Fire Dynamics

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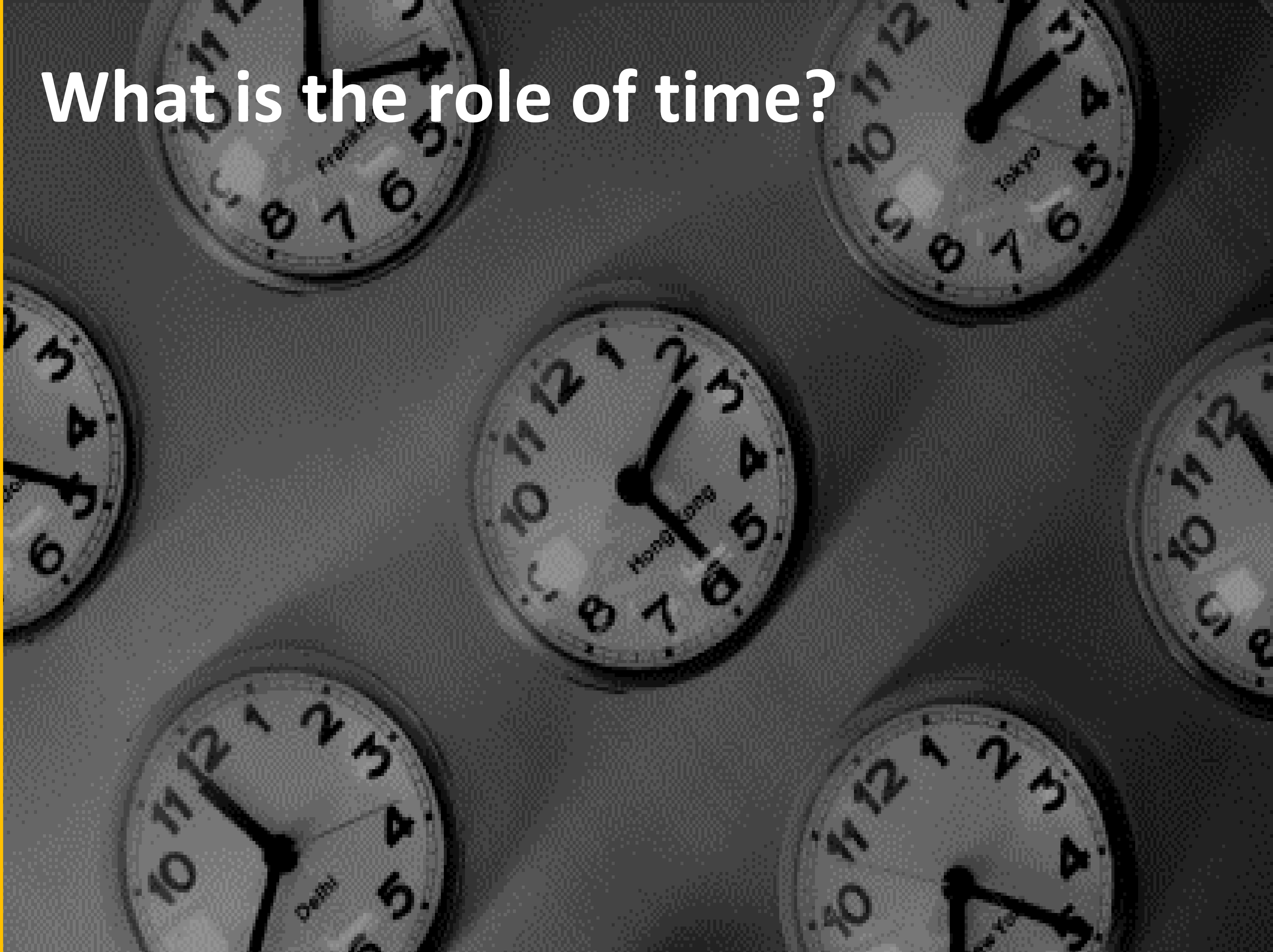
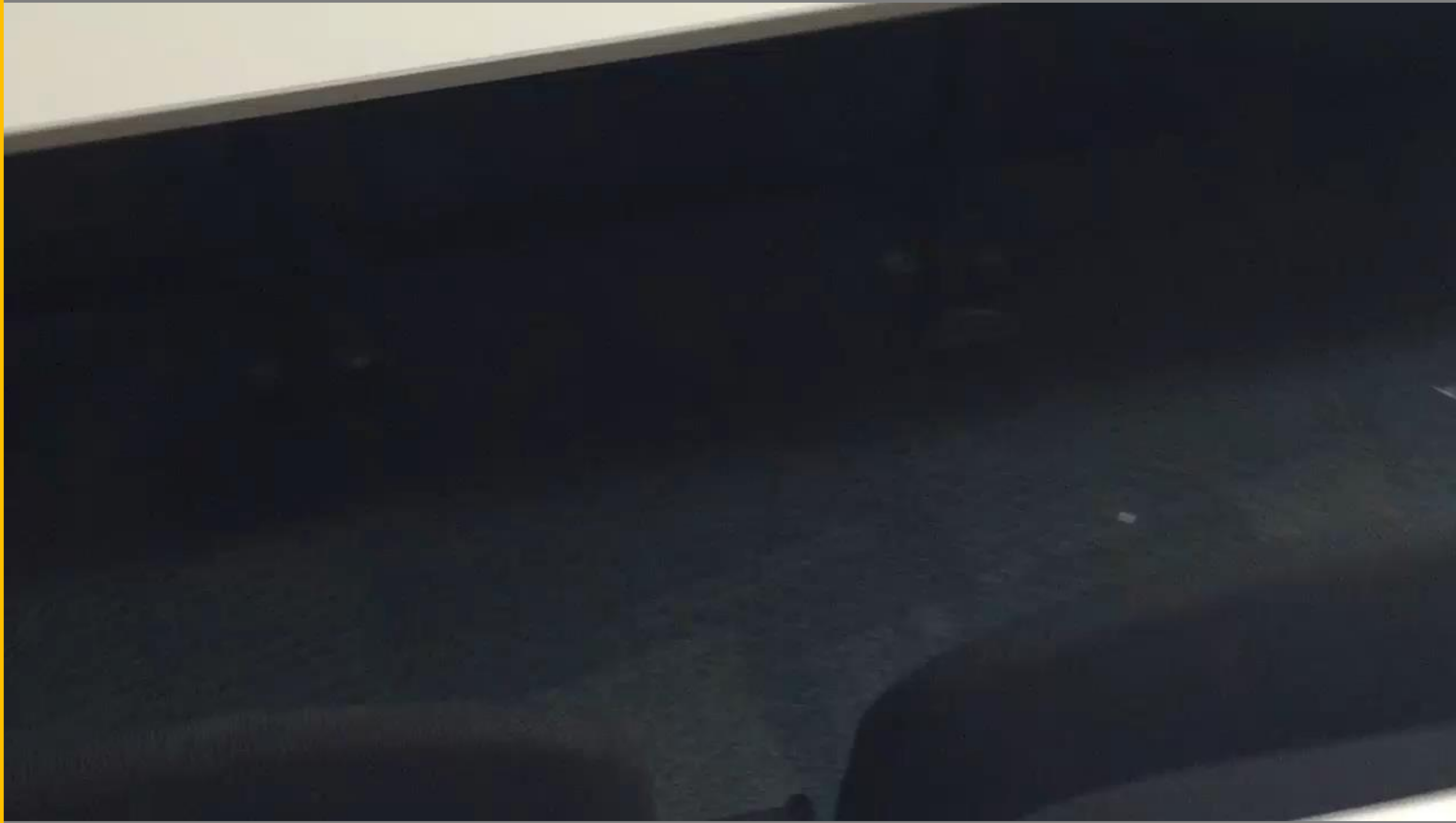
- Fire Dynamics: The combustion problem within Fire Safety Engineering

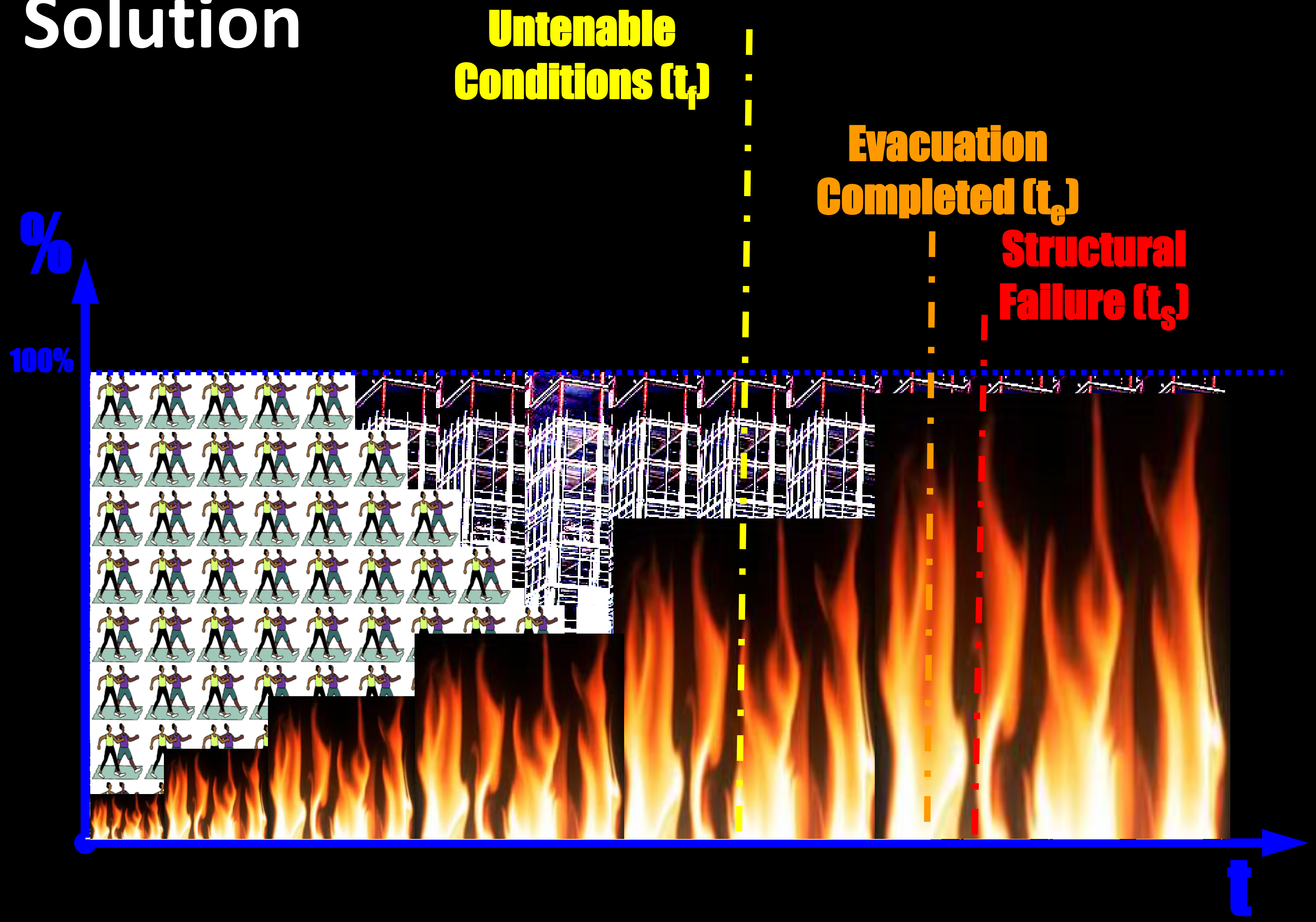
What is the role of time?



RSET (Required Safe Egress Time)



Solution



Untenable Conditions (t_f)
Evacuation Completed (t_e)
Structural Failure (t_s)
%
100%
t

ASET (Available safe Egress Time)

Objectives

$$t_e <<<< t_f$$ RSET<<<<ASET

$$t_e <<<< t_S$$

$$t_s \longrightarrow \infty$$

Fire Safety Strategy

RSET

- We need to establish egress times(t_e)

- R.S.E.T. (t_e) – Required Safe Egress Time

Egress Time (t_e)

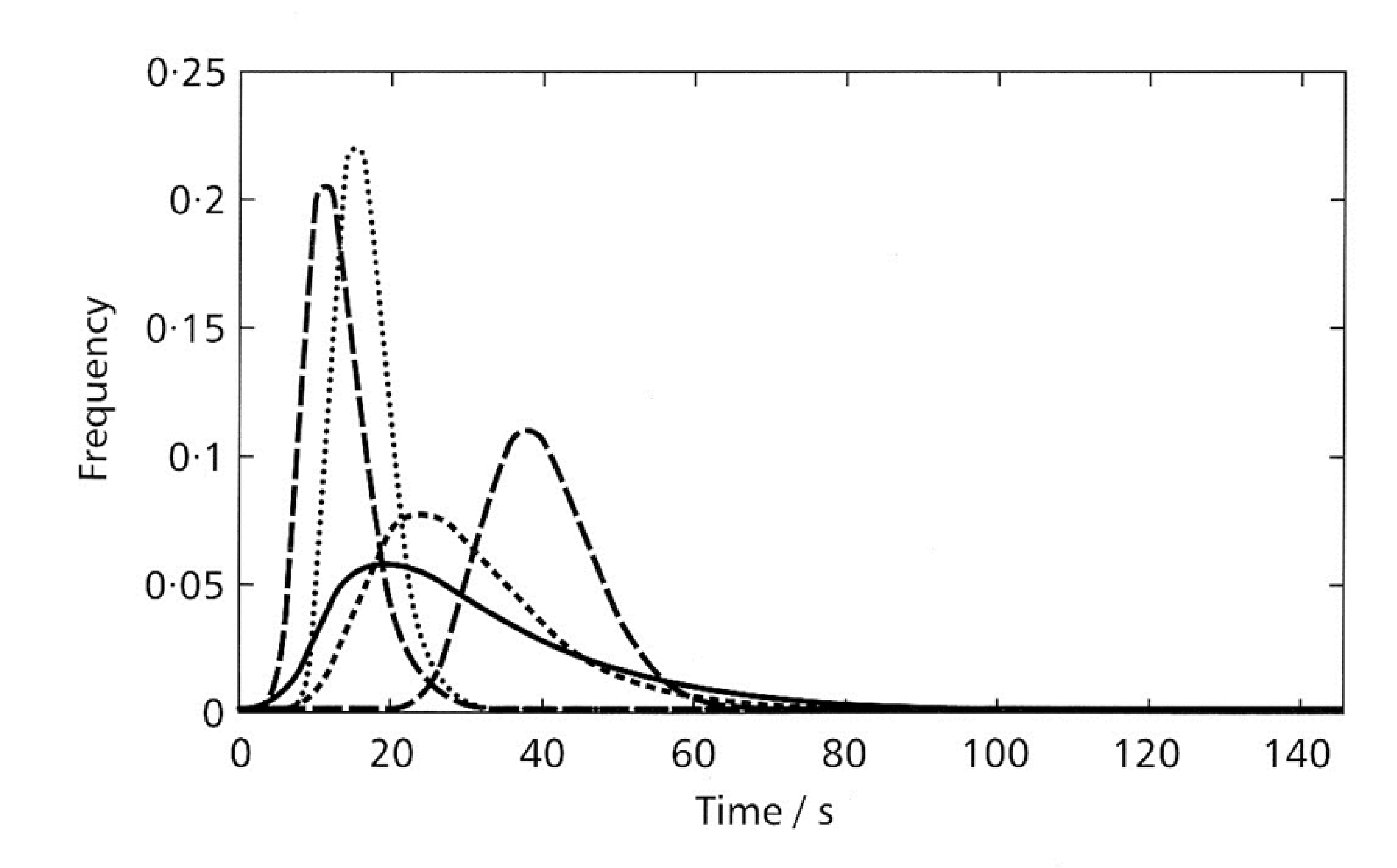
$$t_e = \cancelto{\approx 0}{t_{de}} + t_{pre} + t_{mov}$$

