \sqrt{\frac{D_{Fire}}{g}} \approx 0.5$$

$$D_{Fire} \nearrow if \; U_H \nearrow \Rightarrow f_B \searrow$$

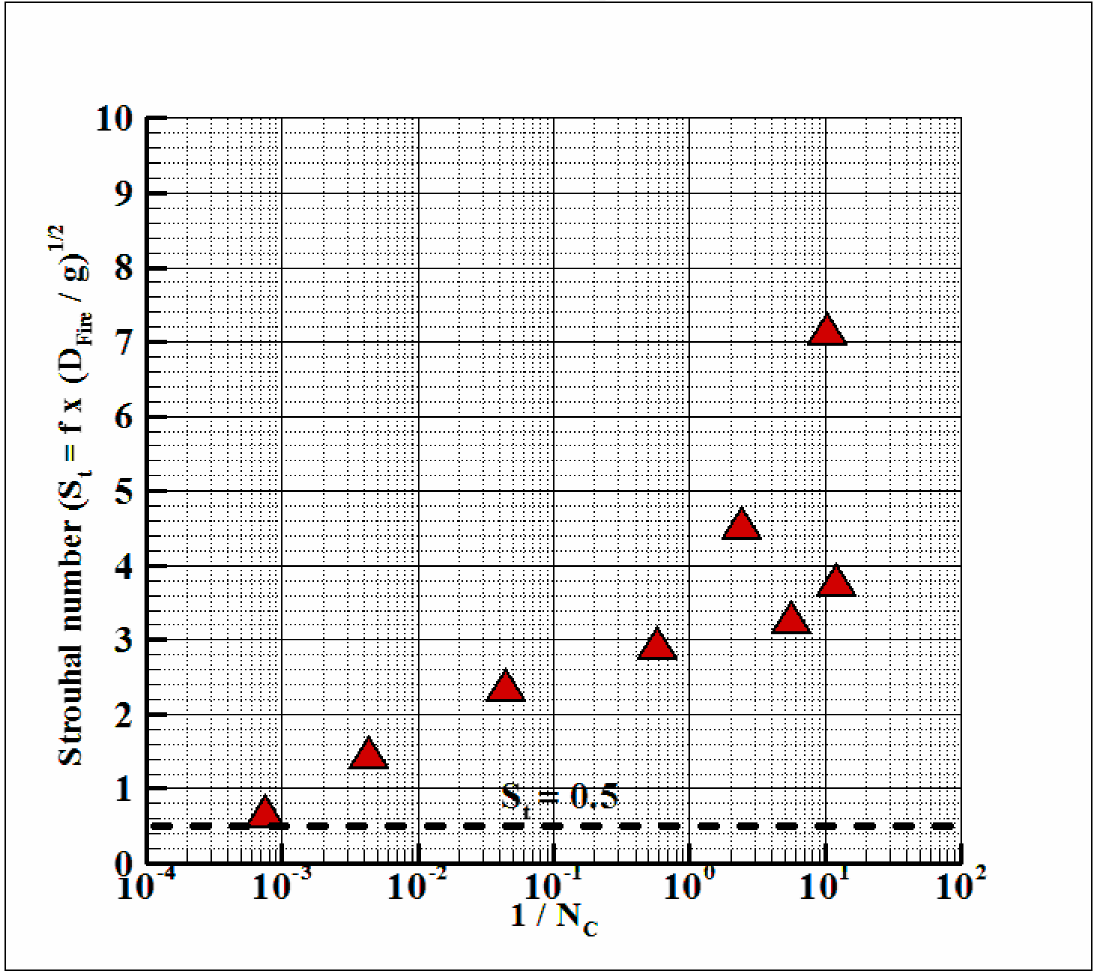

Rudy Trujillo/USFS

Strouhal number (wind scale) versus convective Byram number



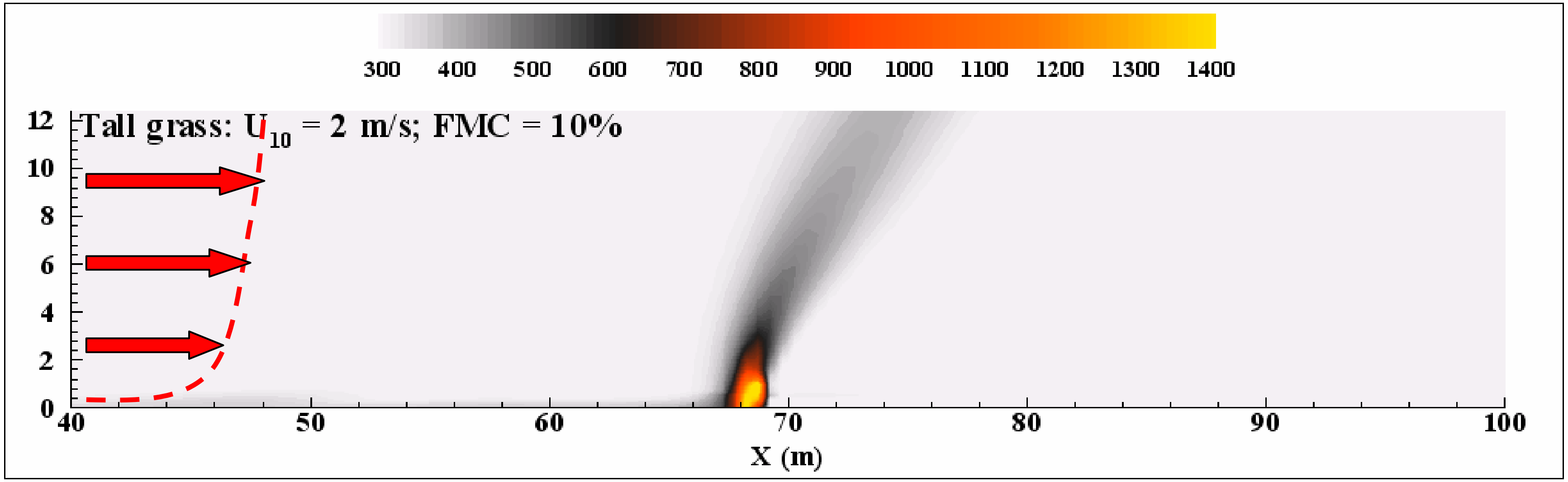
Turbulence/canopy interaction (KH) (St = 0.093)
(streamwise direction)

Strouhal number (plume scale) versus convective Byram number



Pool fire (St = 0.5)

