DIME
Università degli Studi di Genova

Fire Safety Systems

21st November 2016
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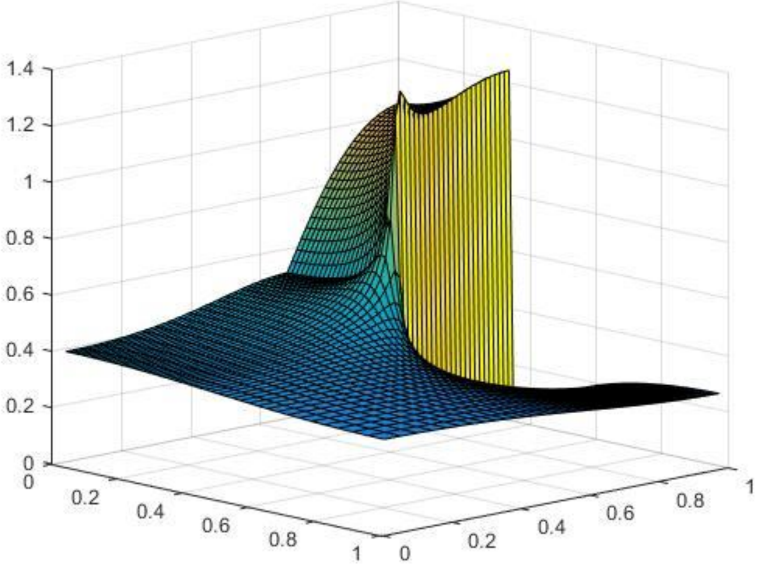
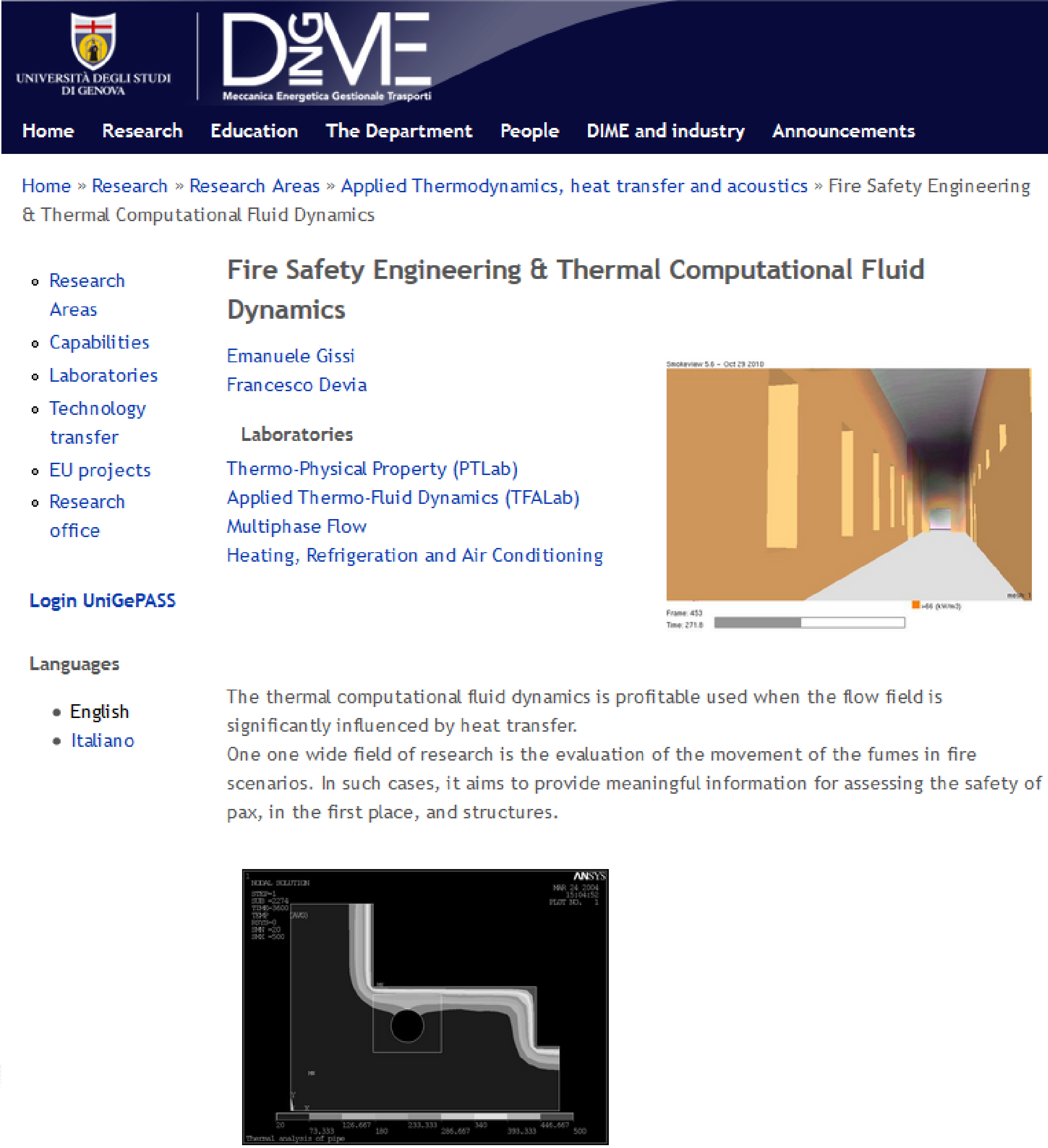
- **Applied thermodynamics**
- **Heat transfer**
- **CFD**
- **Thermal radiation**





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- Research Areas
- Capabilities
- Laboratories
- Technology transfer
- EU projects
- Research office

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Languages

- English
- Italiano

Fire Safety Engineering & Thermal Computational Fluid Dynamics

Emanuele Gissi
Francesco Devia

Laboratories

Thermo-Physical Property (PTLab)
Applied Thermo-Fluid Dynamics (TFALab)
Multiphase Flow
Heating, Refrigeration and Air Conditioning

The thermal computational fluid dynamics is profitable used when the flow field is significantly influenced by heat transfer.
One one wide field of research is the evaluation of the movement of the fumes in fire scenarios. In such cases, it aims to provide meaningful information for assessing the safety of pax, in the first place, and structures.

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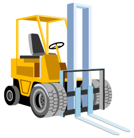
Aim of this lesson



- Recalling some basic aspect of fire
- Giving you some general hints on Fire Safety Engineering activities
- Generally describing Fire, Smoke, Smoke Movement in Buildings
- Showing application to a real case

…basic of Fire Safety Engineering

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General scheme of this lesson

- Some general premises
- Physical aspects
- Movies, photo and pictures (interesting?)
- Main flame parameters: temperature, power, product of combustion, soot, radiation, etc…
- Equation of (hot) fluid flow
- Chimney effect
- Hot fluid stratification and Zone-models