- t_e – Egress time
- t_{de} – Detection time
- t_{pre} – Pre-Movement time
- t_{mov} – Displacement time

$$\boxed{t_e = t_{pre} + t_{mov}}$$

Pre-Movement Time (t_{pre})

- Purely statistical – can be very long and brings great uncertainty

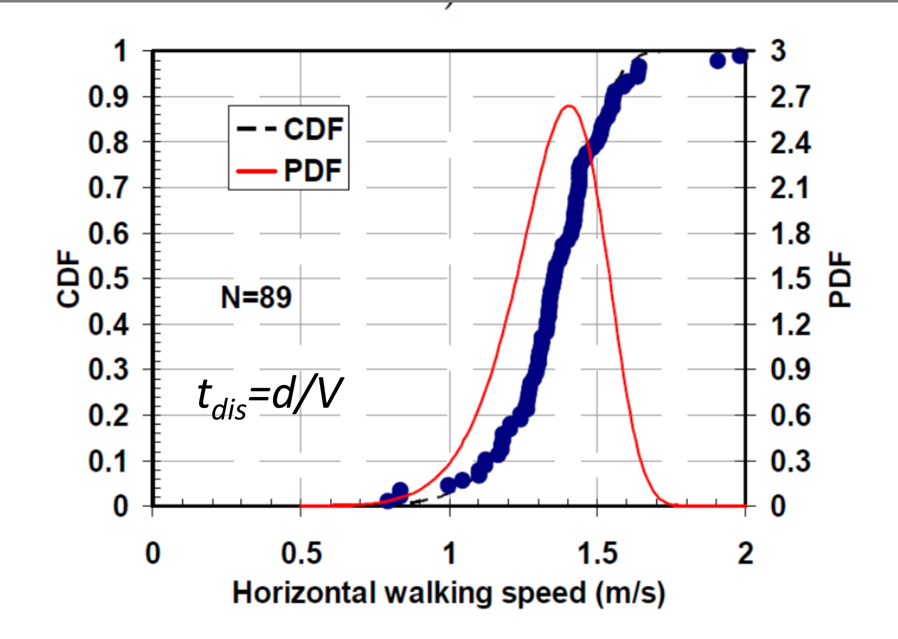


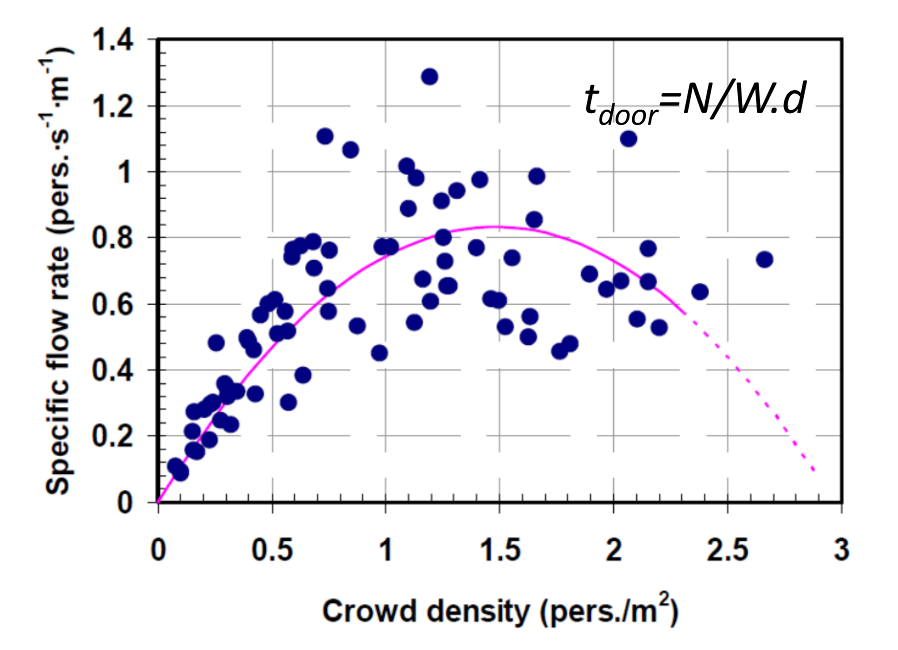
Movement Time

- Travel distance $d=d_{max}$
- Conservative travel velocity: 1 m/s

$$t_{mov}=t_{dis}+t_{door} << 150\ s$$

2.5 min



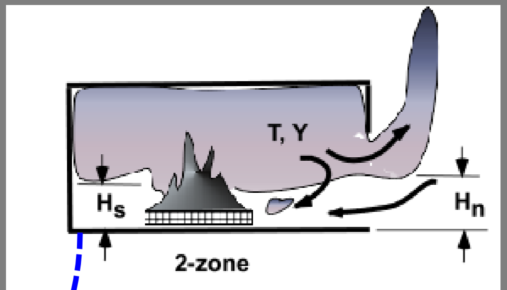


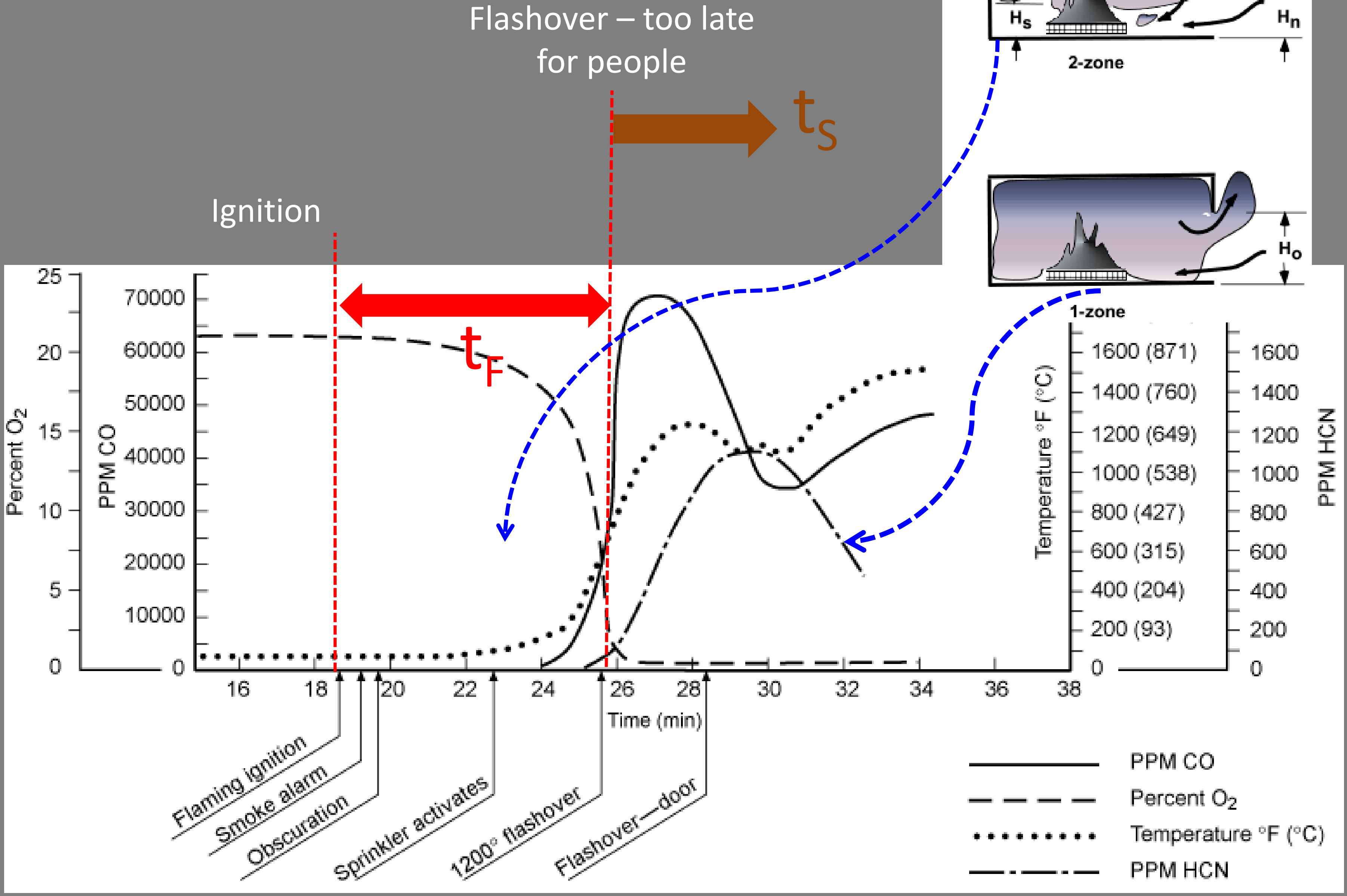
ASET

- A.S.E.T.: Available Safe Egress Time (t_f)

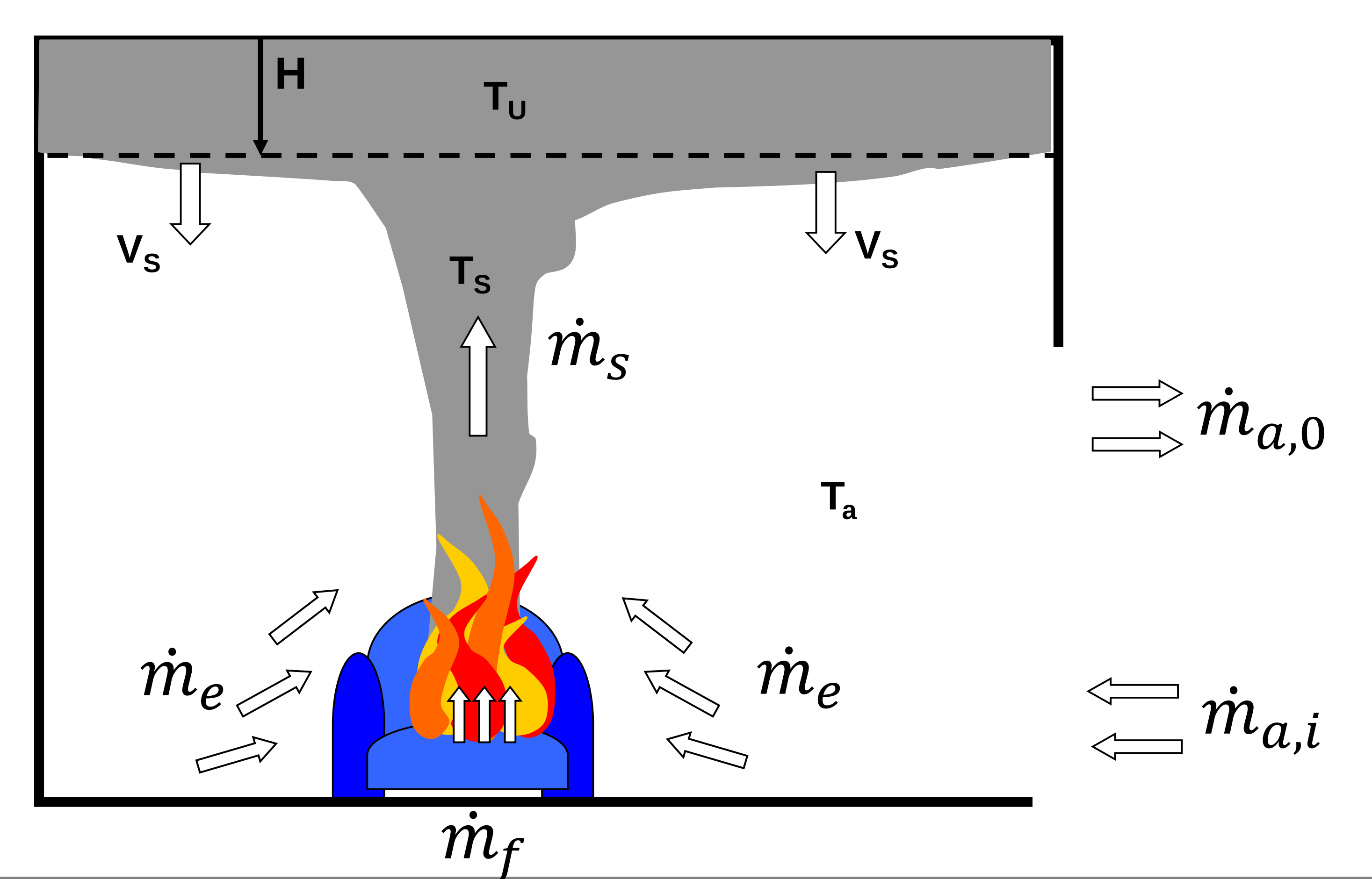
Fire

Timeline


T, Y
Hs
Hn
2-zone


Flashover – too late for people
t_S
Ignition
t_F
Ho
1-zone
Percent O2
PPM CO
25
20
15
10
5
0
70000
60000
50000
40000
30000
20000
10000
0
16
18
20
22
24
26
28
30
32
34
36
38
Time (min)
Temperature °F (°C)
1600 (871)
1400 (760)
1200 (649)
1000 (538)
800 (427)
600 (315)
400 (204)
200 (93)
0
PPM HCN
1600
1400
1200
1000
800
600
400
200
0
Flaming ignition
Smoke alarm
Obscuration
Sprinkler activates
1200° flashover
Flashover—door
PPM CO
Percent O2
Temperature °F (°C)
PPM HCN

The Pre-Flashover Compartment Fire

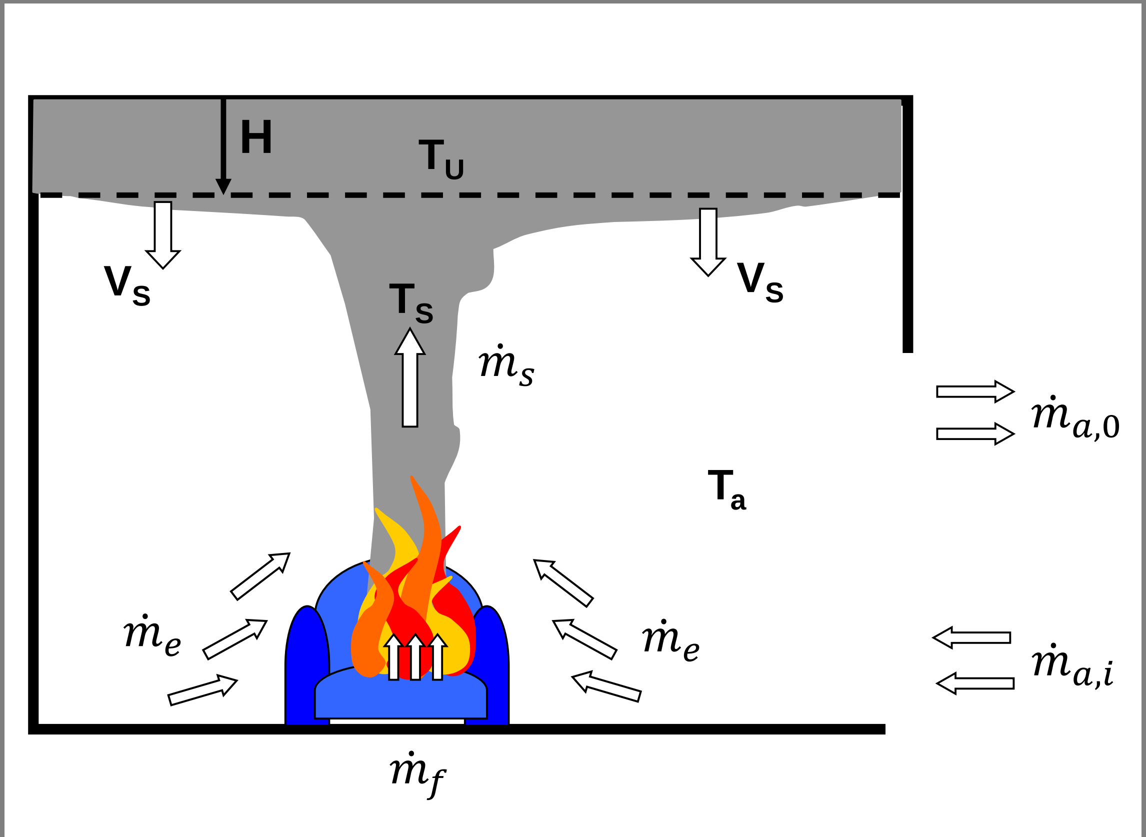


Approach

- Zone Model – Divides the room into two well defined zones
  - Upper Layer – Hot combustion products
  - Lower Layer – Cold air