Effect of an unsteady (sinusoidal) inlet wind flow

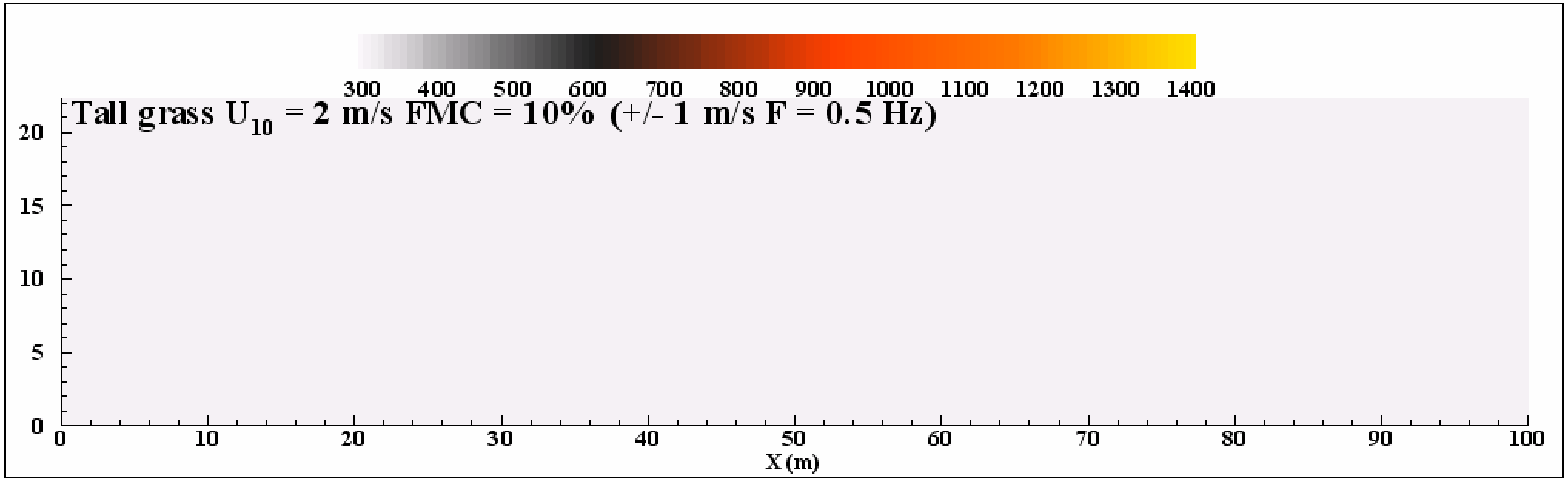


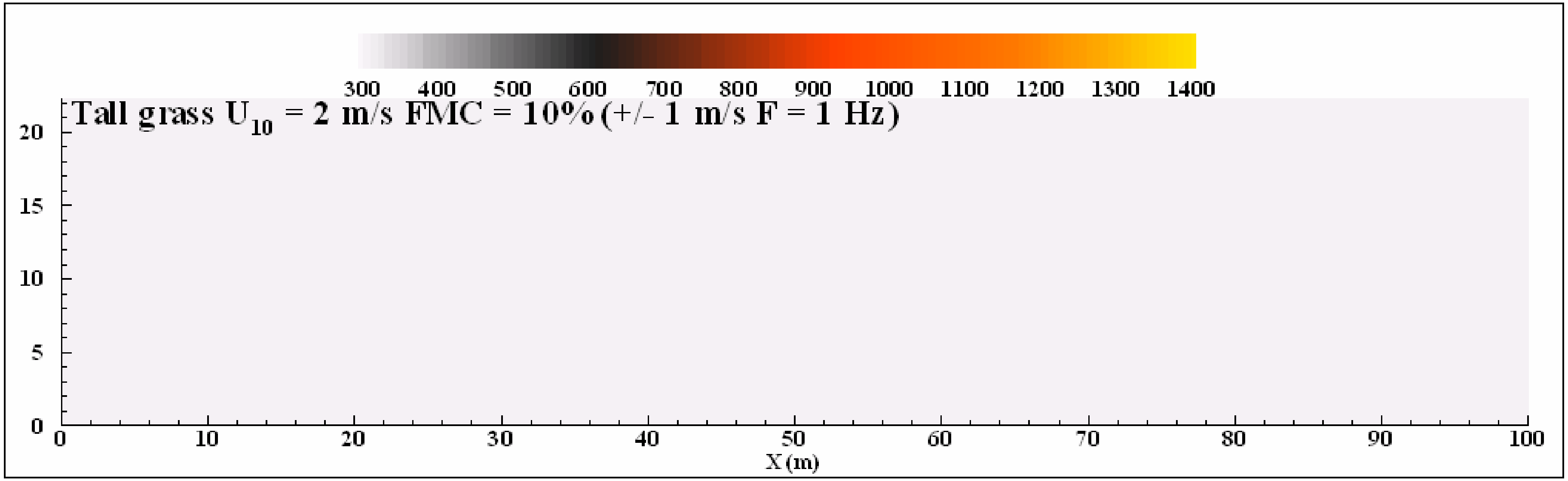
$$U_X = A \times U_{10} \times Ln\left(\frac{z+z_0}{z_0}\right) + \Delta U_{10}\sin\left(2\pi \times f \times t\right)$$

$$U_{10} = 2\,m/s \quad \Delta U_{10} = 1\,m/s \quad f = 0-3\,Hz \quad z_0 = 0.01\,m$$