- Presentation of a real case

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It’s Christmas time…

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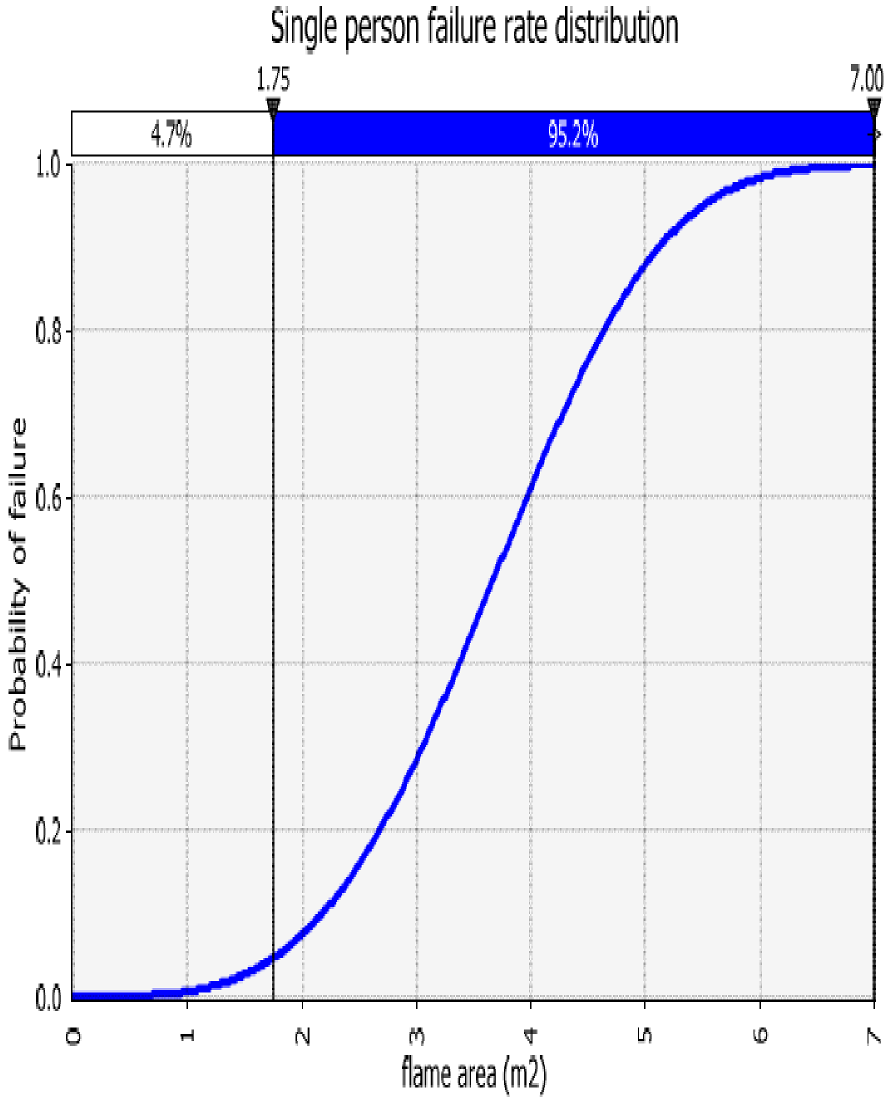
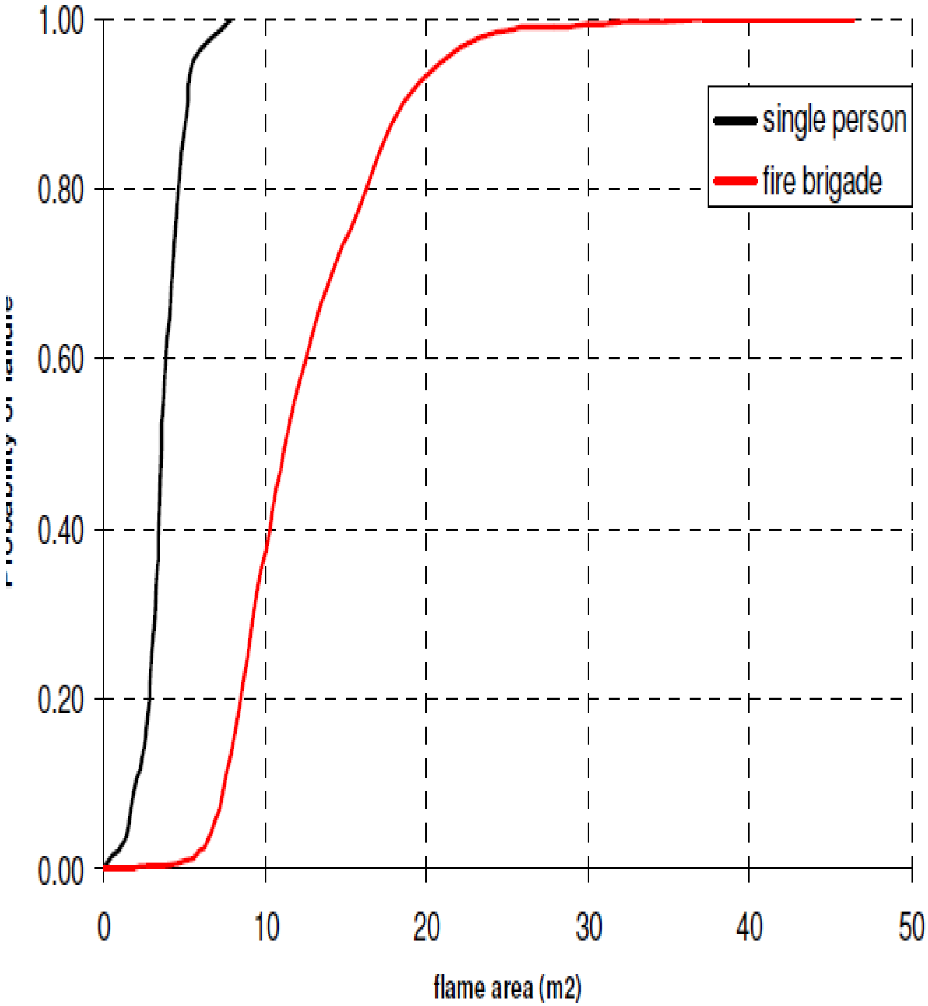
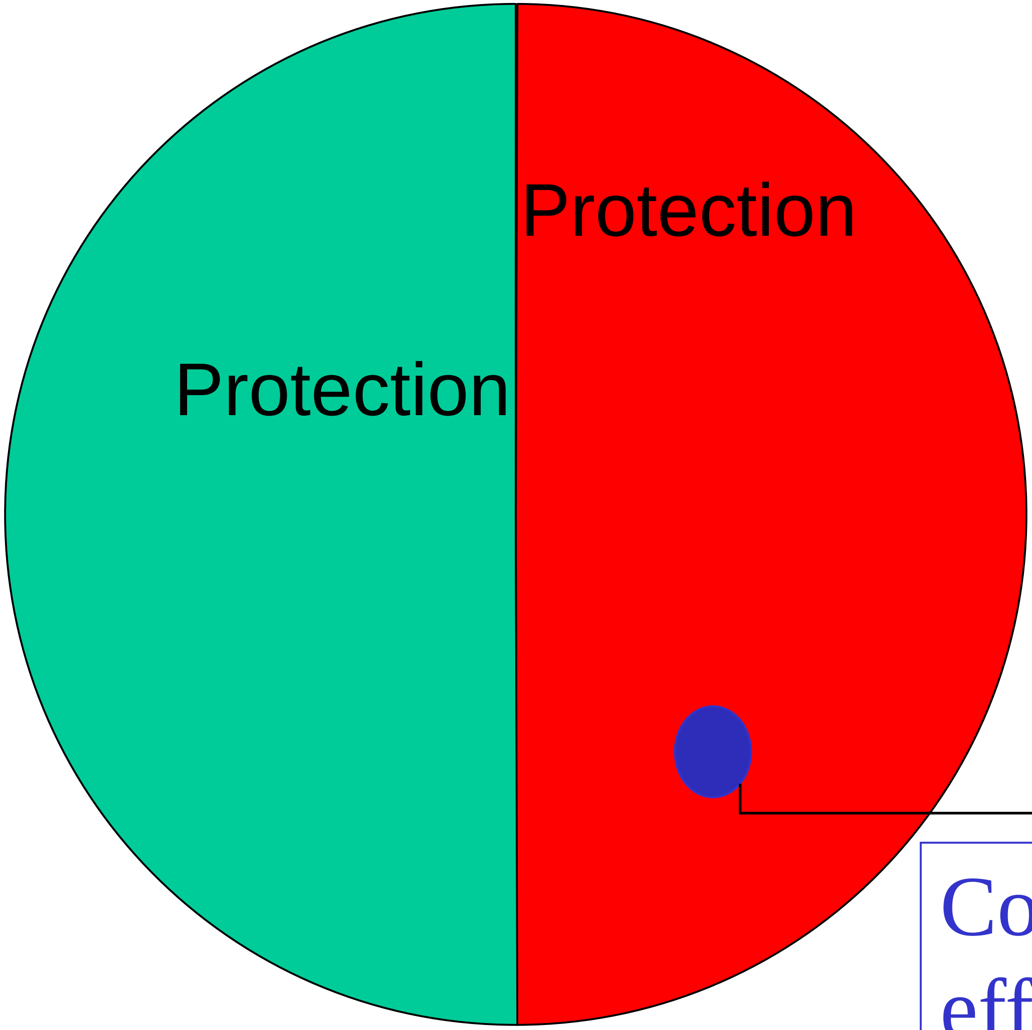
Extinguishing failure rates