- Implies strong simplifications but help understand the dynamics of the problem

The Evolution of the Smoke Layer



- **Upper Layer** - The parameters that need to be evaluated are:
  - The temperature of the upper layer:
    T_u
  - The velocity at which the Upper Layer descends:
    $V_S = \frac{dH}{dt}$

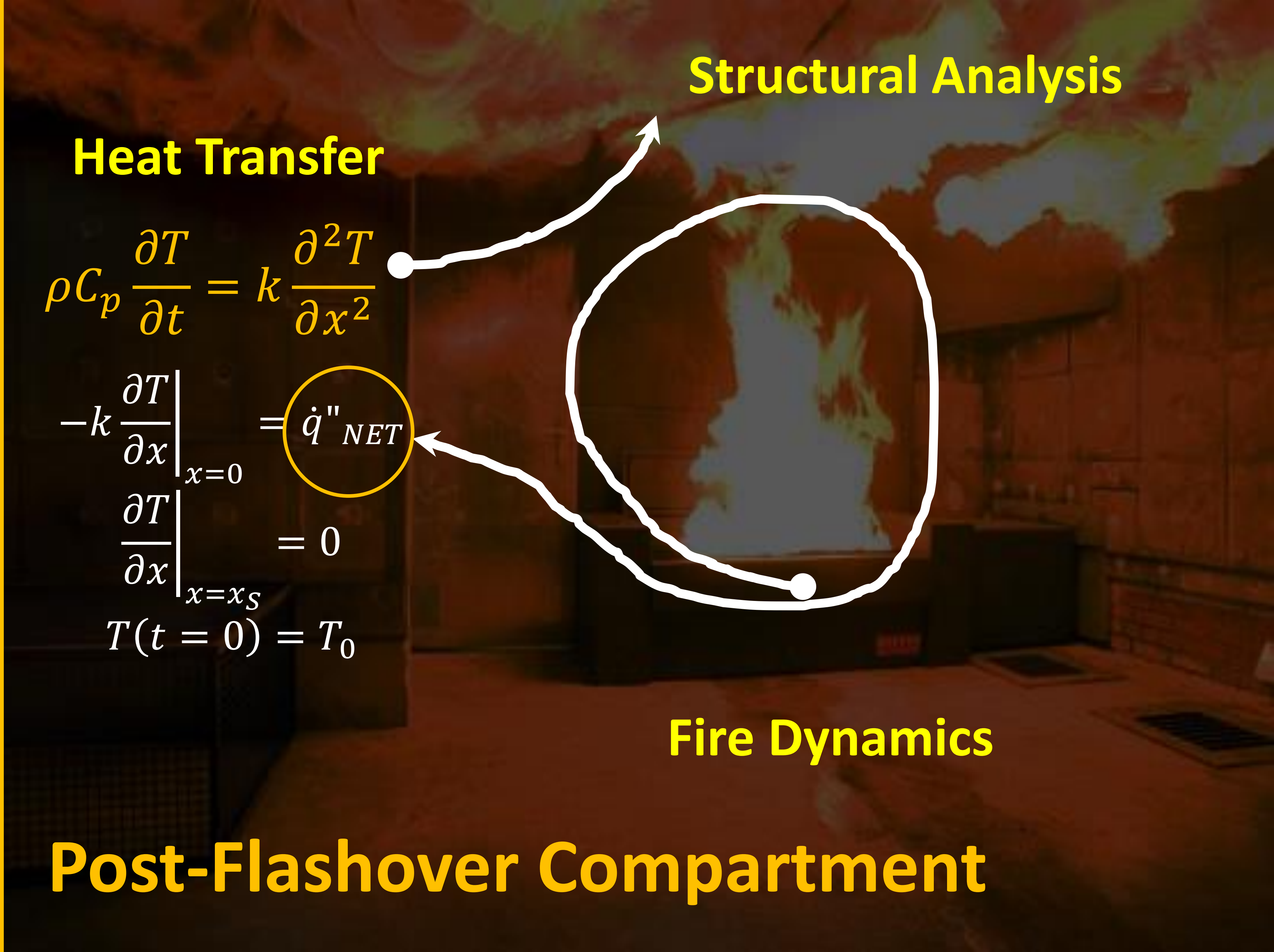
Conservation Equations

- These parameters can be obtained from, the ideal gas law and conservation of mass and energy in the Upper Layer

$$P = \rho R T_{\mathrm{u}}$$

$$\frac{\partial}{\partial t}\big(A\rho(T_{\mathrm{u}})H(t)\big) = \dot{m}_s$$

$$\frac{\partial}{\partial t}\big(A\rho(T_{\mathrm{u}})H(t)C_p T_{\mathrm{u}}\big) = \dot{m}_s C_p T_s$$



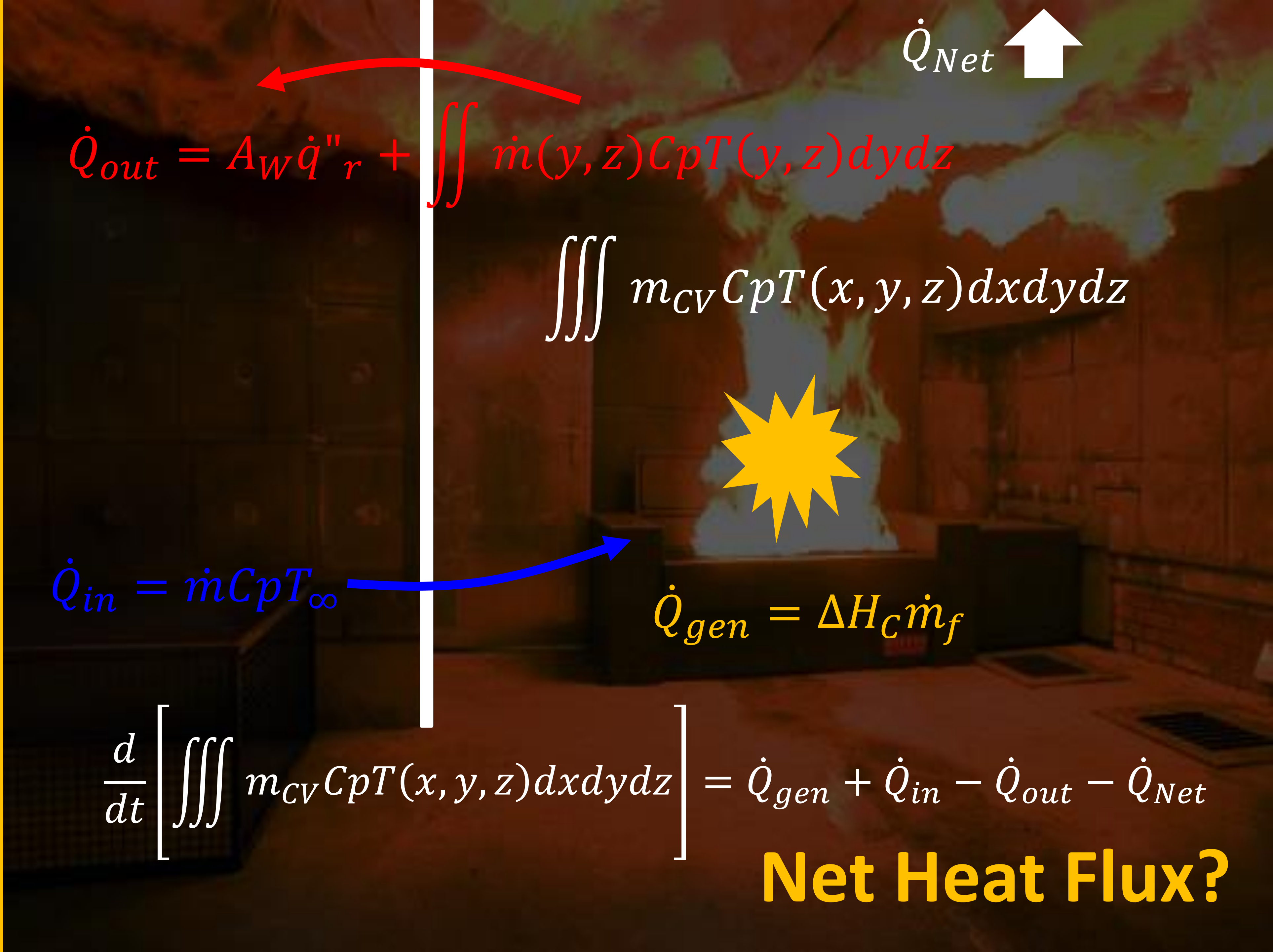
$$\rho C_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2}$$

$$-k \left. \frac{\partial T}{\partial x} \right|_{x=0} = \dot{q}''_{NET}$$

$$\left. \frac{\partial T}{\partial x} \right|_{x=x_S} = 0$$

$$T(t=0) = T_0$$

Post-Flashover Compartment



$$\dot{Q}_{Net}$$

$$\dot{Q}_{out} = A_W \dot{q}''_r + \iint \dot{m}(y,z)CpT(y,z)dydz$$

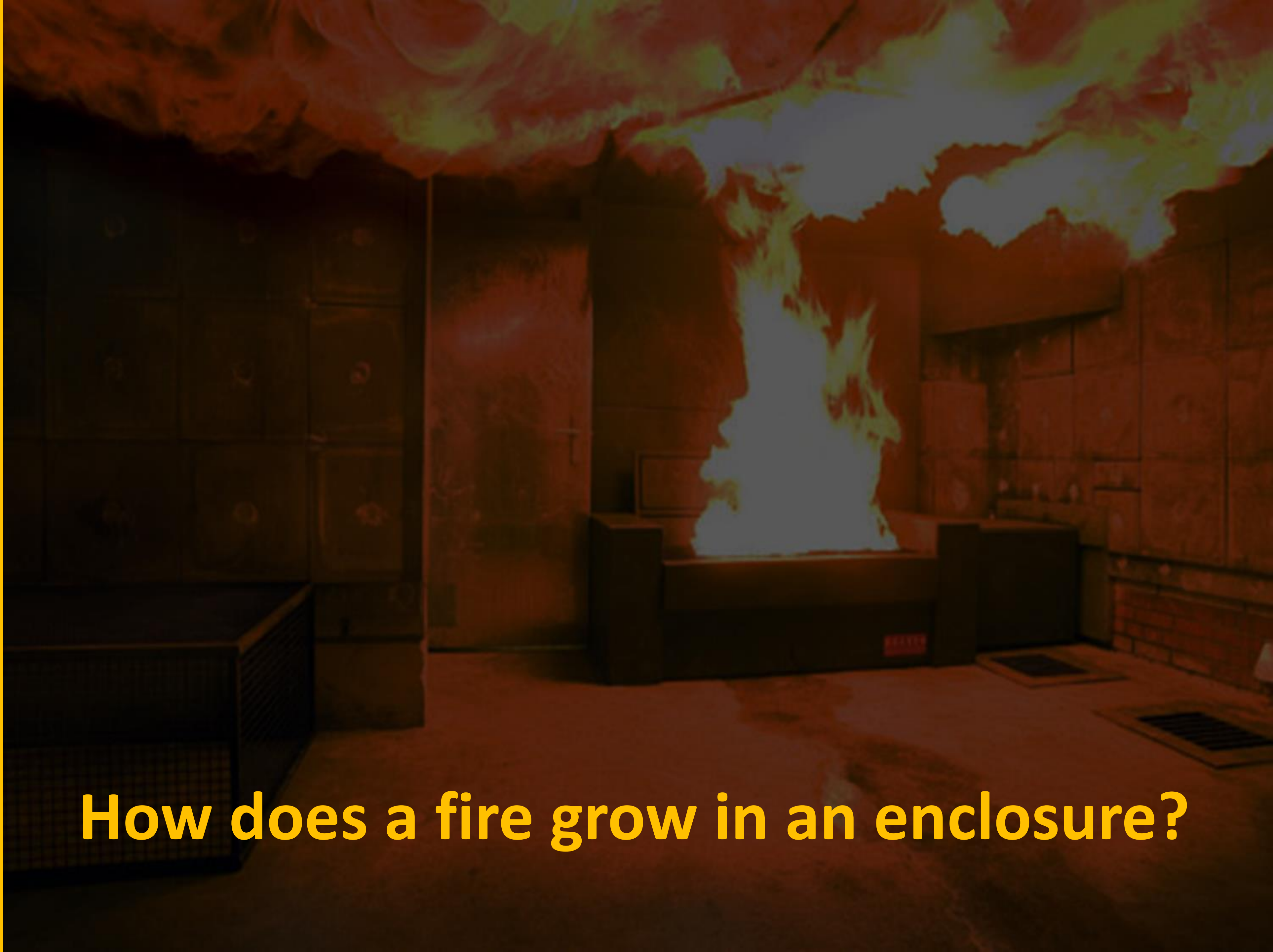
$$\iiint m_{CV} CpT(x,y,z)dxdydz$$

$$\dot{Q}_{in} = \dot{m}CpT_\infty$$

$$\dot{Q}_{gen} = \Delta H_C \dot{m}_f$$

$$\frac{d}{dt}\left[\iiint m_{CV} CpT(x,y,z)dxdydz\right] = \dot{Q}_{gen} + \dot{Q}_{in} - \dot{Q}_{out} - \dot{Q}_{Net}$$

Net Heat Flux?



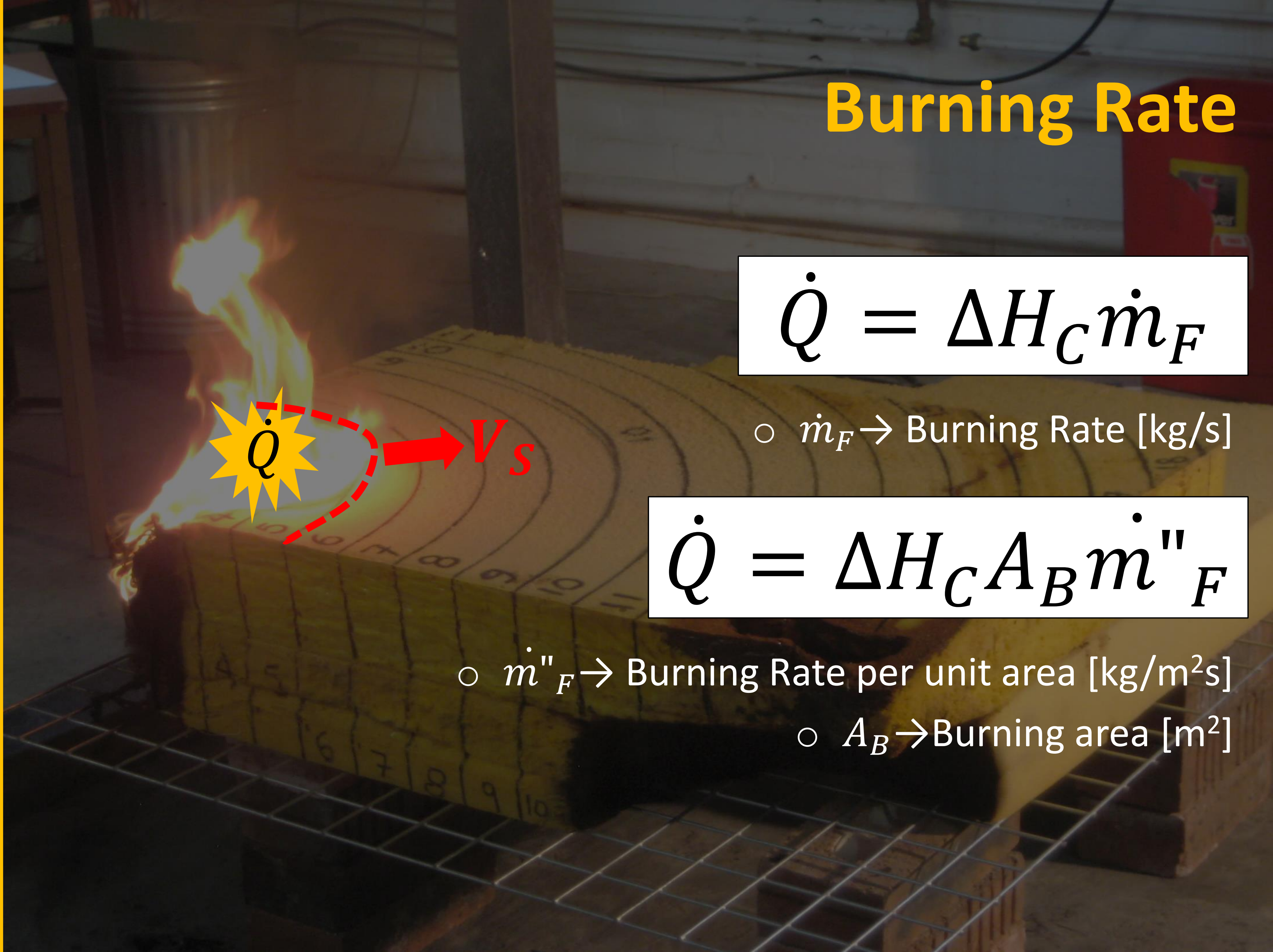
How does a fire grow in an enclosure?