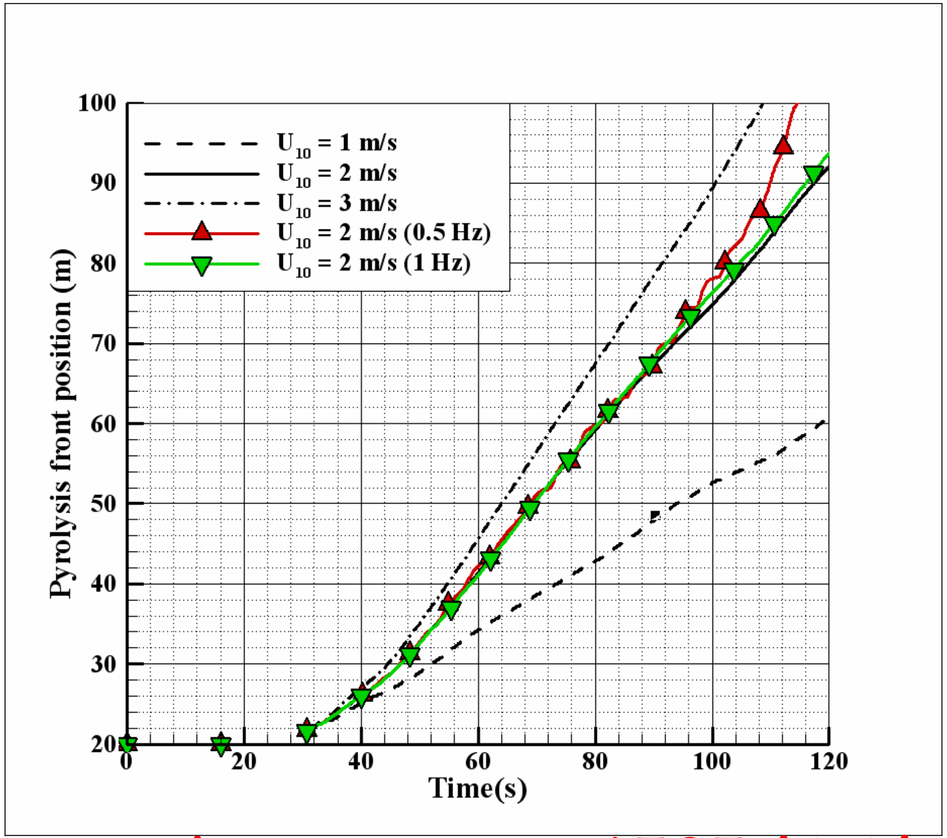
Pitts Prog. Energy Combust. Sci. 1991
Morvan Combust. Sc. Tech. 2014

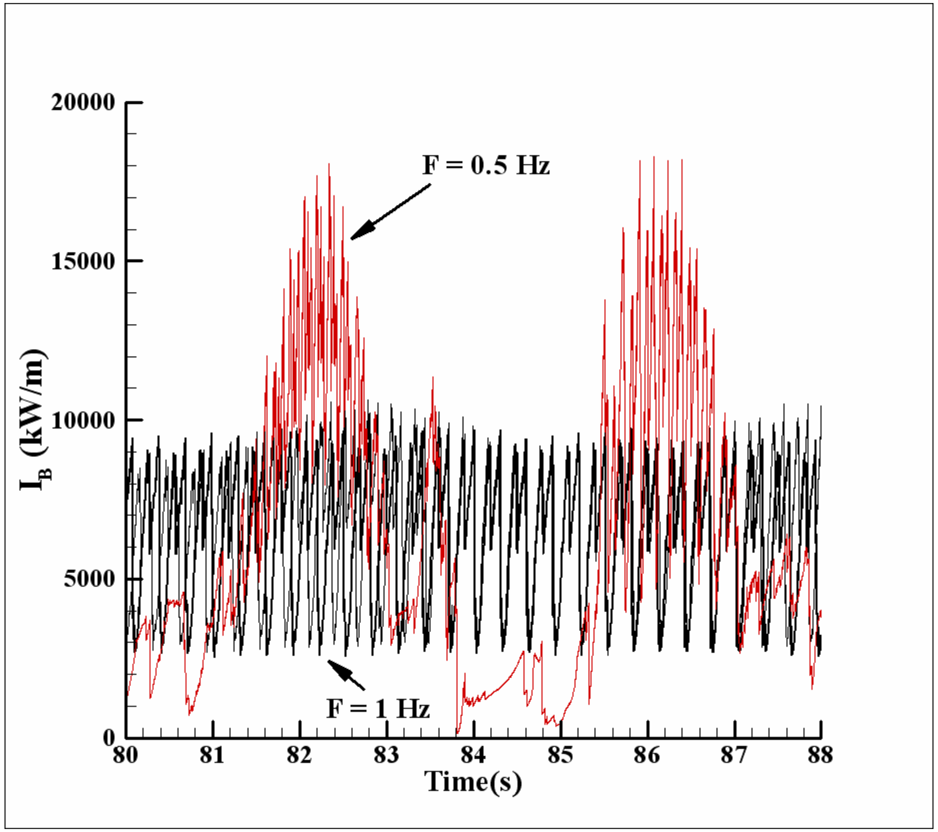
Grassland fires: temperature field U_{10} = 2 m/s +/- 1 m/s