"Probabilistic Framework for Onboard Fire Safety" A Grandison, Z. Wang , E. Galea, M.Patel (UOG), P. Lohrmann (BMT), N. Themelis (NTUA), W. Cai, G. Mermiris (SSRC)

Fire Safety Engineering



Control of effluent

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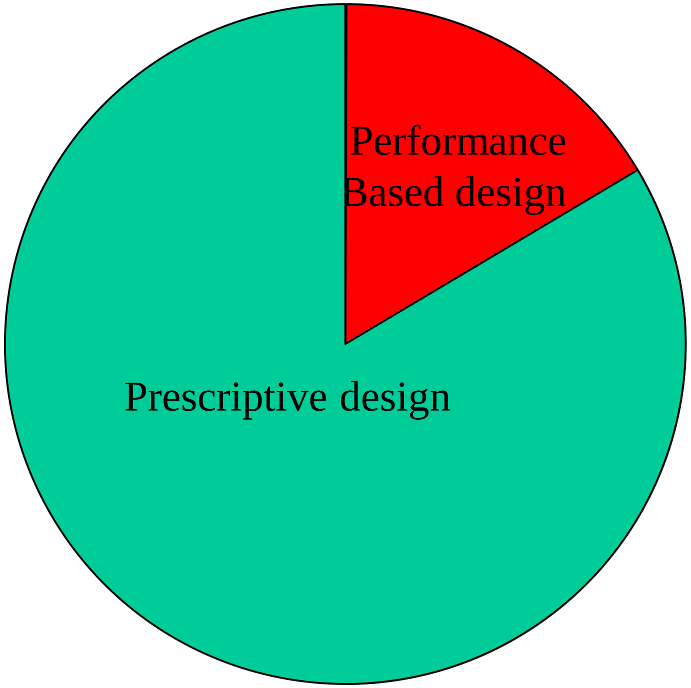
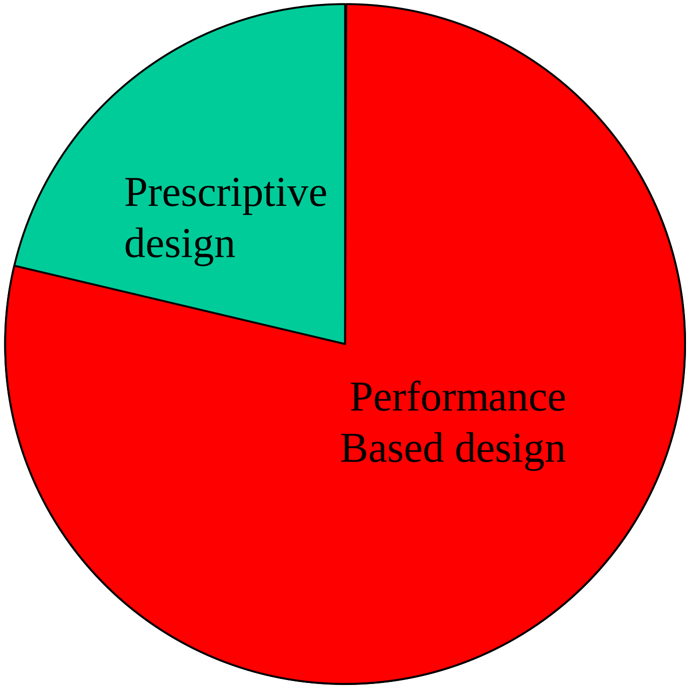
Fire Safety Engineering



# of activity



Costs, effort, complexity, time…

Prescrittive vs. Performance based design

Prescrittive

Define a set o systems, procedures and devices that fulfil to the requirement of a norm:

- experience
- tradition
- physical consuetude

Generate the norm through a non-linear process

Performance based

Define a set o systems, procedures and devices that accomplish to a task:

- physical law (models)
- mathematical models
- approximation and uncertainties

Generate results through errors and misjudgements

Antefact 1:

Why undertake a performance-based approach to FSE (Fire Safety Engineering)?

- Because, after careful considerations, it’s impossible to find any other way, i.e. it is clear that one must proceed in derogation of the prescriptive rules

How to proceed …?

- One have to define prevention, protection, mitigation and management, in order to ensure a level of safety, which must be, at least, equivalent to the one ensured by the prescriptive rules and… prove it

Project phases

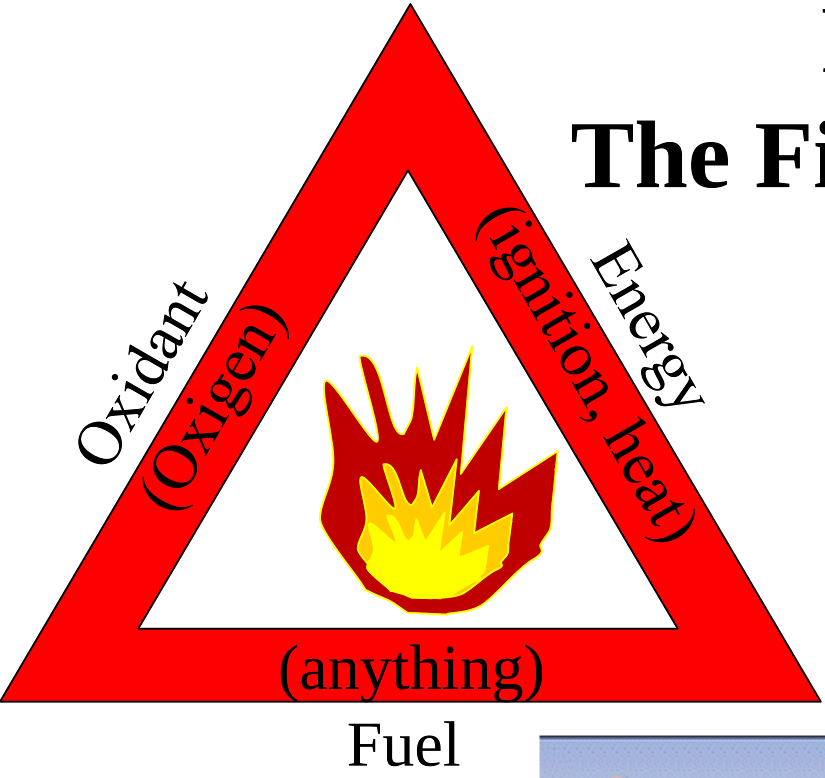
- **Phase 1 Preliminary analysis and project definition Phase 2 Definition of target level of safety (explicitly quantitative performance)**
- **Phase 3 Definition of Fire scenarios**
- **Phase 4 Design of solution**
- **Phase 5 Definition of fire safety management plan**