Combustion

- Heat of Combustion (ΔH_C): Energy released per kg of fuel burnt – Complete Combustion

Fuel	ΔH_C [MJ/kg$_{FUEL}$]
Hydrogen	141.80
Propane	50.35
Gasoline	47.30
Paraffin	46.00
Kerosene	46.20
Coal (Lignite)	15.00
Wood	15.00
Peat (dry)	15.00
PVC (Poly-Vinyl-Chloride)	17.50
PE (Poly-Ethylene)	44.60

Burning Rate



$$\dot{Q} = \Delta H_C \dot{m}_F$$

- $\dot{m}_F \rightarrow$ Burning Rate [kg/s]

$$\dot{Q} = \Delta H_C A_B \dot{m}''_F$$

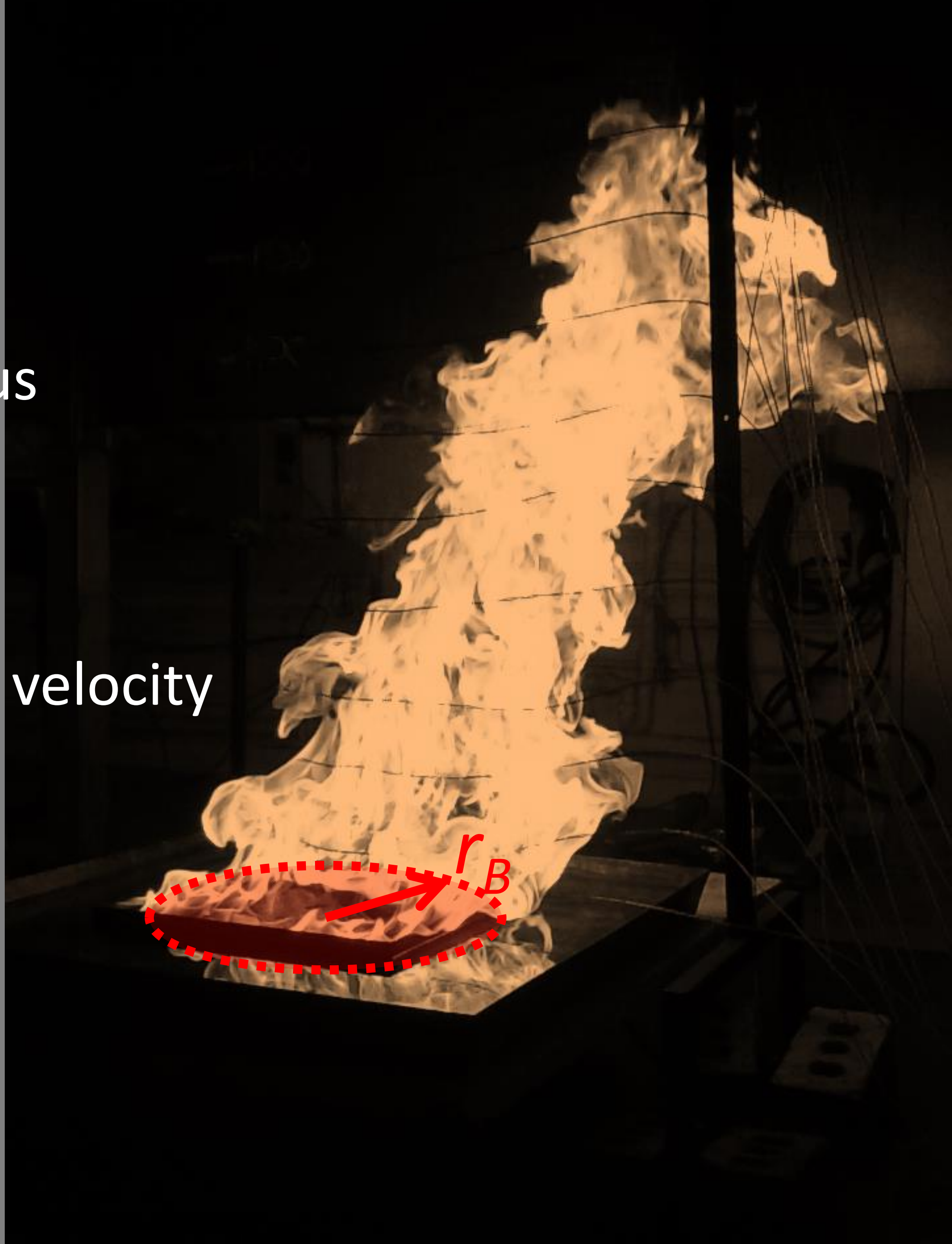
- $\dot{m}''_F \rightarrow$ Burning Rate per unit area [kg/m^{2}s]
- $A_B \rightarrow$ Burning area [m^2]

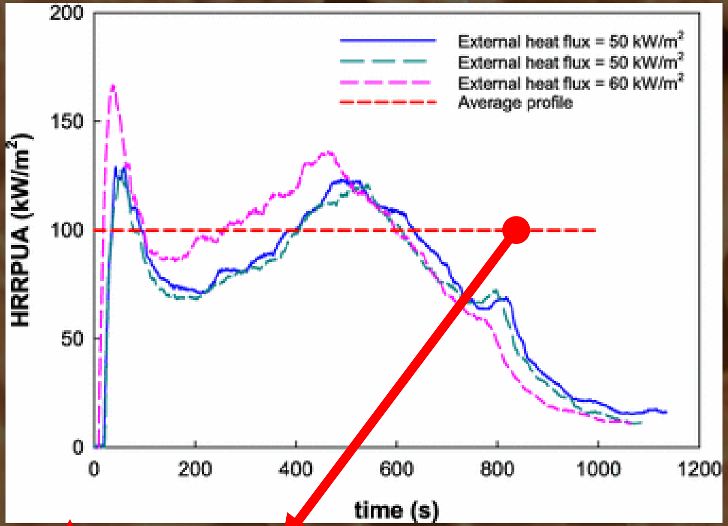
Design Fire

- $A_B = \pi r_B^2$
  - r_B →burning radius

- $r_B = V_S t$
  - V_S→Flame spread velocity
  - t→time

$$\boxed{A_B = (\pi V_S^2)t^2}$$





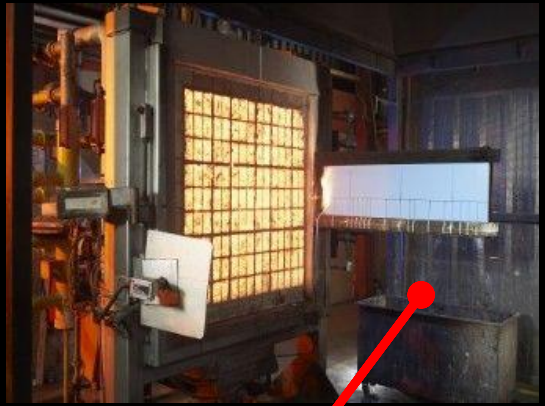
$$\dot{Q} = \Delta H_C A_B \dot{m}''_F$$

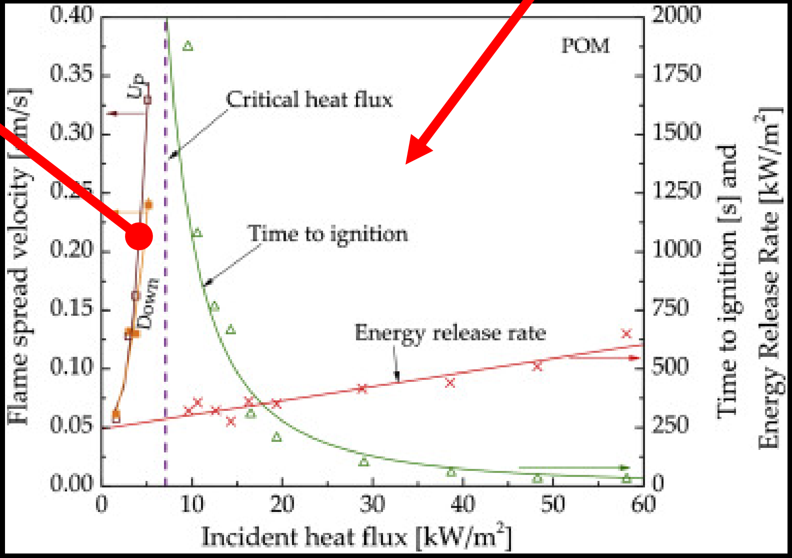
$$A_B = (\pi V_S^2) t^2$$

$$HRRPUA = \Delta H_C \dot{m}''_F$$

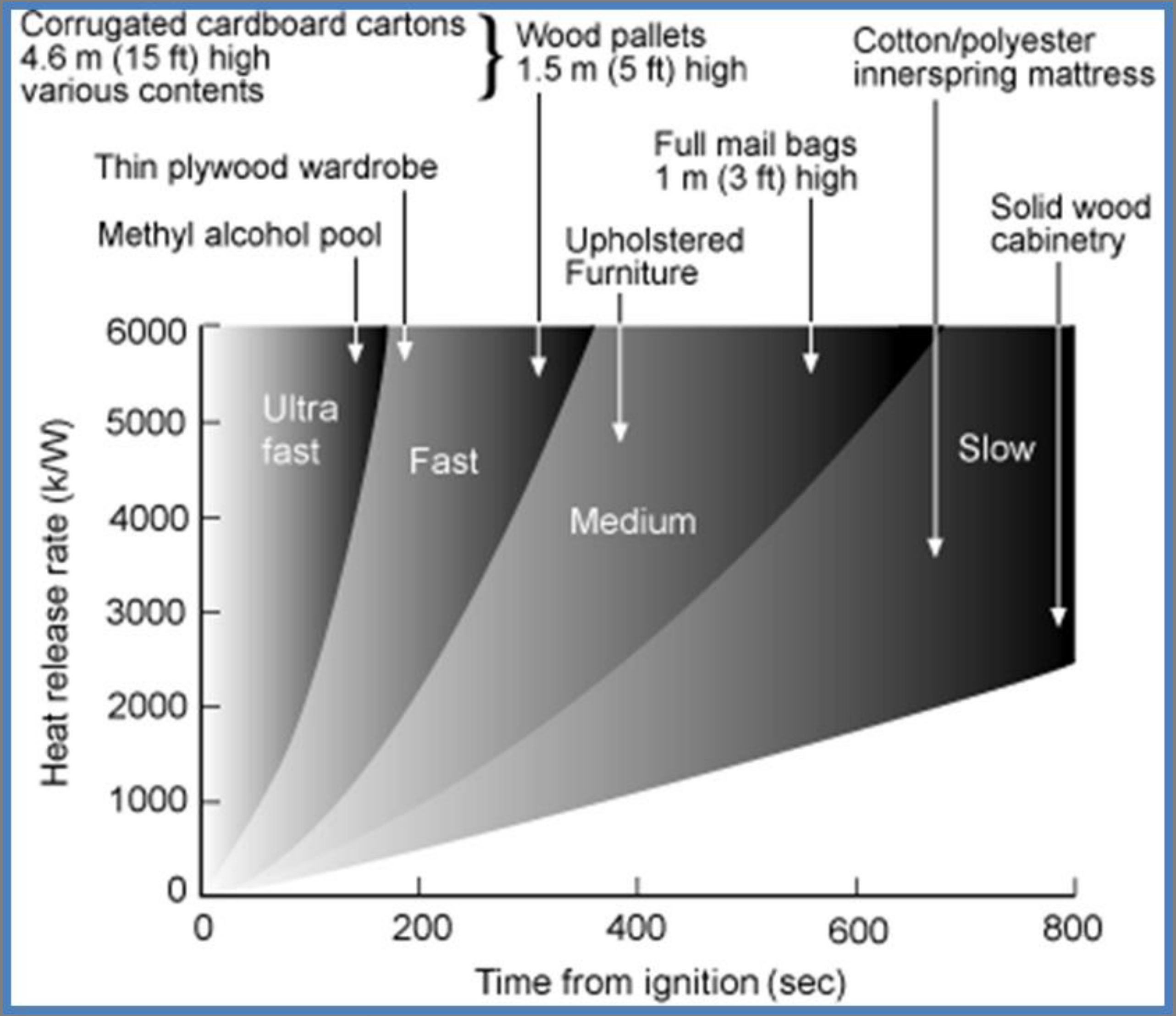
$$\dot{Q} = [\pi \Delta H_C V_S^2 \dot{m}''_F] t^2$$

$$\dot{Q} = \alpha t^2$$





Normalized Design Fires



Class	α
Ultra Fast	0.1876
Fast	0.0469
Medium	0.0117
Slow	0.0029

Conservation of Mass

$$\dot{m}_S = \dot{m}_F + \dot{m}_A$$

$$\frac{\dot{m}_F}{\dot{m}_A} = \frac{10\ cm^3}{100x50x5\ cm^3} = 4\ x\ 10^{-4}$$

≈ 0

$$\boxed{\dot{m}_S = \dot{m}_F + \dot{m}_A}$$

$$\boxed{\dot{m}_S \approx \dot{m}_A}$$

Show Video

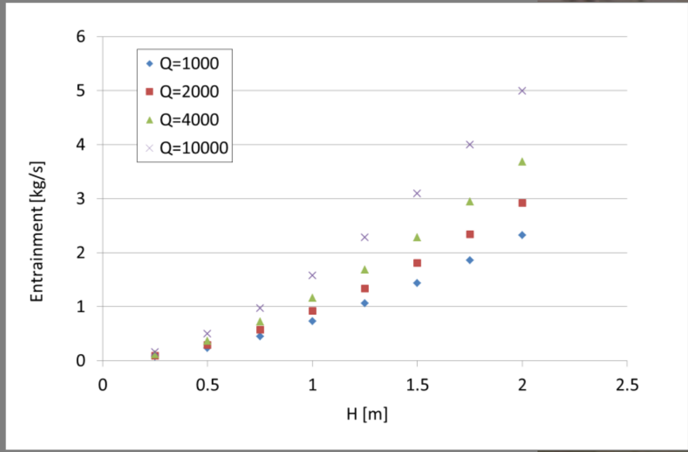
Conservation of Energy

$$\dot{Q} = \dot{m}_A C_p (T_S - T_A)$$

- $C_p \rightarrow$ Specific Heat (J/kgK)
- $T_S \rightarrow$ Smoke temperature
- $T_A \rightarrow$ Ambient temperature