Trajectory of the pyrolysis front (T_S = 500 K) Fireline intensity



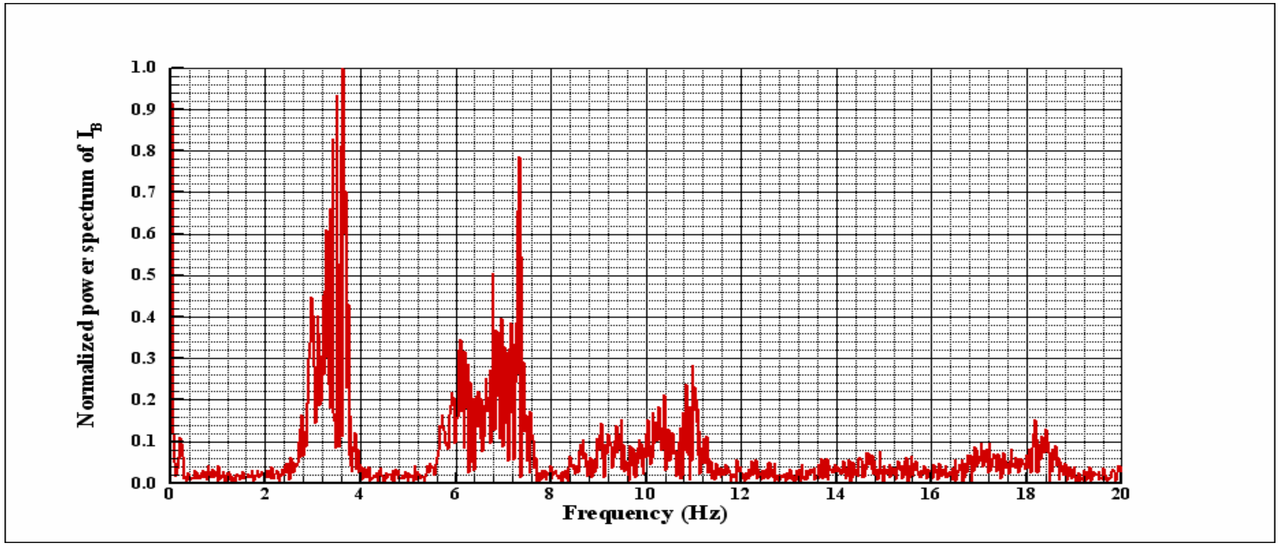


Steady → $\langle I_B \rangle$ = 6505 kW/m

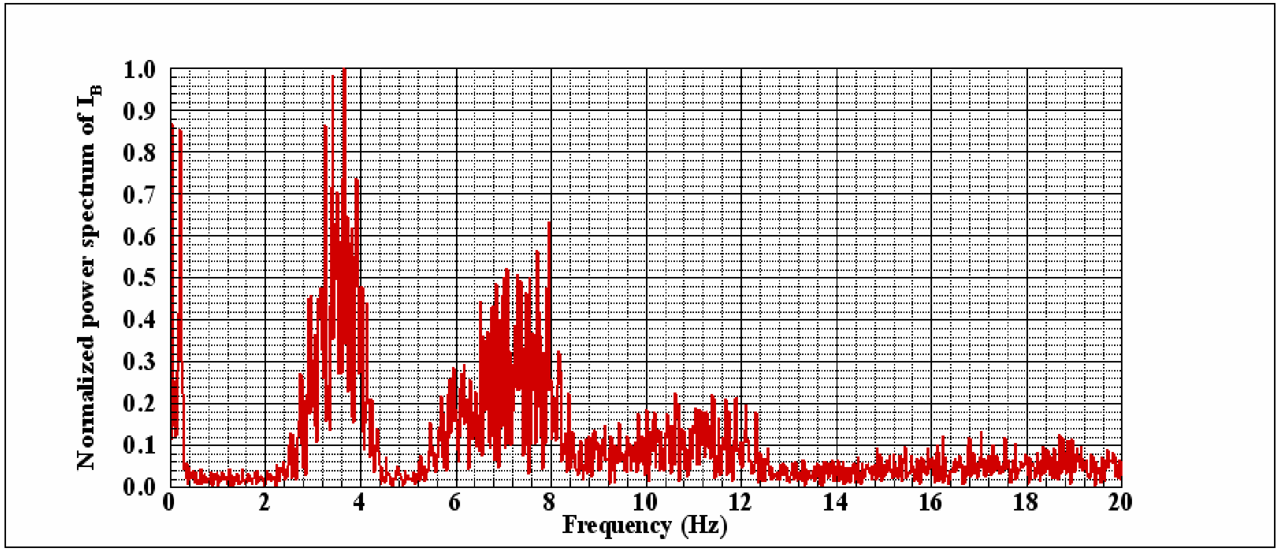
F = 0.5 Hz → $\langle I_B \rangle$ = 6972 kW/m (+7%)

F = 1 Hz → $\langle I_B \rangle$ = 6742 kW/m (+3.6%)