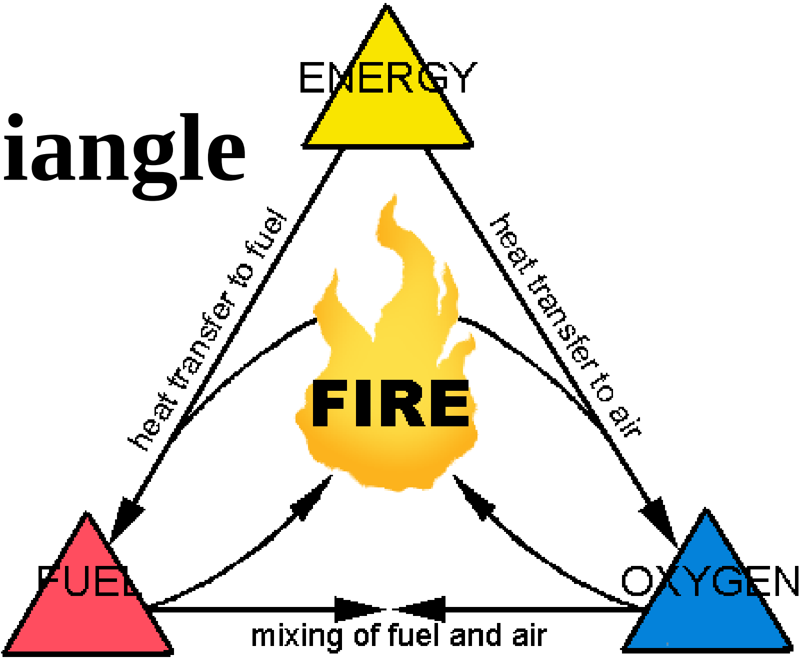
Let’s start at the very beginning…

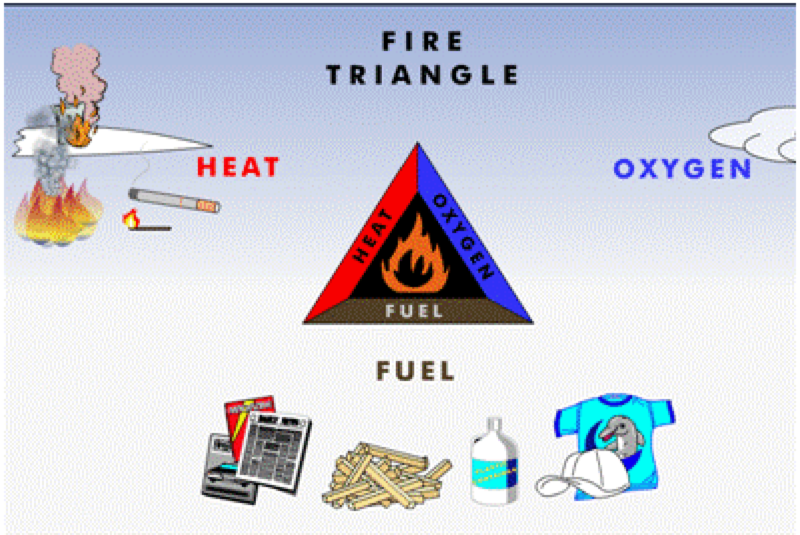
Fire?

What is fire?

FIRE
The Fire Triangle







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Fire? What is fire?

History of a candle
(combustion of liquid and solids)

Michael Faraday (1791-1867):
The Chemical History of A Candle, 1860

http://www.interactives.co.uk/candle.htm
http://www.gutenberg.org/ebooks/14474
http://www.fordham.edu/halsall/mod/1860Faraday-candle.asp

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Fire in compartment, material class III

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PARAMETERS AFFECTED BY HUGE UNCERTAINTY

Main parameters

- **SMOKE**
  - **Mass flow rate**
  - **m = 0.065 $(HRR)^{1/3}$ $Y^{5/3}$**

m [kg/s] smoke mass flow rate

HRR [kW]

Y [m] height*

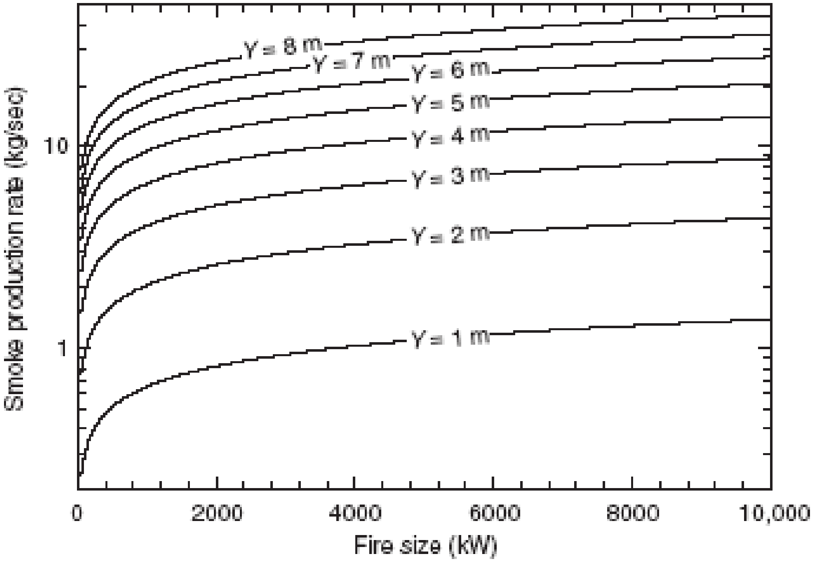

FIGURE 3.9.7 Smoke Production Rates for Steady Fires with Various Distances from the Virtual Origin

Smoke mass flow rate depends HRR

FIRE PROTECTION HANDBOOK- Sec 3 chap 9

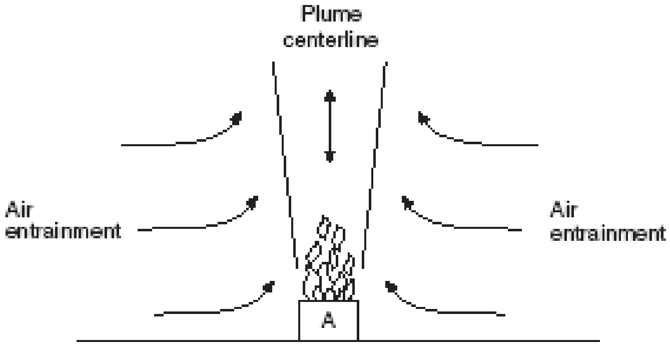

FIGURE 2.4.2 Fire in the Open. Note: A = source of fire.