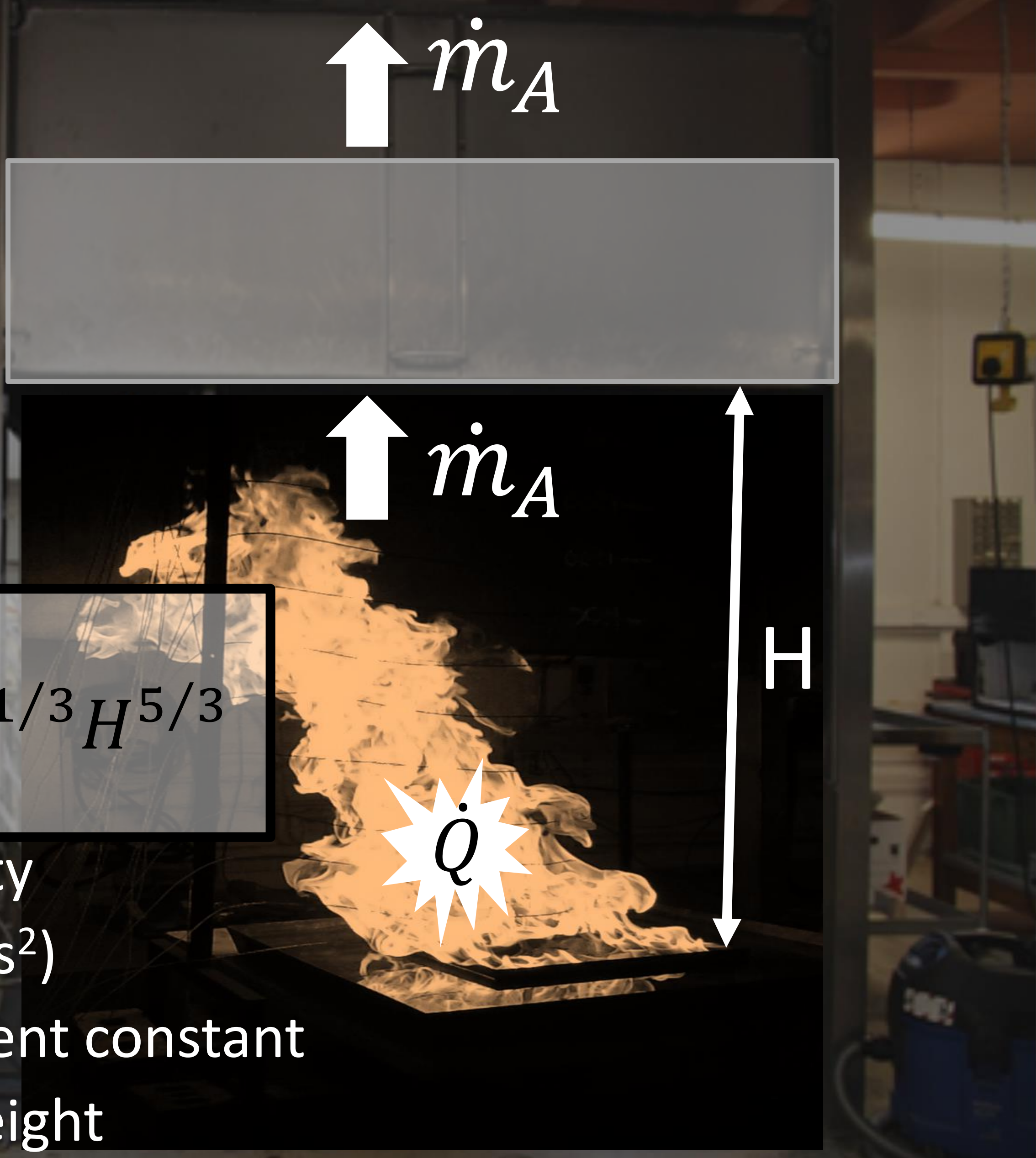
$$\boxed{T_S = T_A + \frac{\dot{Q}}{\dot{m}_A C_p}}$$

Entrainment



$$\dot{m}_A = E\left(\frac{g\rho_A^2}{C_p T_A}\right)^{1/3} \dot{Q}^{1/3} H^{5/3}$$

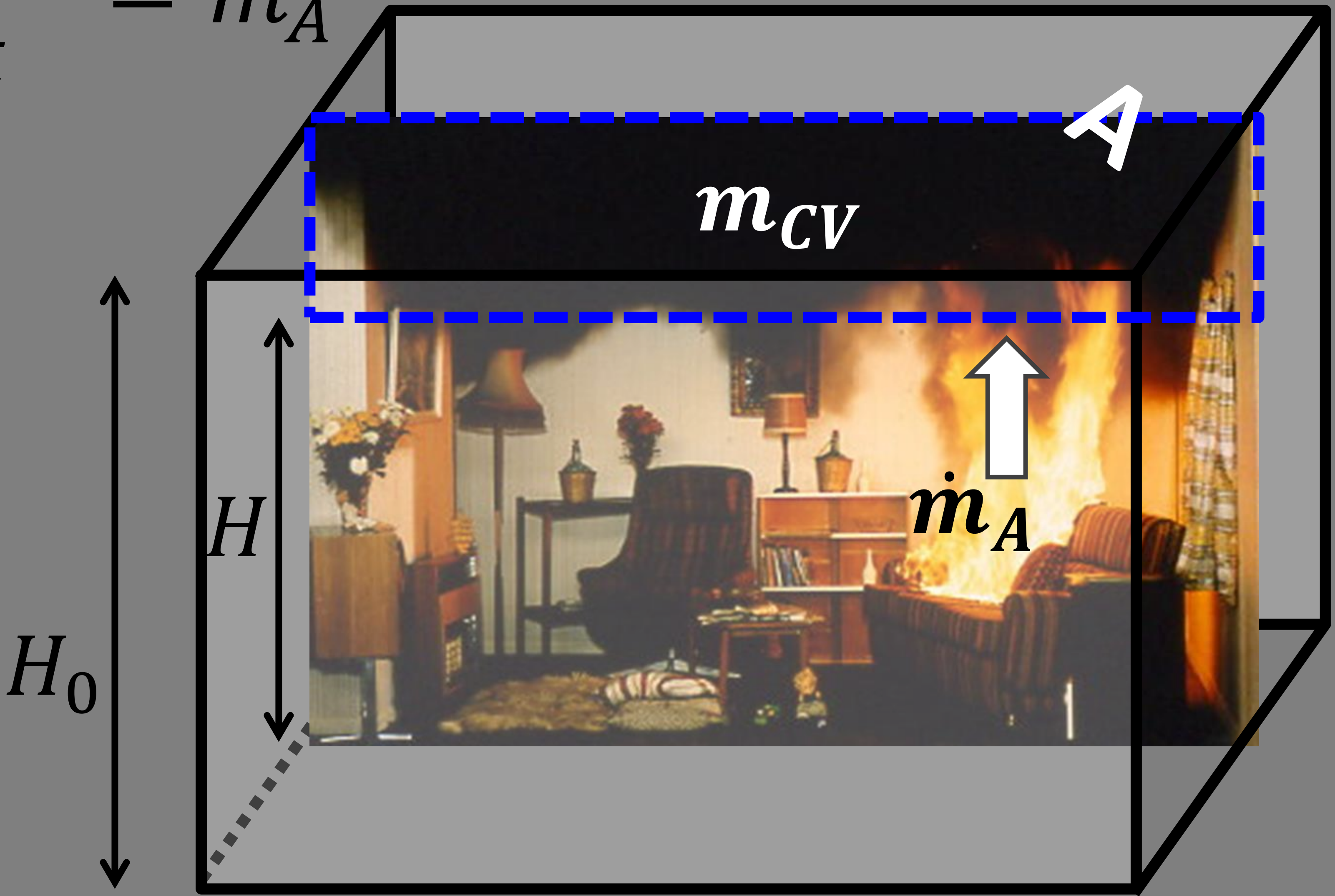
- ρ_A→Ambient density
- g→gravity (9.81 m/s²)
- $E = 0.2$→Entrainment constant
- H→ Entrainment height



Conservation of Mass: Hot Layer

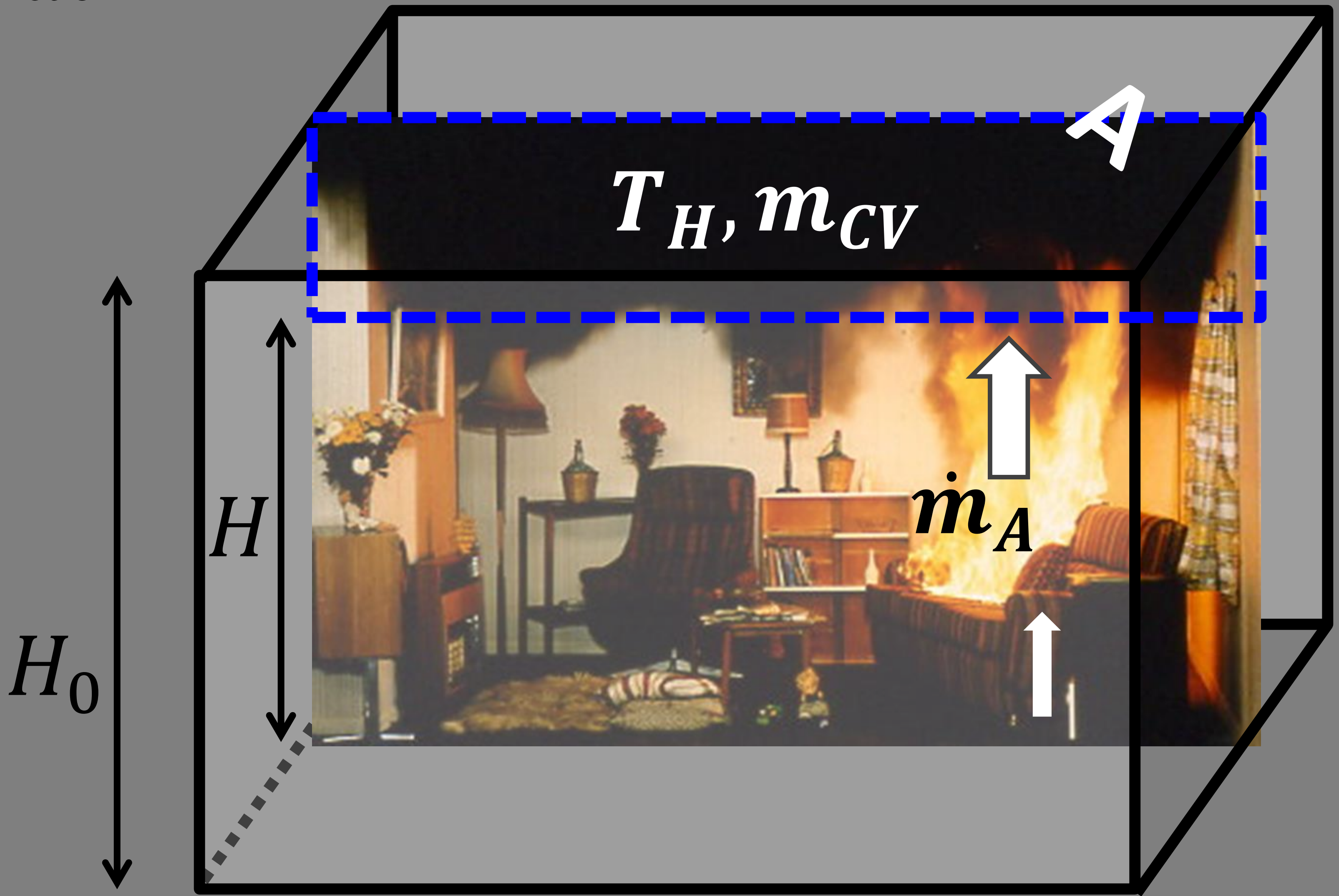
$$\frac{dm_{CV}}{dt} = \dot{m}_A$$

$$m_{CV} = \rho_H A(H_0 - H)$$



Conservation of Energy

$$\frac{d(m_{CV}C_pT_H)}{dt} = \dot{m}_A C_p T_S$$

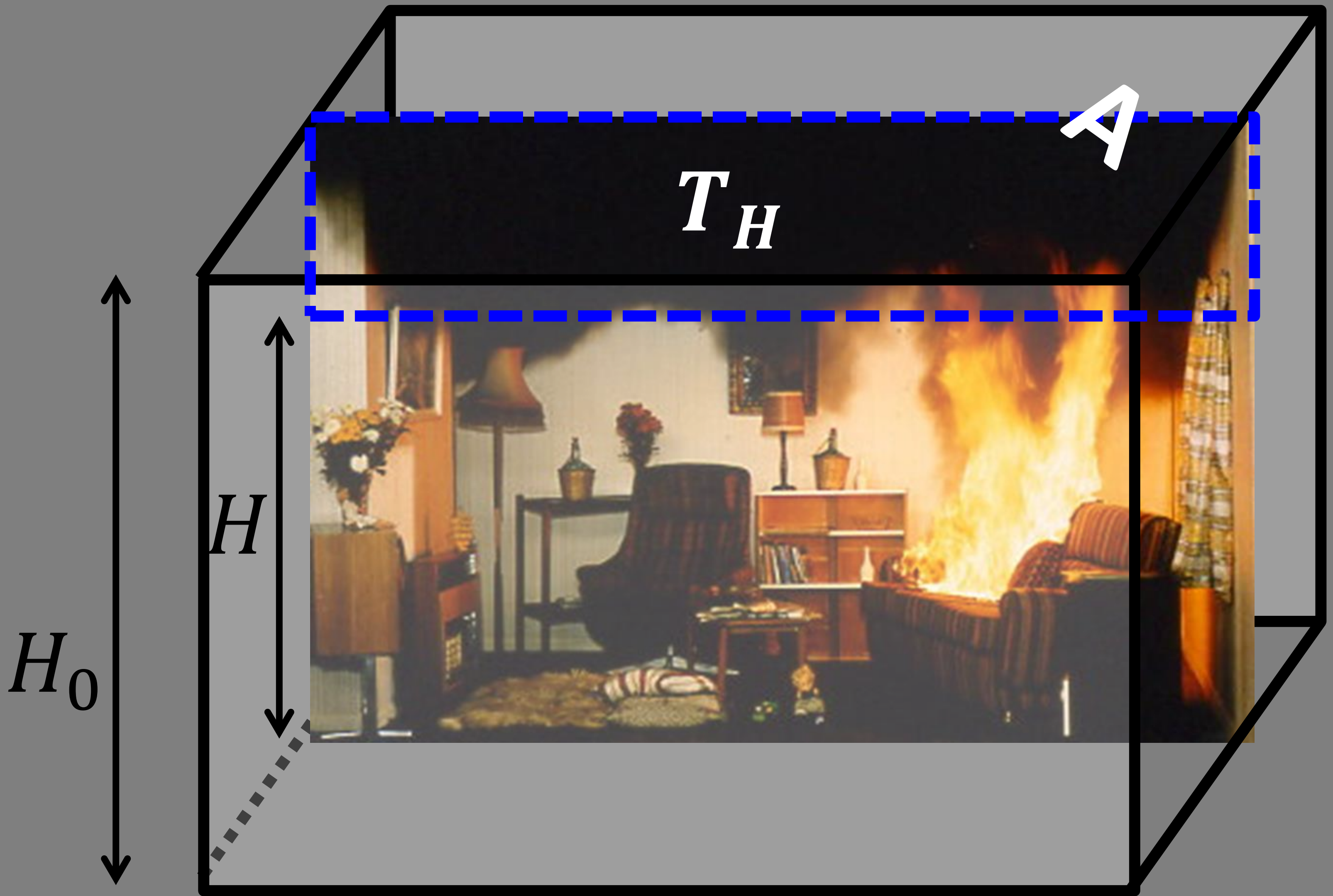


Can be solved using an Excel Spreadsheet

- $P = \rho R^* T \qquad or \qquad \rho_2 = \frac{T_1}{T_2}\rho_1$
- $\dot{Q} = \alpha t^2$
- $T_S = T_A + \frac{\dot{Q}}{\dot{m}_A C_p}$
- $\dot{m}_A = E\left(\frac{g\rho_A^2}{C_p T_A}\right)^{1/3} \dot{Q}^{1/3} H^{5/3}$
- $\frac{dm_{CV}}{dt} = \dot{m}_A \qquad m_{CV} = \rho_H A(H_0 - H) \rightarrow \Delta H_t = \frac{m_{CV,t+1}}{A\rho_2}$
- $\frac{d(m_{CV} C_p T_H)}{dt} = \dot{m}_A C_p T_S \rightarrow T_{H,t+1} = \frac{m_{CV,t} T_{H,t} + \dot{m}_A \Delta t T_S}{m_{CV,t+1}}$