Fireline intensity normalized spectrum

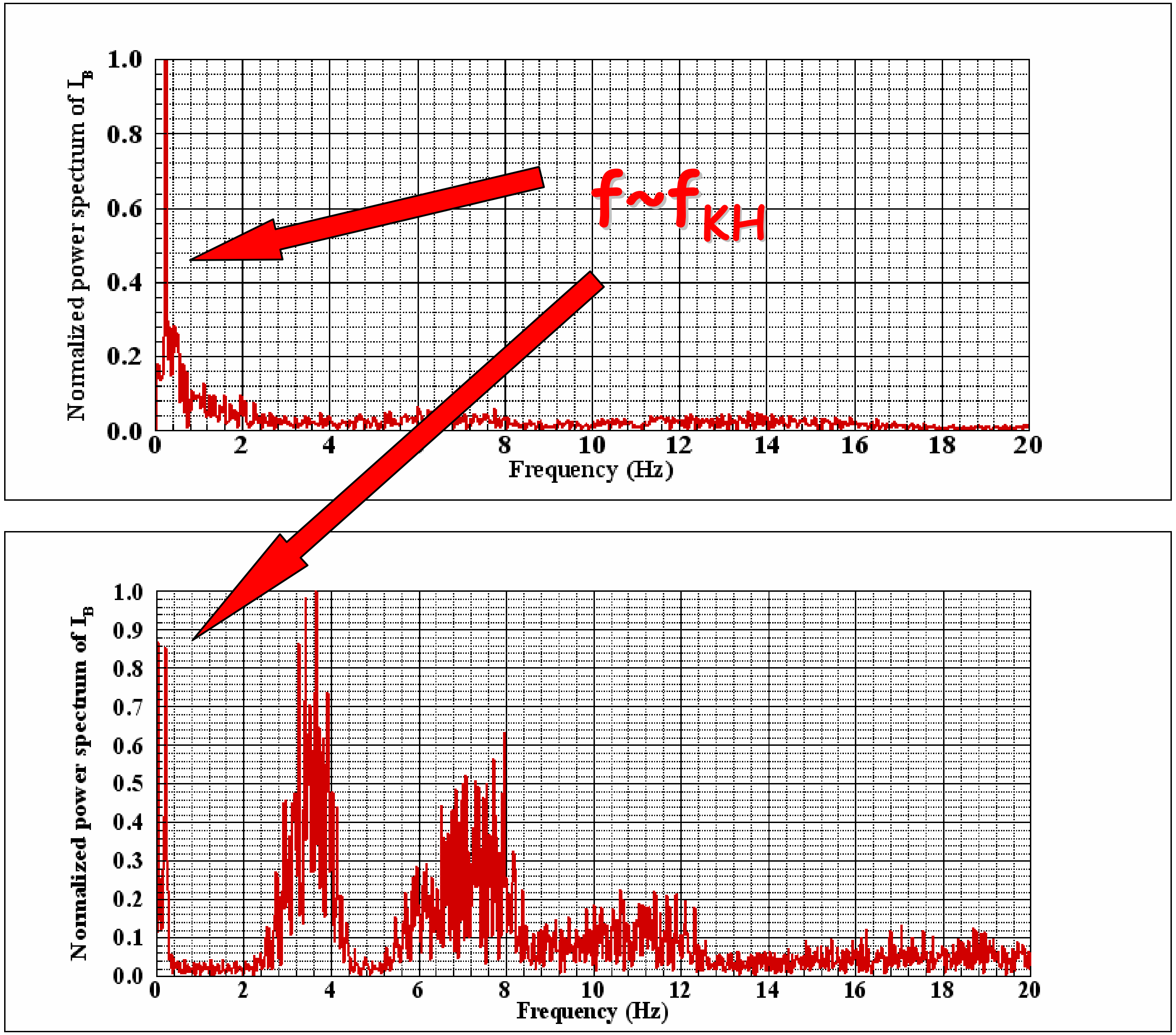


steady



F=1 Hz

Fireline intensity normalized spectrum



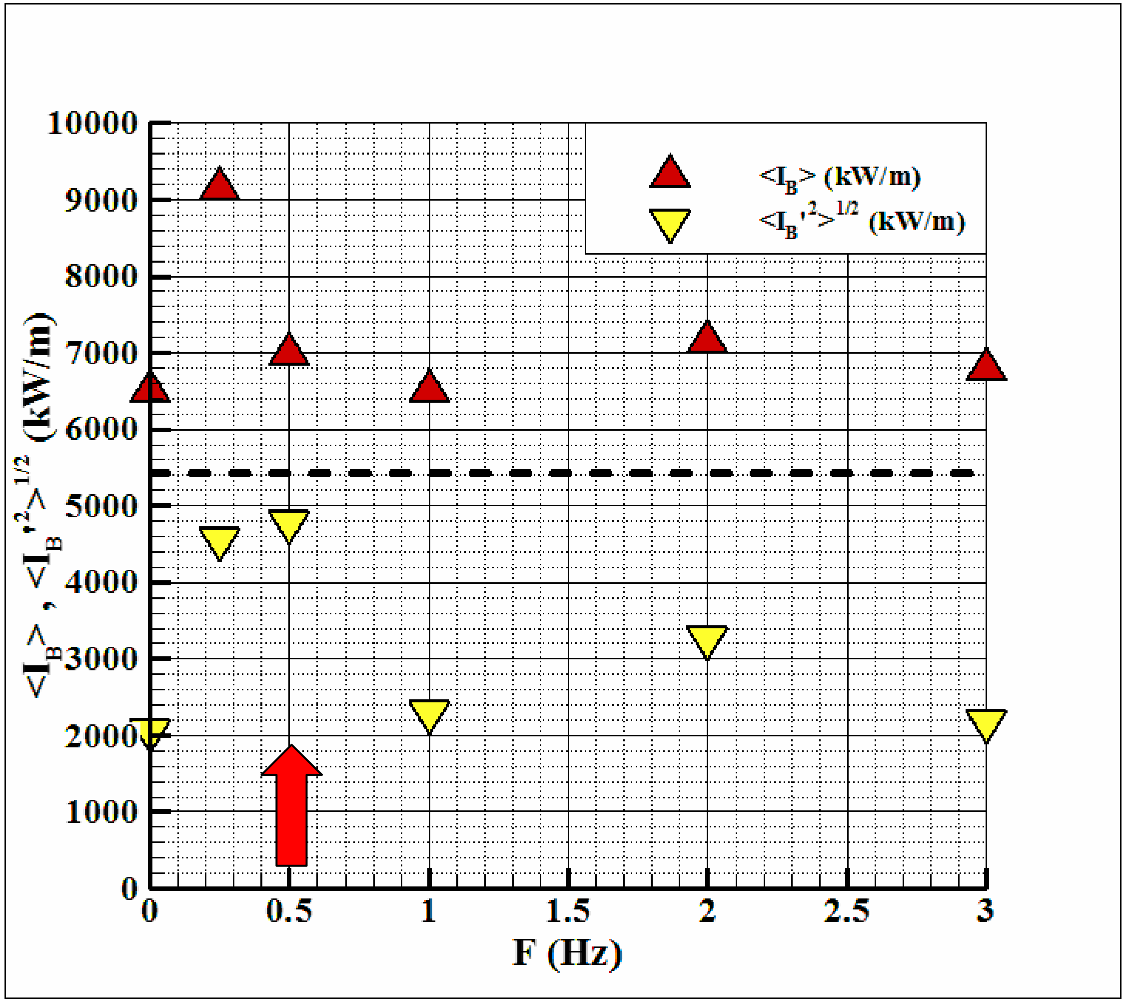
$f \sim f_{KH}$

F=0.5 Hz

F=1 Hz

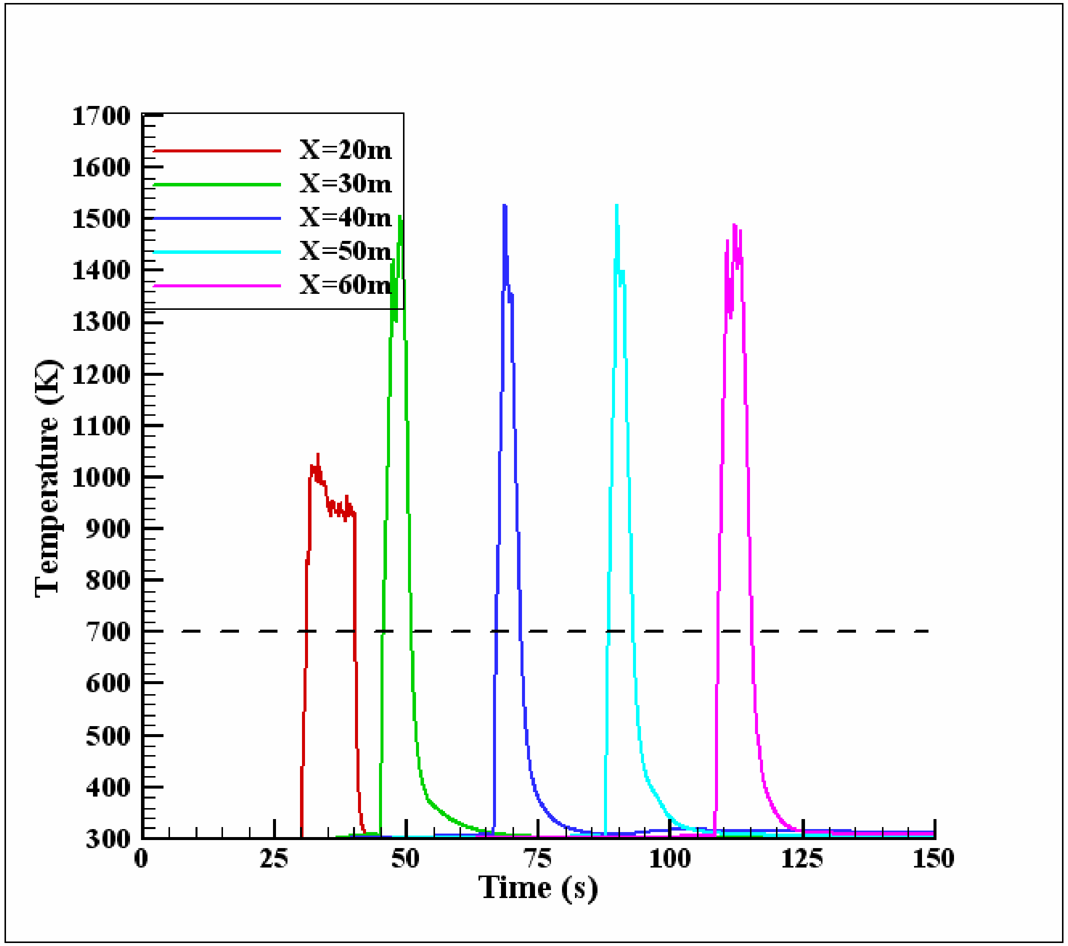
Fire intensity and standard obtained for U_{10} = 2 m/s and a sinusoidal time variation (f = 0.26 – 3 Hz)