Main parameters

- **SMOKE TEMPERATURE**

depends on instantaneous value of
Heat Release Rate and
on the type of fuel combustible matter

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Main parameters

- **SMOKE - SOOT**

(Soot production)
Depends on instantaneous value of
Heat Release Rate and
on the type of fuel combustible matter

Soot Yield
$X_{soot} = kg/kg_{fuel}$
$X = 0.01\text{-}0.03\ kg/kg_{fuel}$

Main parameters

Toxic effluents (asphyxiant on not) depend on the advancement of the reaction, on instantaneous value of Heat Release Rate and on the type of fuel

- **SMOKE**
  - **Chemical species:**
  - **O_2**
  - **CO_2**
  - **CO**
  - **HCN**
  - **…**

Production of ….

$X_{\dots} = kg/kg_{fuel}$

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Uncertainties in experimental measurements of Heat Release Rate

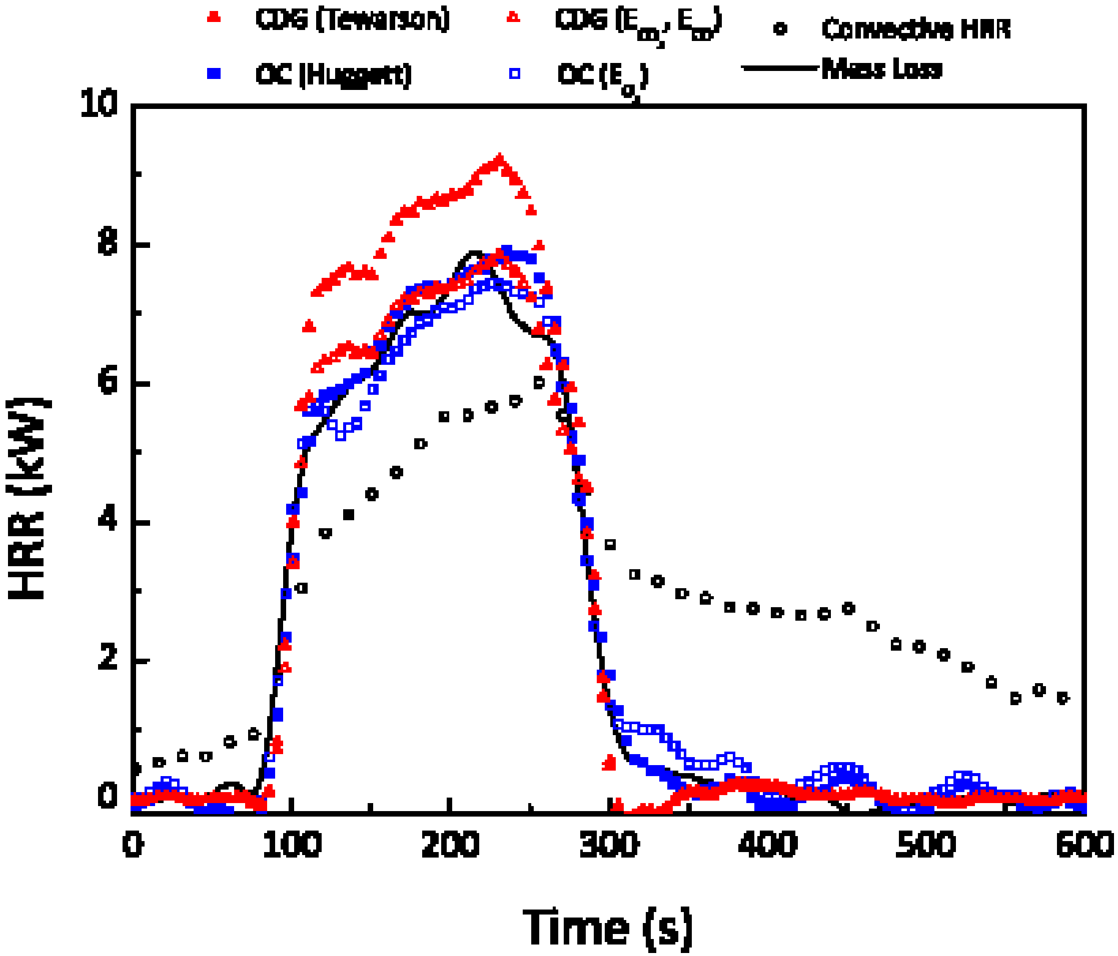

Figure 5.7. PMMA HRR estimations using various techniques and assumptions. OC (Huggett) and CDG (Tewarson), respectively refer to OC and CDG principles using Huggett and Tewarson energy constants. OC (E_{O_2}) and CDG (E_{CO_2}, E_{CO}) represent OC and CDG principles used with stoichiometric energy coefficients.

THERMAL AND CHEMICAL BEHAVIOUR *of an* ENERGETIC MATERIAL *and a* HEAT RELEASE RATE ISSUE

H. BITEAU PhD thesis

Effect of "interpretation" of measurements

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Heat Release Rate per Unit Area [kW/m²]

HRRPUA

MEASURED

(two examples from SFPE Handbook)