Example: Slow Growing Fire

$$H_0 = 2.75\,m, X_0 = 4.75\,m, Y_0 = 3.5\,m$$

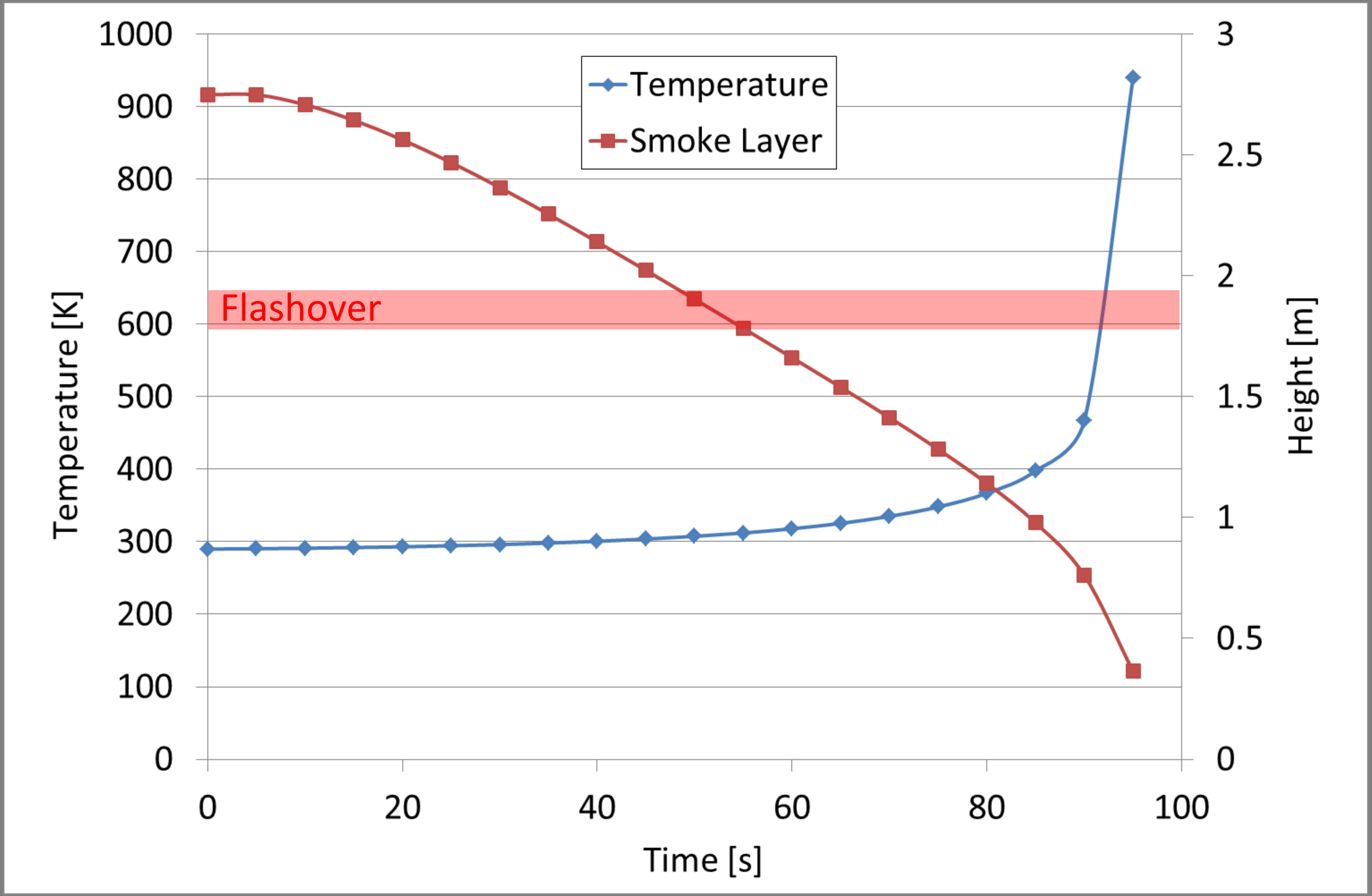


Implementation

α(slow)	0.0029	W/s2	H0	2.75	m	$E\left(\frac{g\rho_A^2}{C_p T_A}\right)^{1/3}$	
E	0.2		X0	4.75	m		0.073042309
g	9.81	m/s2	Y0	3.5	m		
ρA	1.2	kg/m3	A	16.625			
Cp	1	J/kg/K					
TA	290	K					
Δt	5	s					

$t_{t+1} = t_t + \Delta t$	$\dot{Q} = \alpha t^2$	$H_{t+1} = H_0 - \Delta H_t$	$\dot{m}_A = E\left(\frac{g\rho_A^2}{C_p T_A}\right)^{1/3} \dot{Q}^{1/3} H^{5/3}$	$T_S = T_A + \frac{\dot{Q}}{\dot{m}_A C_p}$	$m_{CV,t+1} = m_{CV,t} + \dot{m}_A \Delta t$	$T_{H,t+1} = \frac{m_{CV,t} T_{H,t} + \dot{m}_A \Delta t T_S}{m_{CV,t+1}}$	$\rho_2 = \frac{T_1}{T_2}\rho_1$	$\Delta H_t = \frac{m_{CV,t+1}}{A\rho_2}$
0	0	2.75	0	290	0	290	1.2	0
5	0.0725	2.75	0.164402464	290.440991	0.822012318	290.440991	1.19817798	0.041266282
10	0.29	2.708733718	0.254478455	291.1395857	2.094404591	290.8654011	1.195302931	0.105395227
15	0.6525	2.644604773	0.320407468	292.0364694	3.696441933	291.3729419	1.191631993	0.18658644
20	1.16	2.56341356	0.368489362	293.1479878	5.538888744	291.9633902	1.187113726	0.280652336
25	1.8125	2.469347664	0.40176389	294.5113562	7.547708193	292.6415303	1.181618273	0.38421671
30	2.61	2.36578329	0.422421744	296.1786592	9.659816913	293.4149198	1.174966491	0.494517608
35	3.5525	2.255482392	0.432332874	298.217048	11.82148128	294.2930322	1.166935299	0.609345303
40	4.64	2.140654697	0.433169816	300.7117344	13.98733036	295.2869274	1.157254474	0.727016571
45	5.8725	2.022983429	0.426418509	303.7716818	16.11942291	296.4091935	1.145597239	0.846361456
50	7.25	1.903638544	0.413359555	307.5392099	18.18622068	297.6740793	1.131563029	0.966723004
55	8.7725	1.783276996	0.395045362	312.2063106	20.16144749	299.0978091	1.114647553	1.087983949
60	10.44	1.662016051	0.372277411	318.0436032	22.02283455	300.6991223	1.094189591	1.21065105
65	12.2525	1.53934895	0.345576763	325.4552195	23.75071836	302.5001482	1.069271528	1.336063479
70	14.21	1.413936521	0.315129487	335.0925749	25.3263658	304.5278443	1.038518983	1.466887413
75	16.3125	1.283112587	0.280665661	348.1207547	26.7296941	306.8165037	0.999653124	1.60835905
80	18.56	1.14164095	0.241166169	366.9593849	27.93552494	309.4125581	0.948333833	1.771878498
85	20.9525	0.978121502	0.194077172	397.9596314	28.90591081	312.3851275	0.874460555	1.988313129
90	23.49	0.761686871	0.132891219	466.7611149	29.5703669	315.8540079	0.745563392	2.385670629
95	26.1725	0.364329371	0.04030385	939.3796419	29.77188615	320.0745138	0.370457251	4.833999439

Compartment Evolution



Summary

- Zone Model – Divides the room into two well defined zones
  - Upper Layer – Hot combustion products
  - Lower Layer – Cold air
- Provides the evolution of the height and temperature of the hot layer
  - It depends on an entrainment correlation
  - Results form a simple mass and energy balance between two control volumes
  - Breaks down when the smoke layer gets close to the floor, when the two control volumes become one and the entrainment correlation is no longer valid

Post-Flashover compartment Fire

Structural Analysis

The collapse of the WTC towers emphasizes the need for a detailed structural analysis of optimized buildings – ie. Tall Buildings

Existing Framework

1962-1972

1969-1976

1958

1975

Structural Analysis

Heat Transfer

$$\rho C_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2}$$

$$-k \left.\frac{\partial T}{\partial x}\right|_{x=0} = \dot{q}''_{NET}$$

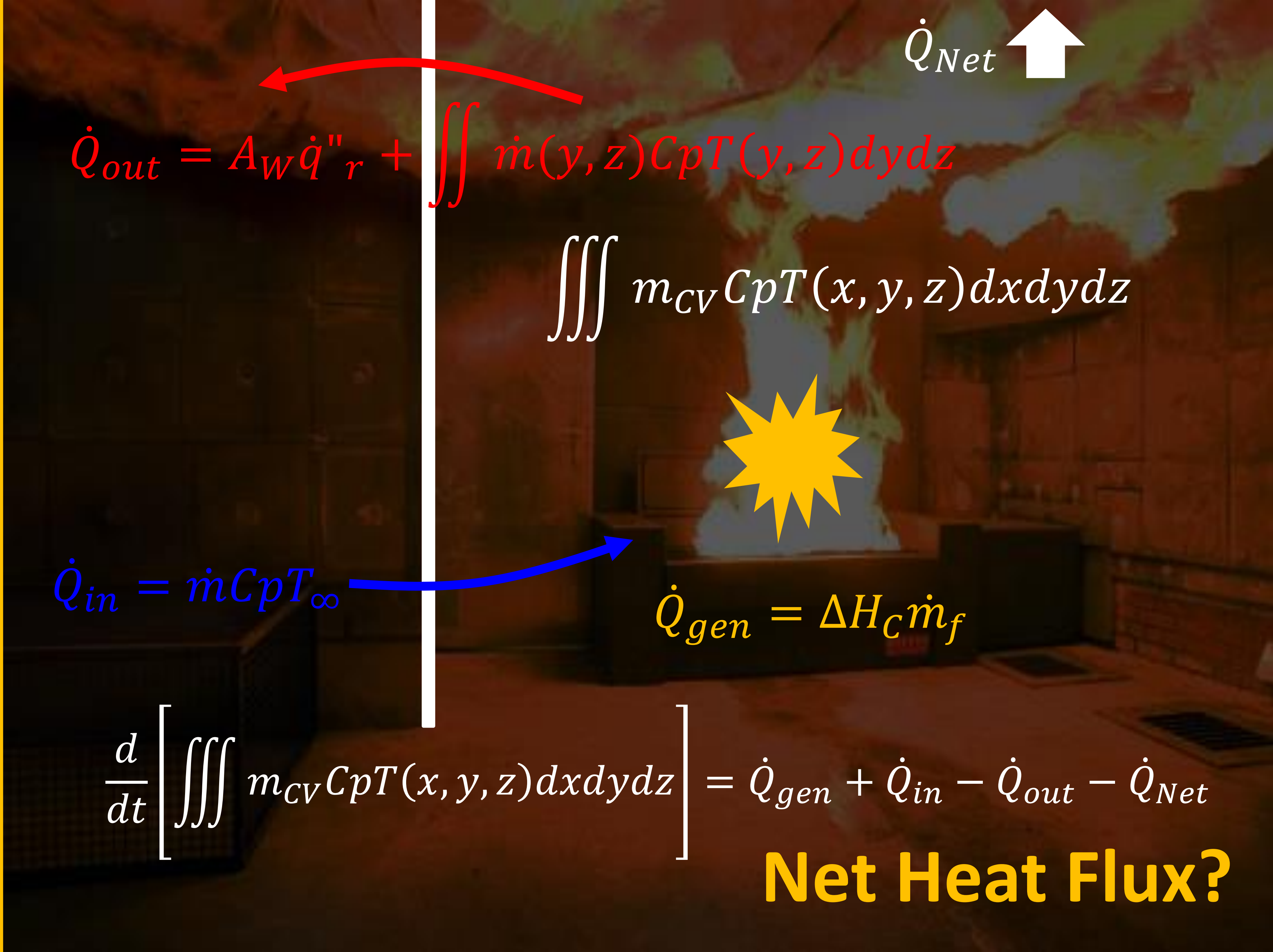
$$\left.\frac{\partial T}{\partial x}\right|_{x=x_S} = 0$$

$$T(t=0) = T_0$$

Fire Dynamics

Back to the basics …

Too Complicated!



The Compartment Fire

- It was understood that solving the full energy equation was not possible
- The different characteristic time scales of structure and fire do not require such precision

- Looked for a simplified formulation: The Compartment Fire

Typical Compartment

Thomas & Heselden (1972)

- Realistic scale compartment fires (~4 m x 4 m x 4 m) aimed at delivering average temperatures
- Simple instrumentation: Single/Two thermocouples

Regime I

Regime II

Thomas, P.H., and Heselden, A.J.M., "Fully developed fires in single compartments", CIB Report No 20. Fire Research Note 923, Fire Research Station, Borehamwood, England, UK, 1972.

Assumptions – Regime I

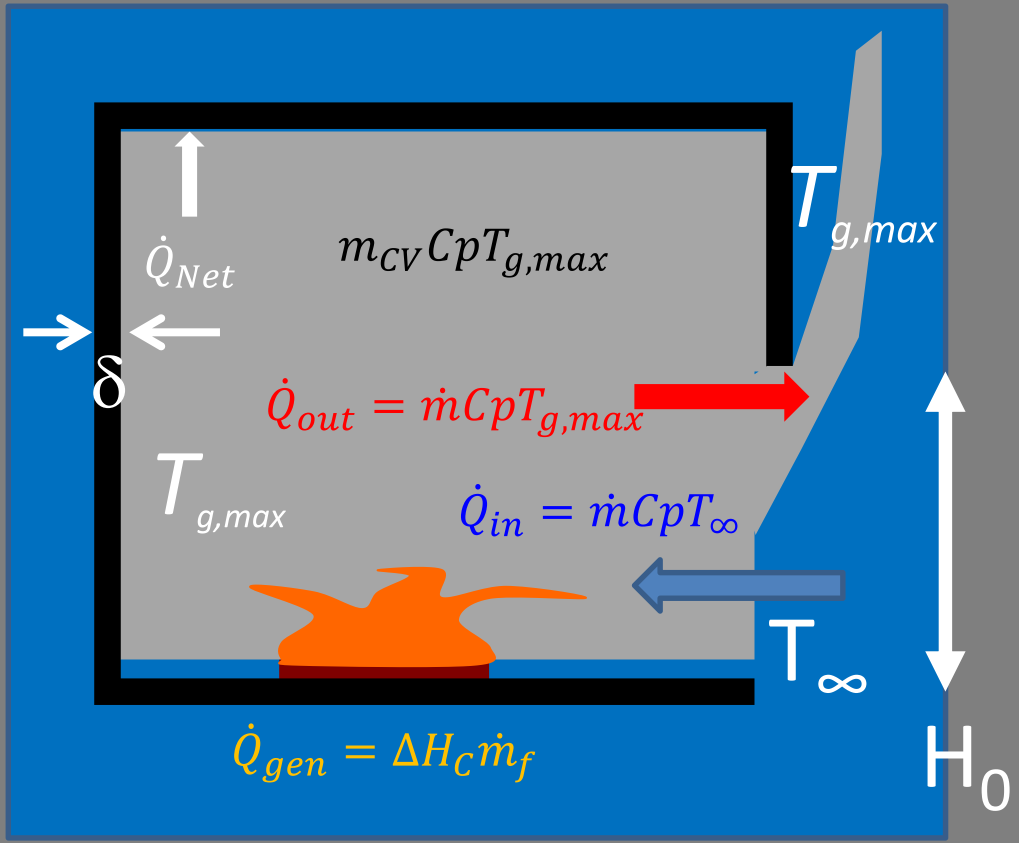
- The heat release rate is defined by the complete consumption of all oxygen entering the compartment and its subsequent transformation into energy, $\dot{Q} = \dot{m} Y_{O_2,\infty} \Delta H c_{O_2}$.
  - Eliminates the need to define the oxygen concentration in the outgoing combustion products
  - Eliminates the need to resolve the oxygen transport equation within the compartment.
  - Limits the analysis to scenarios where there is excess fuel availability
  - Chemistry is fast enough to consume all oxygen transported to the reaction zone
  - The control volume acts as a perfectly stirred reactor.
  - The heat of combustion is assumed to be an invariant/ the completeness of combustion is independent of the compartment.
- Radiative losses through the openings are assumed to be negligible therefore $\dot{Q}_{out}$ is treated as an advection term (3% of the total energy released (Harmathy)).
- There are no gas or solid phase temperature spatial distributions within the compartment.
- Mass transfer through the openings is governed by static pressure differences ($\dot{m} = C A_O \sqrt{H_O}$)
  - all velocities within the compartment to be negligible
  - Different values of the constant were derived by Harmathy and calculated by Thomas for different experimental conditions.