(f_{KH} = 0.26 Hz)



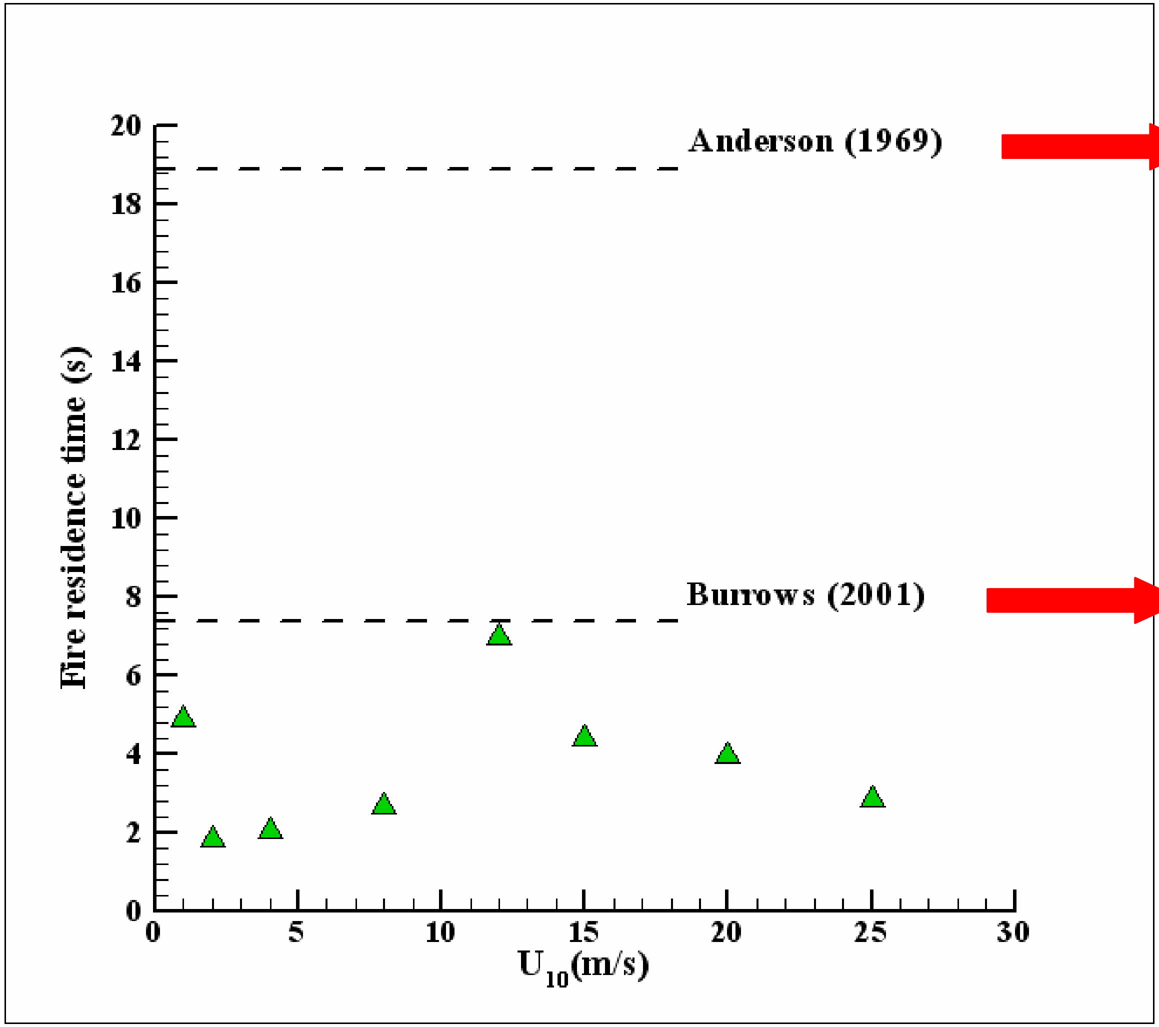
2 × f_{KH}

Evaluation of the fire residence time from the time history of the temperature in the fuel layer



(z = 0.25 m, fuel depth = 0.7 m)

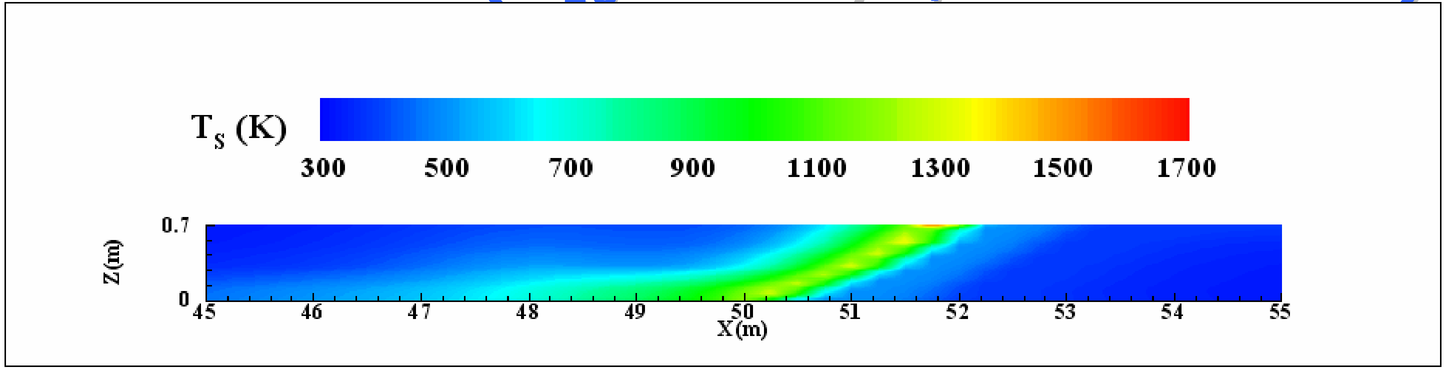
Fire residence time versus 10m open wind velocity