3–12 **Hazard Calculations**

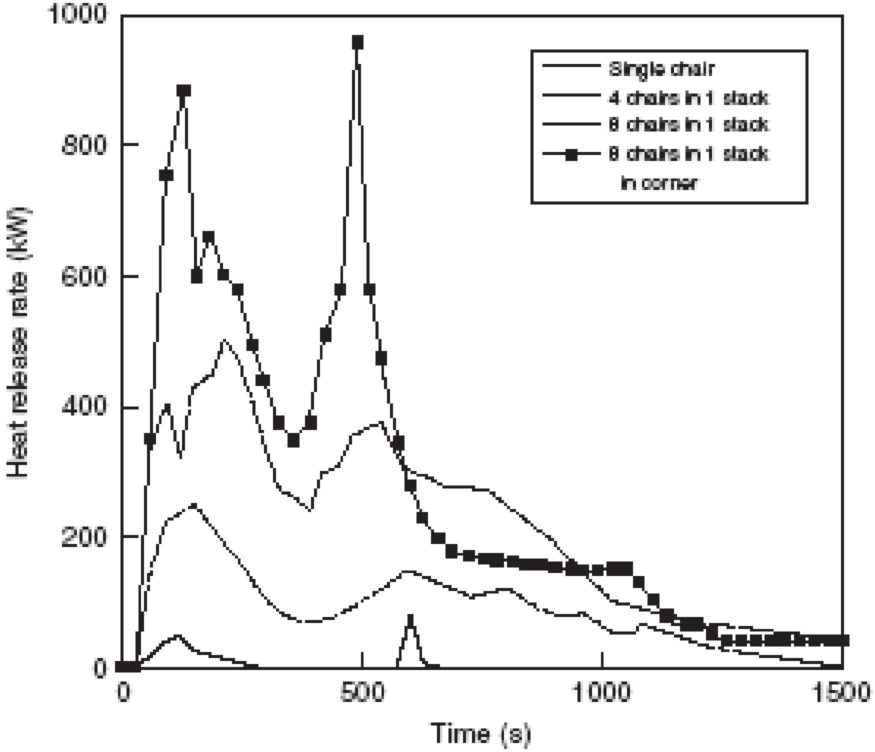

Figure 3-1.16. *Metal-frame, upholstered stacking chairs.*

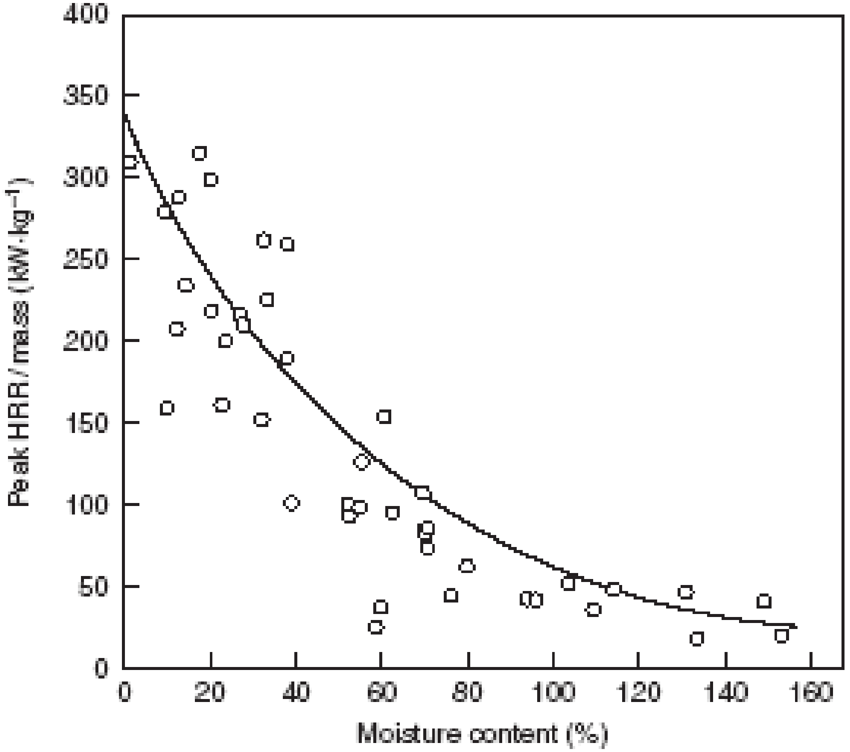

Figure 3-1.17. *The peak HRR for Douglas fir Christmas trees, as a function of moisture and mass.*

HRR magnitude

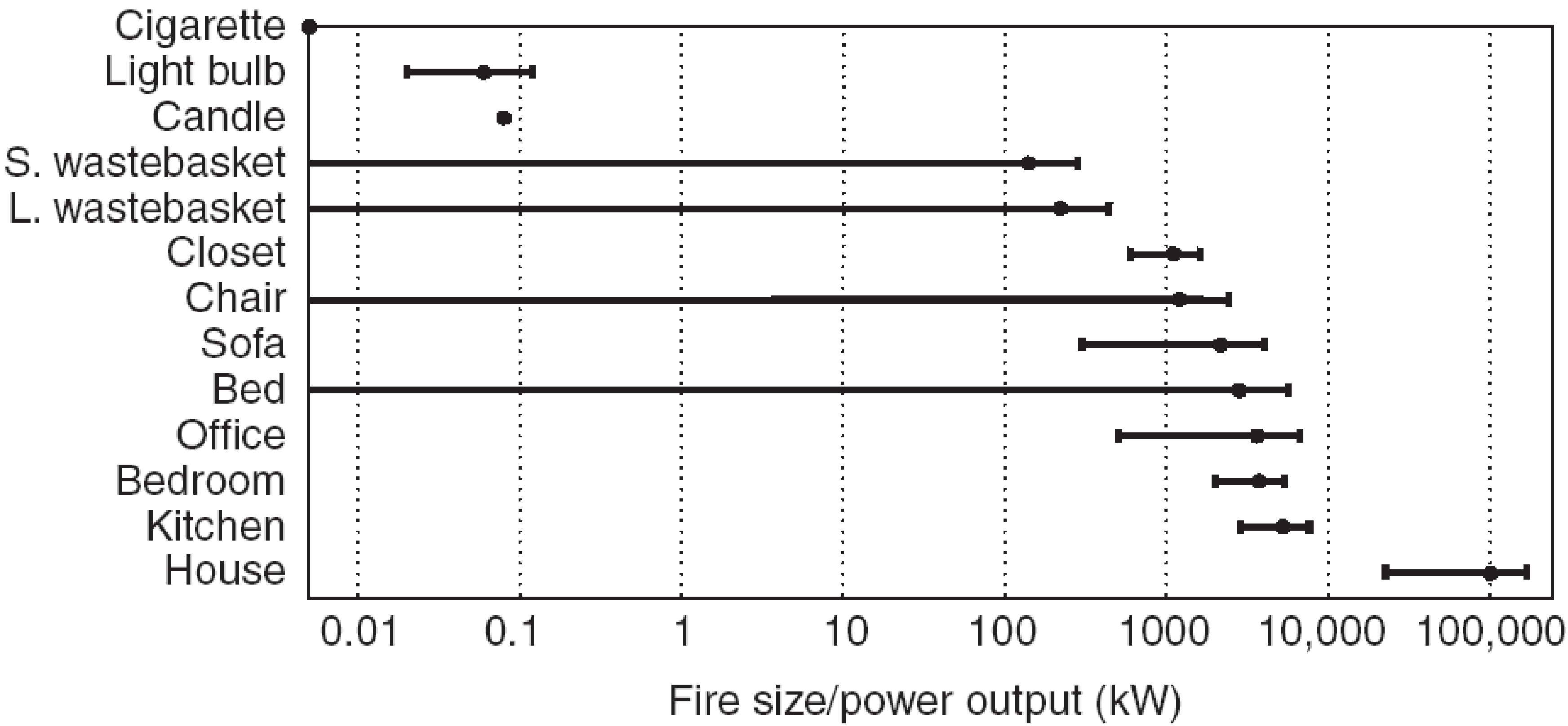

FIGURE 3.9.3 Maximum Fire Sizes for Common Combustible Objects (Sources: NUREG 1805, “Fire Dynamics Tools (FDTs)”[11]; ASTM STP 614, *Fire Standards and Safety*[12])

HOW?

- **Analysis of FIRE SCENARIO**
  - **What is burning**
    - Heat release rate per unit area
      - (HRRPUA); Heat of combustion; speed of reaction
        - > NFPA 555
  - **Amount of burning fuel**
    - Amount of fuel; propagation
      - Heat transefer; convection and radiation
        - > NFPA 555
- **Actions**
  - **Analysis of the effects of the actions**

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NFPA Handbook Sec 5- Chap3 3-93
Introduction to Fire Modeling
Craig L. Beyler Philip J. DiNennoDouglas J. Carpenter John M. Watts, Jr.