Maximum Compartment Temperature

$$\frac{d}{dt}[m_{CV}CpT_S] = \dot{Q}_{gen} + \dot{Q}_{in} - \dot{Q}_{out} - \dot{Q}_{Net}$$

S.S.

$\dot{Q}_{in} \ll \dot{Q}_{out}$



$$\dot{m}_{in} = \dot{m}_{out} = \dot{m} = CA_O\sqrt{H_O}$$

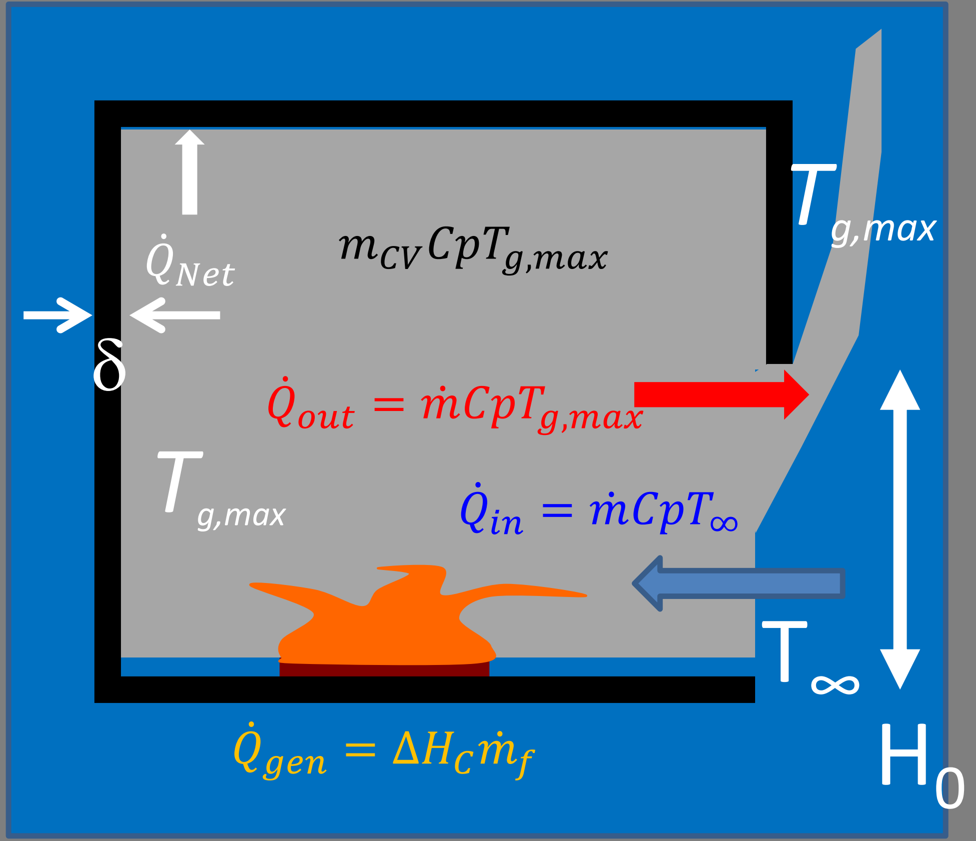
$$\dot{Q}_{gen} = \dot{m}Y_{O_2,\infty}\Delta Hc_{O_2}$$

$$\dot{Q}_{out} = \dot{m}C_pT_{g,max}$$

$$\dot{Q}_{Net} = Ak\frac{(T_{g,max} - T_{\infty})}{\delta}$$

Maximum Compartment Temperature

$$\boxed{0 = \dot{Q}_{gen} - \dot{Q}_{out} - \dot{Q}_{Net}}$$



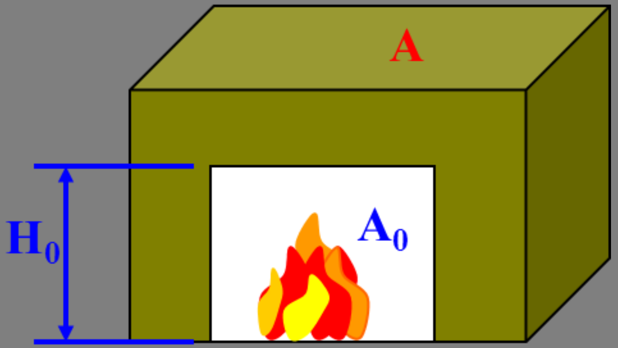
Substituting and solving for $T_{g,max}$

$$\boxed{T_{g,max} = \left(\frac{1 + \frac{T_{\infty}}{T_{CD}}}{1 + \frac{T_F}{T_{CD}}} \right) T_F}$$

$$T_F = Y_{O_2,\infty} \Delta H c_{O_2} / C_p$$

$$T_{CD} = \frac{C Y_{O_2,\infty} \Delta H c_{O_2}}{(k/\delta)} \left(\frac{A_O \sqrt{H_O}}{A} \right)$$

The Data



$$A/A_0\sqrt{H_0}$$

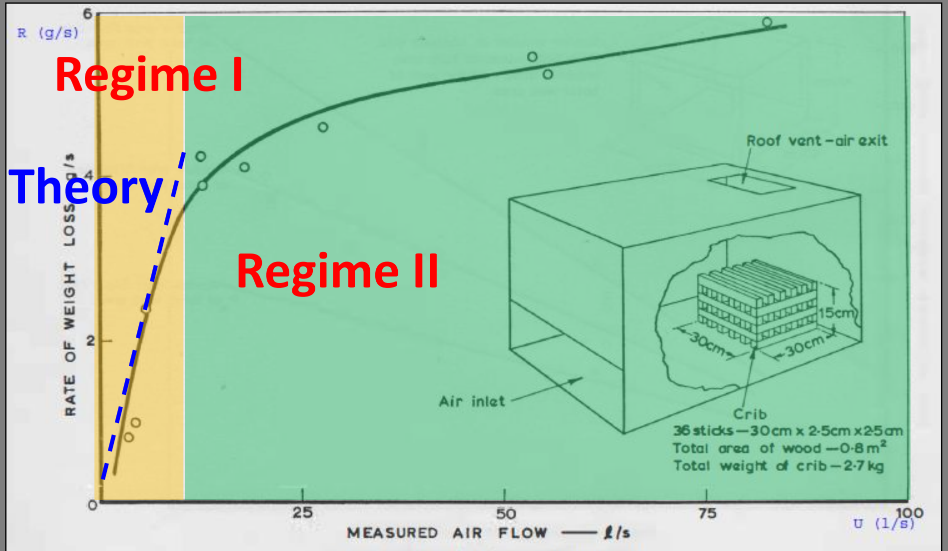
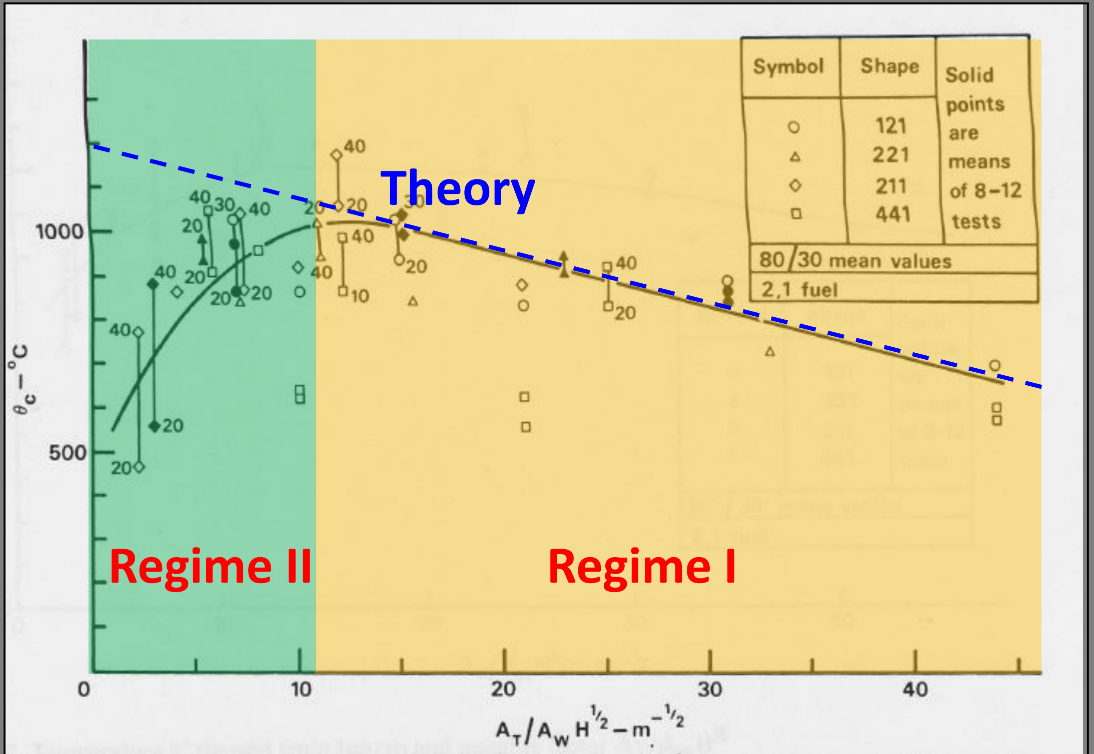


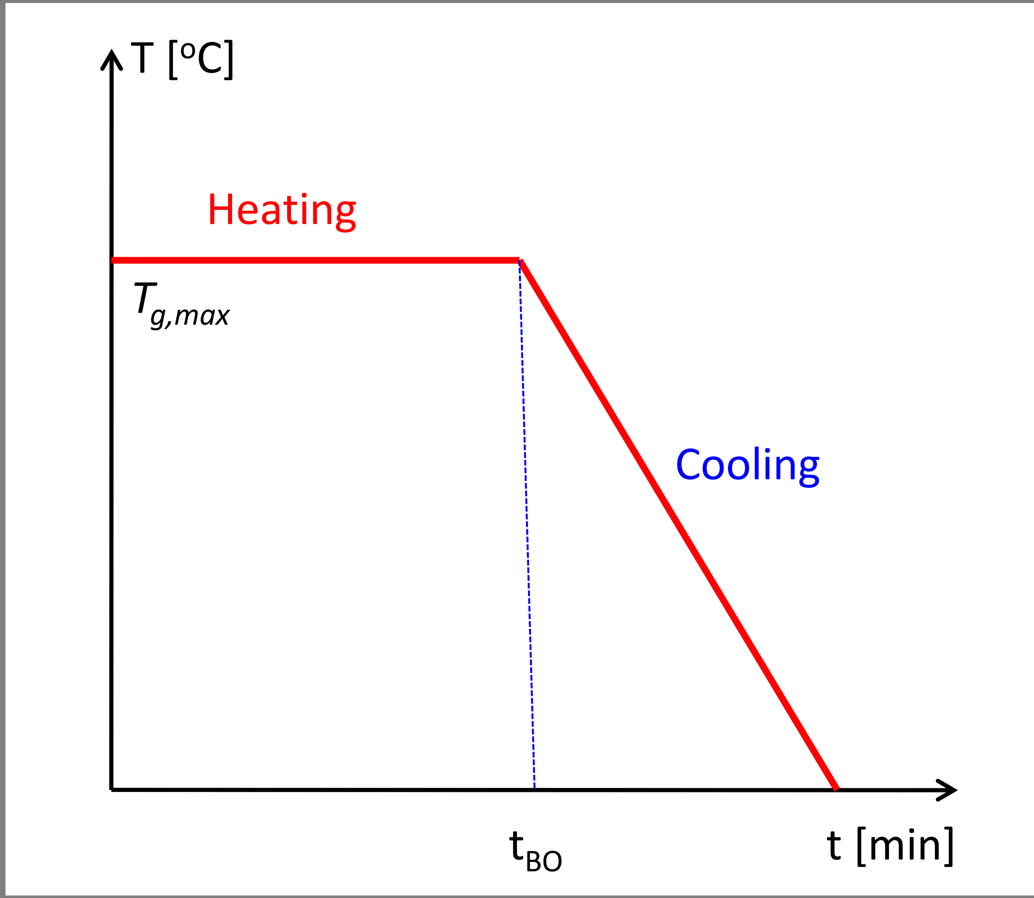
FIG. 2 Effect of air flow on burning rate

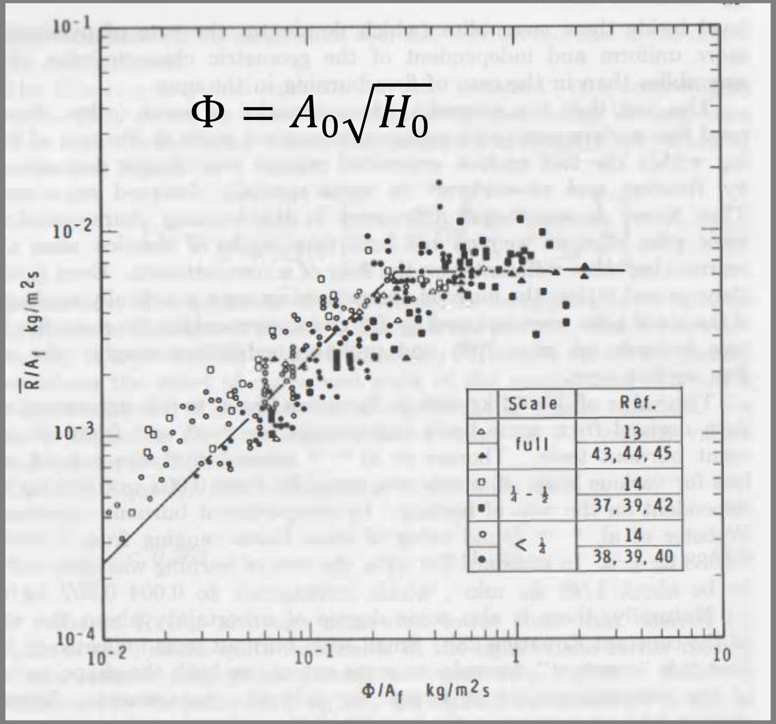


A_T excludes floor and opening. Numbers are fire load densities (kg/m²) at ends of range of temperatures

Design Method

(Law, M., "A Basis for The Design of Fire Protection of Building Structures," Struct. Eng., no. February, pp. 25–33, 1983.)