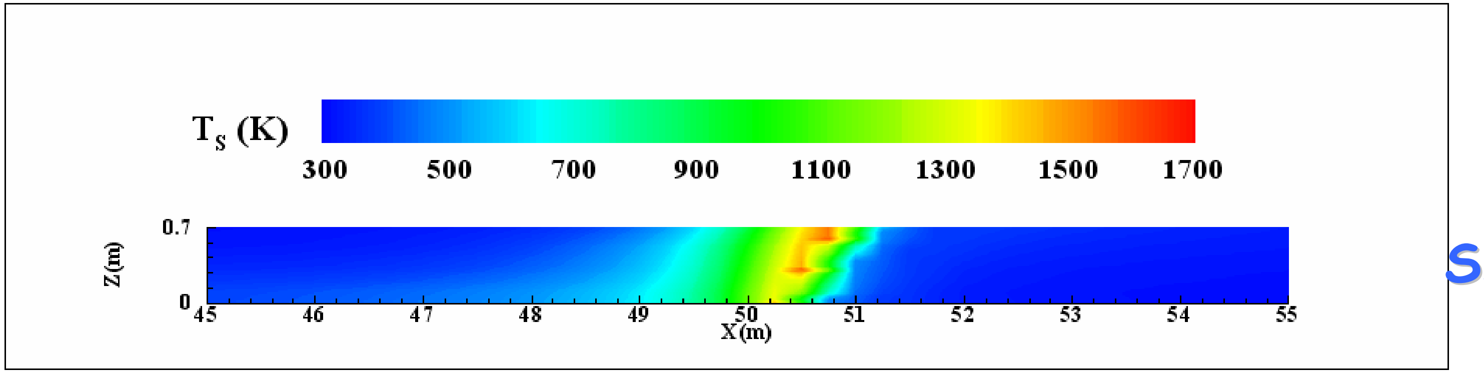
$$\tau_{Res} = \frac{75600}{\sigma_{Fuel}}$$

$$\tau_{Res} = \frac{208487}{\sigma_{Fuel}^{1.236}}$$

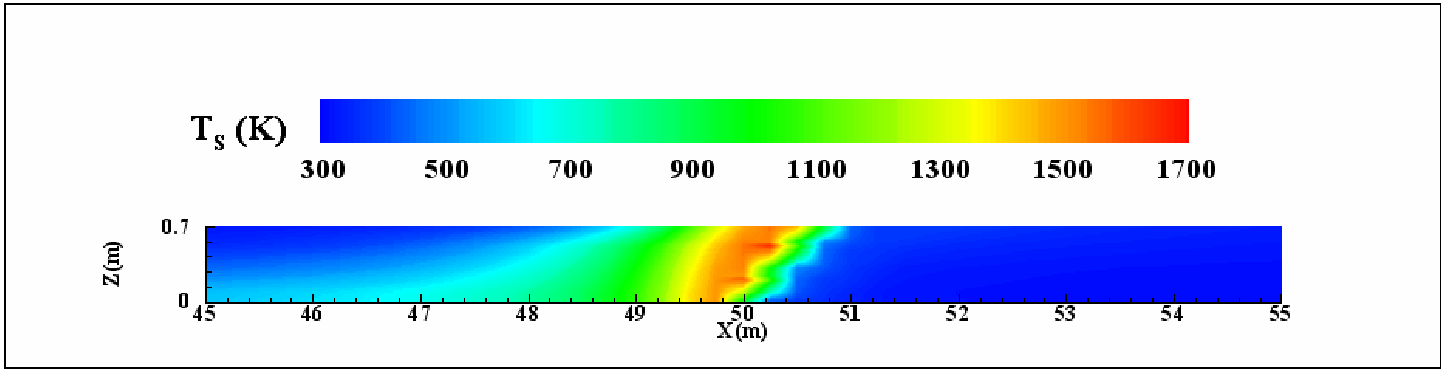
Solid fuel temperature field for various SA/V (U_{10} = 4 m/s, FMC = 10%)