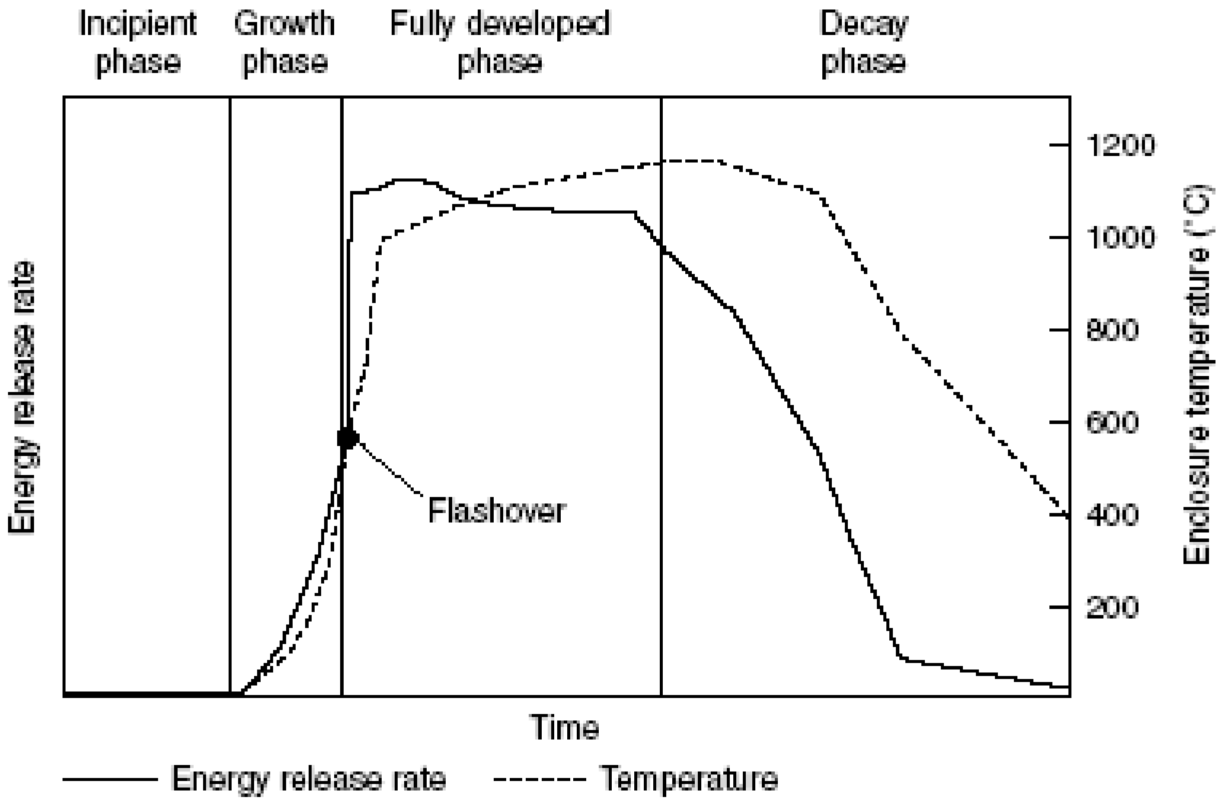
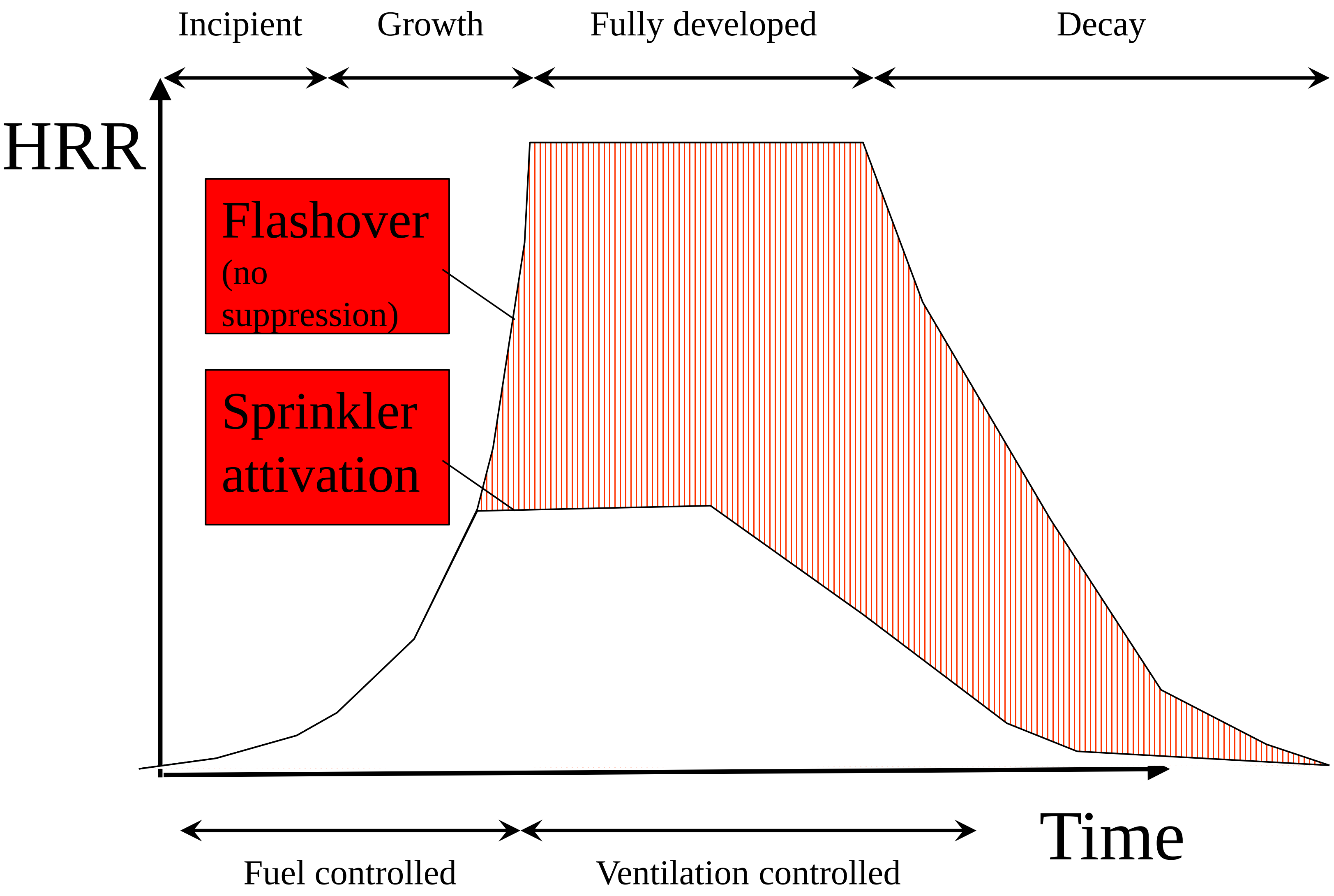