$R = 0.1\ A_0 H_0^{1/2}$ (kg/s)

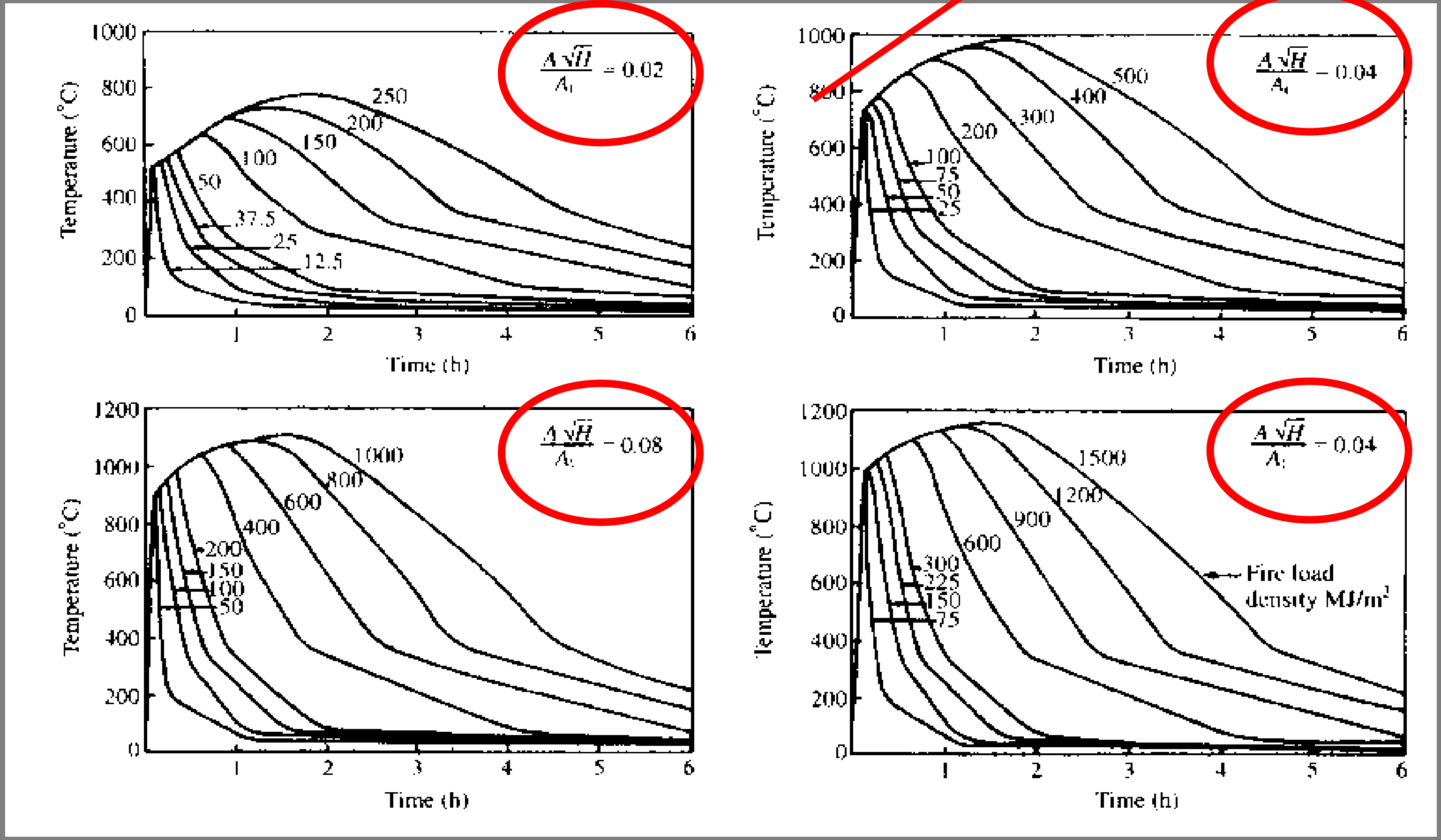
Kawagoe (1958)
Thomas & Heselden (1972)

$$t_{BO} = \frac{M_f}{R}$$

Parametric Fires

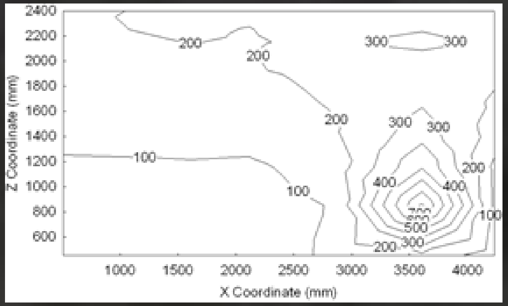
(Pettersson, O. Magnusson, S. E. and Thor, J. "Fire Engineering Design of Steel Structures," Stockholm, Jun. 1976.)

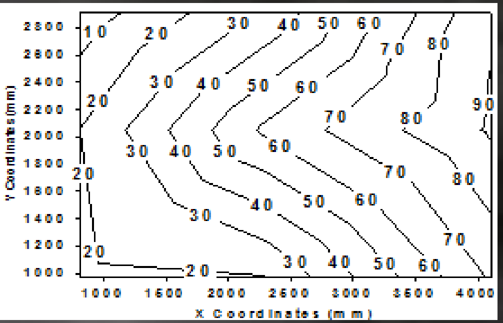
$\dot{Q}_{Net}$

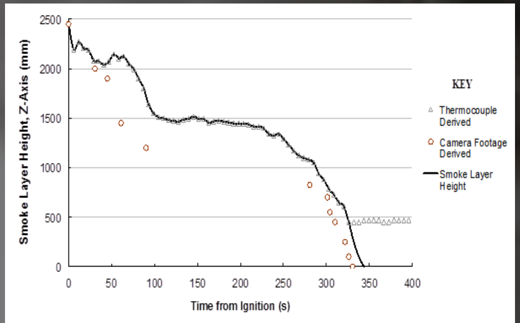


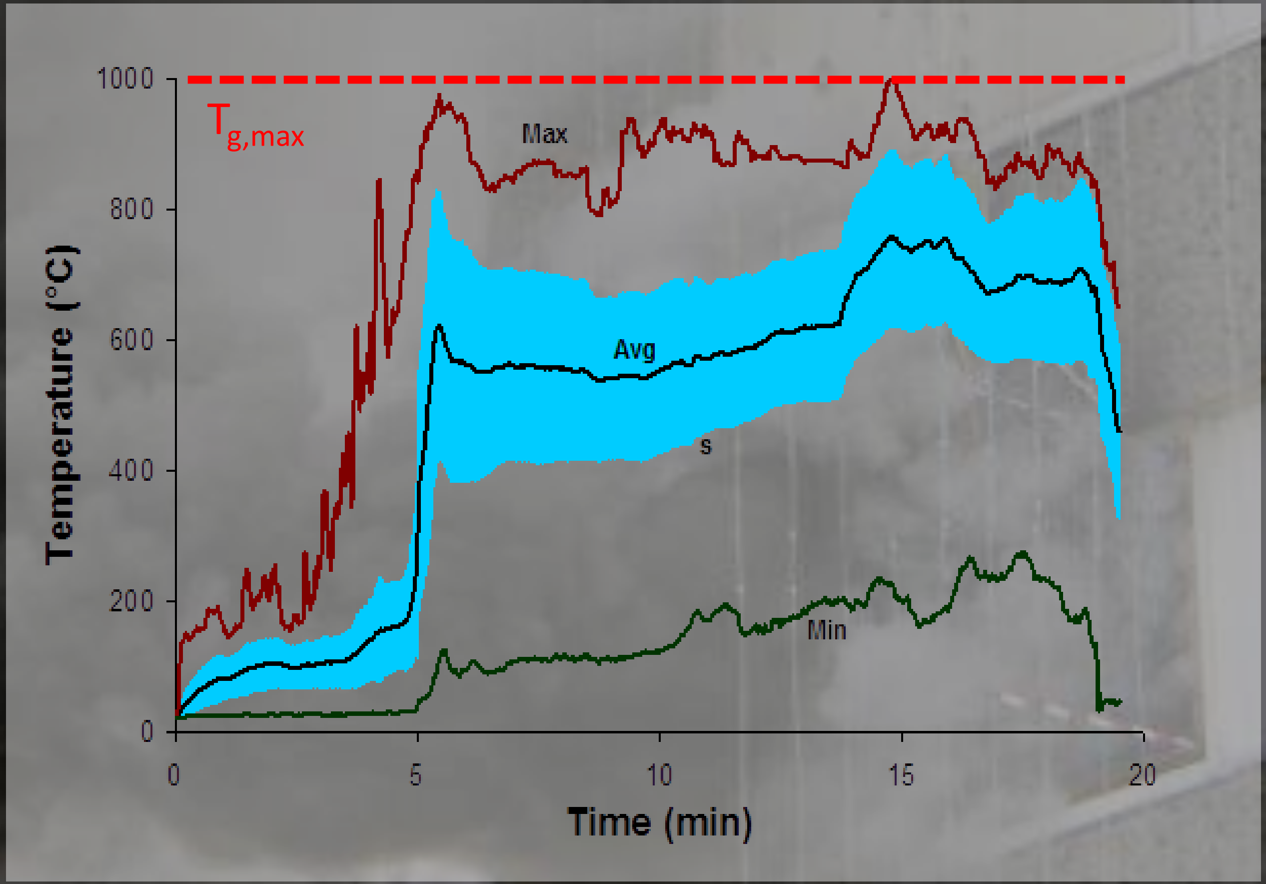
- Recorded temperature evolution – effect of structural heating
- Average temperature – single thermocouple rack (6 – TC)

Realistic Fire









Regime II?

- Data scatter is very large
- Factors such as aspect ratio, nature of the fuel and scale were shown by Thomas & Heselden to have a significant effect on the resulting temperatures
- The relationships between $T_{g,max}$ and R with $A/A_0\sqrt{H_0}$ and $A_0\sqrt{H_0}$ are no longer valid

$$\frac{A}{A_0\sqrt{H_0}}$$

- Quintiere
- McCaffrey
- Pettersson
- Rockett
- Tanaka, etc.

Executive Summary

(SFPE Engineering Guide – Fire Exposures to structural Elements – May 2004)

Designing fire resistance on a performance basis requires three steps:

1. Estimating the fire boundary conditions
2. Determining the thermal response of the structure
3. Determining the structural response

This guide provides information relevant to estimating the fire boundary conditions resulting from a fully developed fire. Methods are provided for fully developed enclosure fires and for fire plumes. Fully developed enclosure fires can be expected in compartments with fuel uniformly distributed over their interiors. For situations where a fire would not be enclosed or for enclosures with sparse distributions or concentrated fuel packets, the methods identified in the fire plumes section should be used.

Several methods are evaluated for fully developed enclosure fires. Law's method is recommended for all roughly cubic compartments and in long, narrow compartments where $\frac{A}{A_o\sqrt{H_o}}$ does not exceed $\approx 18\ m^{-1/2}$. To ensure that predictions are sufficiently conservative in design situations, the predicted burning rate should be reduced by a factor of 1.4 and the temperature adjustment should not be reduced by Law's Ψ factor.

Law's method does not predict temperatures during the decay stage. For cases where a prediction of temperatures during the decay stage is desired, a decay rate of 7°C/min can be used for fires with a predicted duration of 60 minutes or more, and a decay rate of 10°C/min can be used for fires with a predicted duration of less than 60 minutes.

For long, narrow spaces in which $\frac{A}{A_o\sqrt{H_o}}$ is in the range of 45 to 85 $m^{-1/2}$, Magnusson and Thelandersson provide reasonable predictions of temperature and duration. For long, narrow spaces in which $\frac{A}{A_o\sqrt{H_o}}$ is approximately 345 $m^{-1/2}$, Lie's method is recommended.

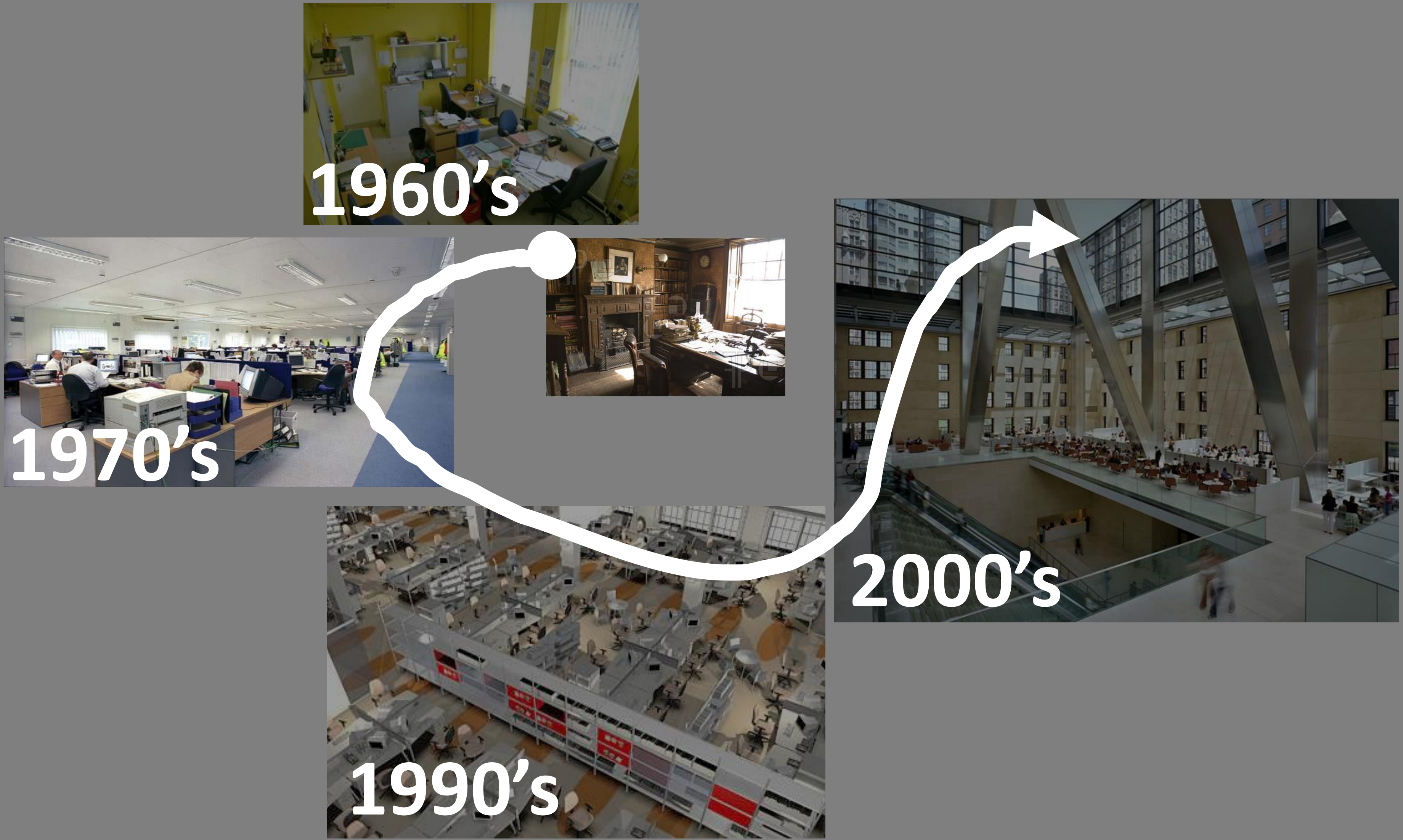
For ranges of $\frac{A}{A_o\sqrt{H_o}}$ that fall outside the ranges identified above, the calculations should be performed using the methods identified for the ranges of $\frac{A}{A_o\sqrt{H_o}}$ that bound the situation of interest, and the most conservative results should be used.

For fire plumes, methods are presented for conducting a bounding analysis and for specific geometries. These geometries include flat vertical walls, corners with a ceiling, unbounded flat ceilings, and an I-beam mounted below a ceiling. Additionally, correlations are provided for axisymmetric plumes for those wishing to conduct a heat transfer analysis from first principles.

Summary

- An elegant framework was established that provided an *“answer”* to a *“fundamental question”*
  - Assumptions were clearly established
  - Limitations were clearly established
- A simple design methodology was developed that provided a *“worst case: $T_{g,max}$ vs t”* curve for the purposes of structural analysis.

The End of the Compartment



“To me there has never been a higher source of earthly honour or distinction than to be remembered through the advances I brought to science.”

Isaac Newton

Philip Humphrey Thomas
(16 June 1926 - 14 January 2014)