SA/V = 500 m^{-1}



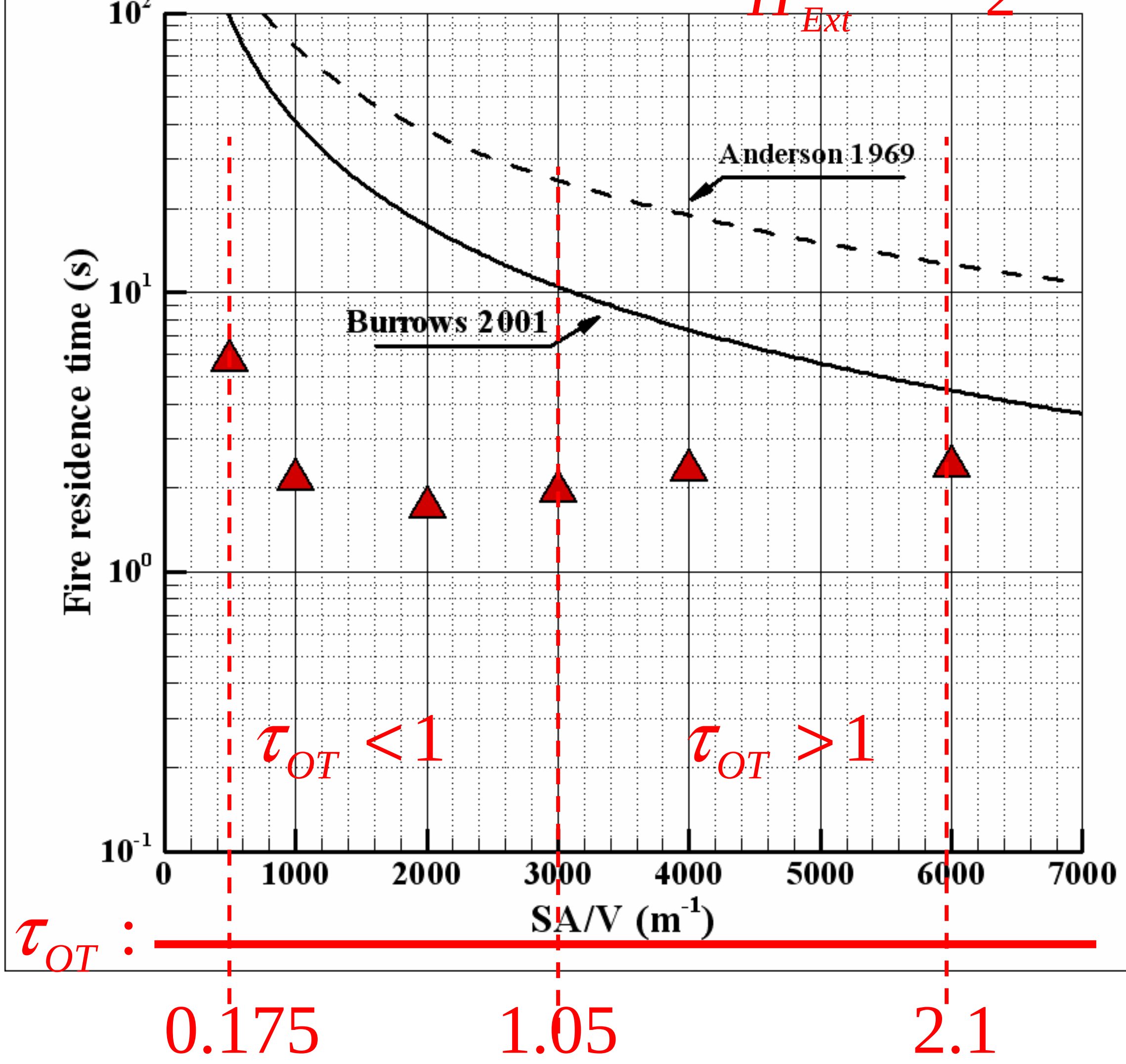
SA/V = 1000 m^{-1}



SA/V = 4000 m^{-1}

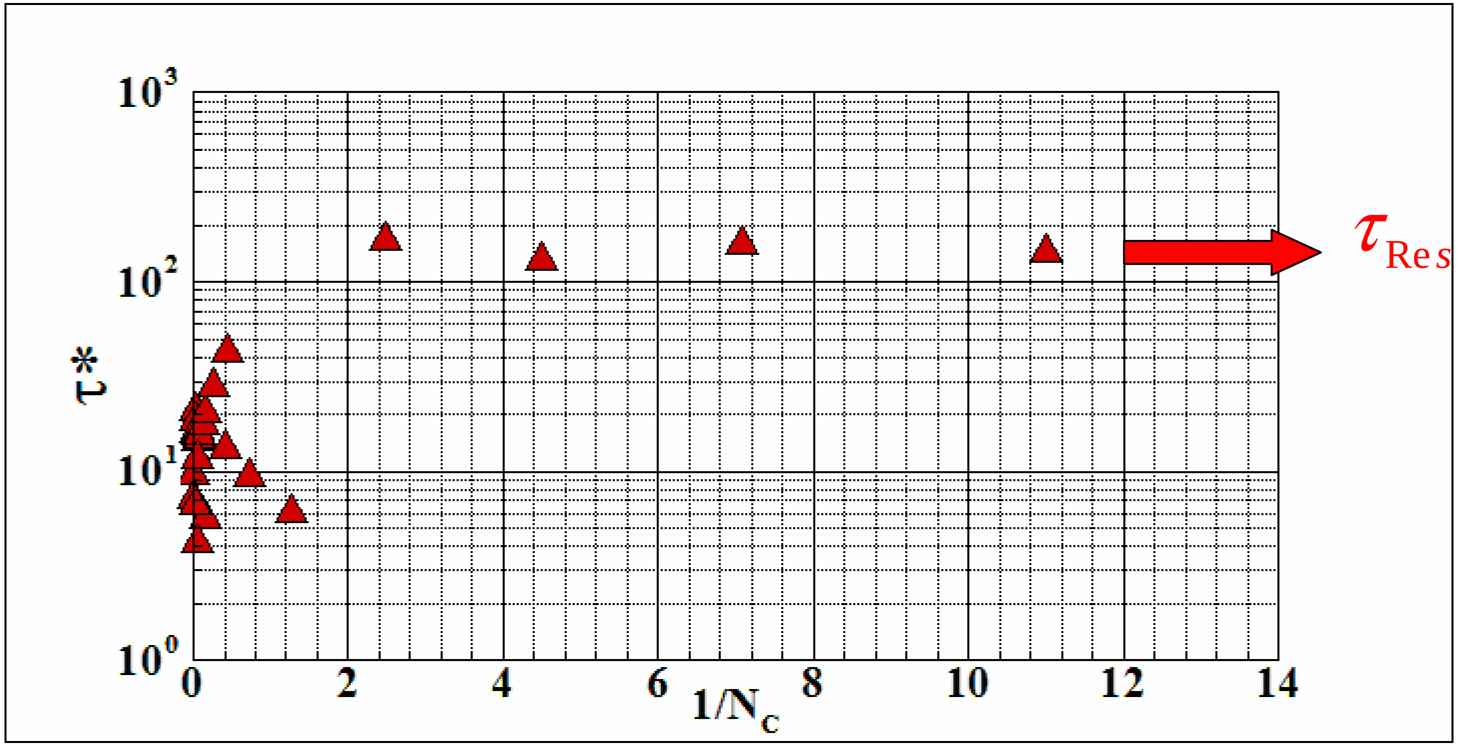
Fire residence time versus SA/V

$$Optical\ thickness = \tau_{OT} = \frac{H_{Fuel}}{H_{Ext}} = \frac{LAI}{2}$$



Reduced fire residence time versus Byram convective number

$$\tau^*_{Res} = \frac{\tau_{Res} \times U_{10} \times LAD}{2} = \frac{\tau_{Res} \times U_{10} \times \alpha_{Fuel} \times \sigma_{Fuel}}{4}$$



$$\tau_{Res} = \frac{75000}{\sigma_{Fuel}}$$

Thank you for attention
Questions ?