FIGURE 3.9.1 Enclosure Fire Development



Safety of people

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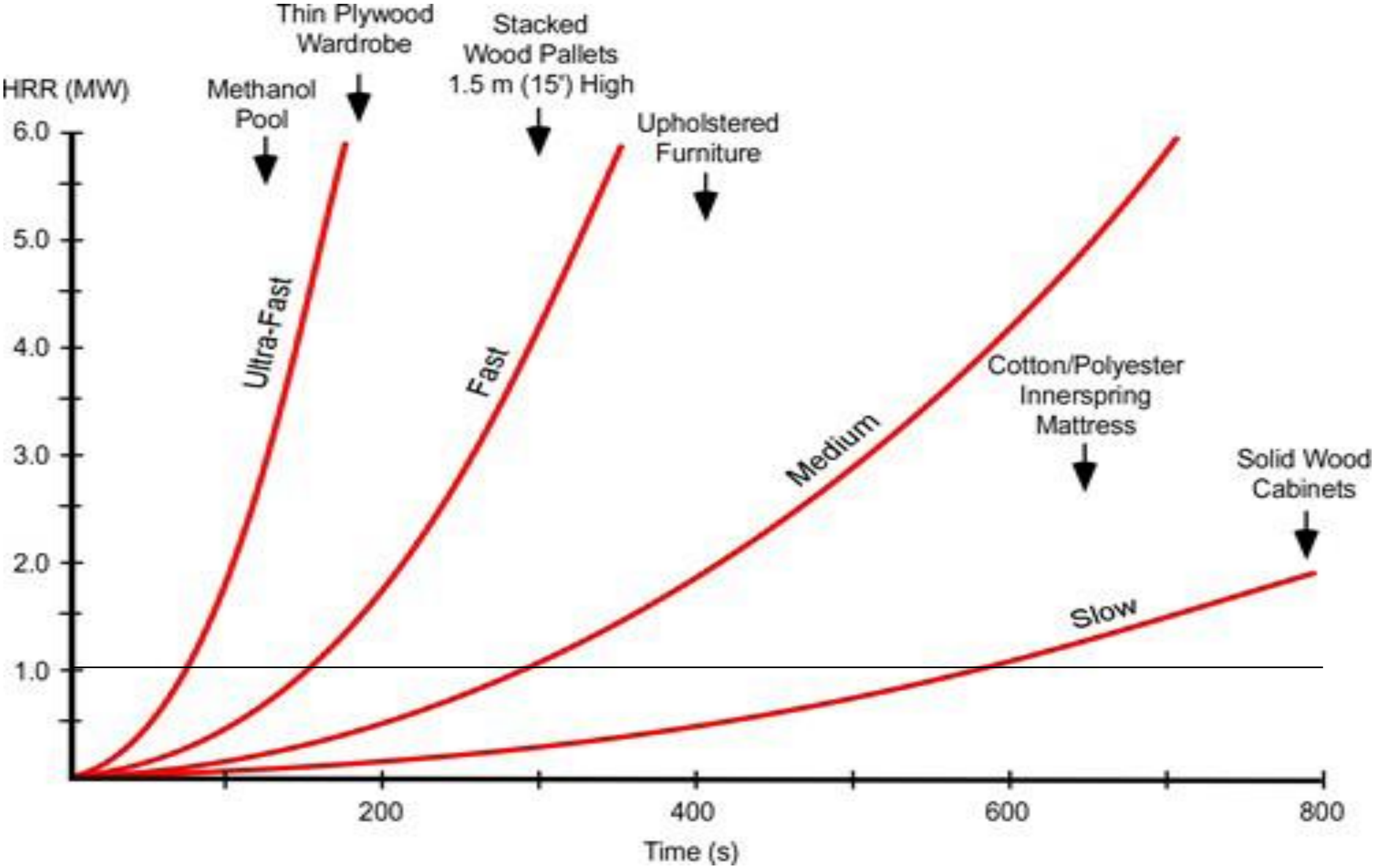
Quadratic curve



Time to get to 1MW	Ultra-Fast	Fast	Medium	Slow
	75 s	150 s	300 s	600 s

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Stress on structures

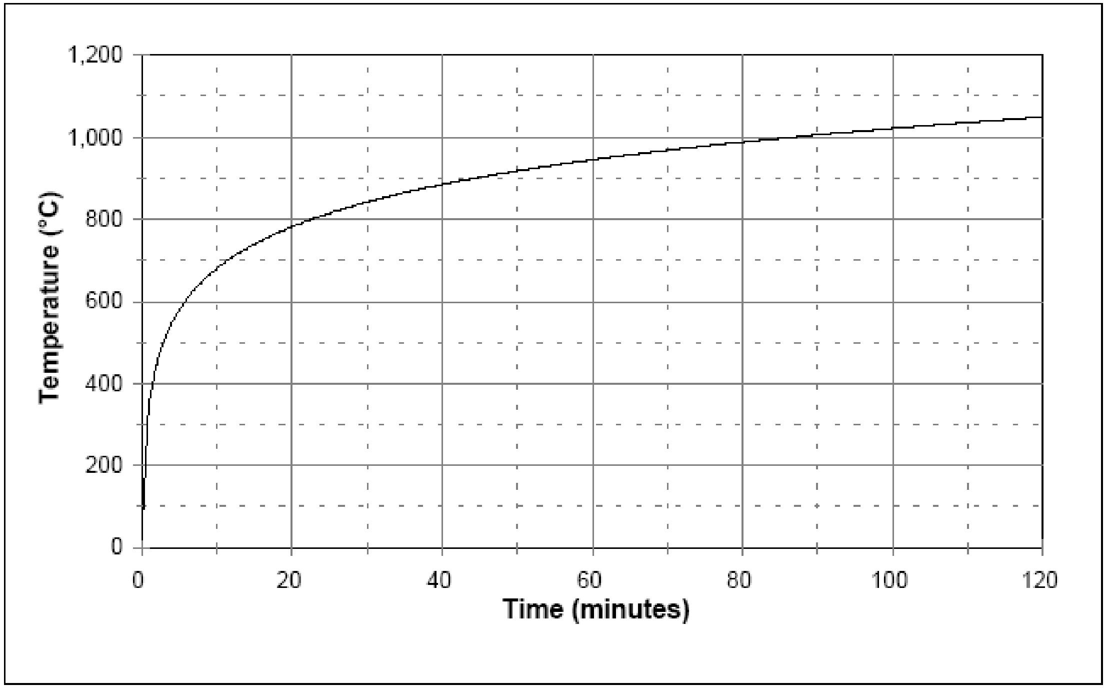

Figure 2.1 ISO 834 Temperature vs Time

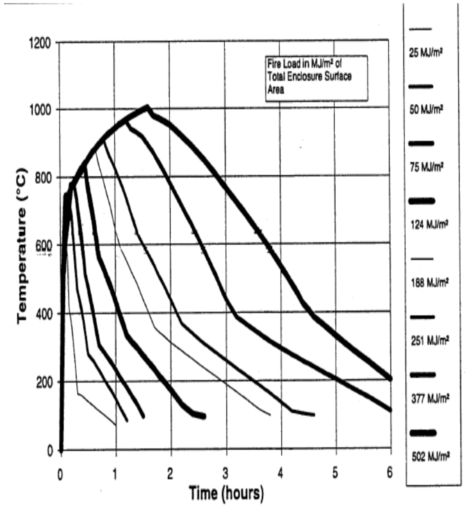

Fig 2.4 Swedish Curves, Ventilation Factor 0.01

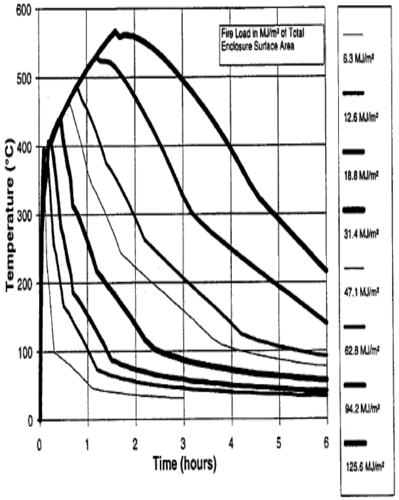

Fig 2.3 Swedish Curves, Ventilation Factor 0.04

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Round-robin study of a priori modelling predictions of the Dalmarnock Fire: Test One Guillermo Rein a,, Jose´ L. Torero a, Wolfram Jahn a, Jamie Stern-Gottfried b,a, Noah L. Ryder c, Sylvain Desanghere d,1, Mariano La´ zaro e, Frederick Mowrer f, Andrew Coles g, Daniel Joyeux h, Daniel Alvear e, Jorge A. Capote e, Allan Jowsey a,b, Cecilia Abecassis-Empis a, Pedro Reszka a

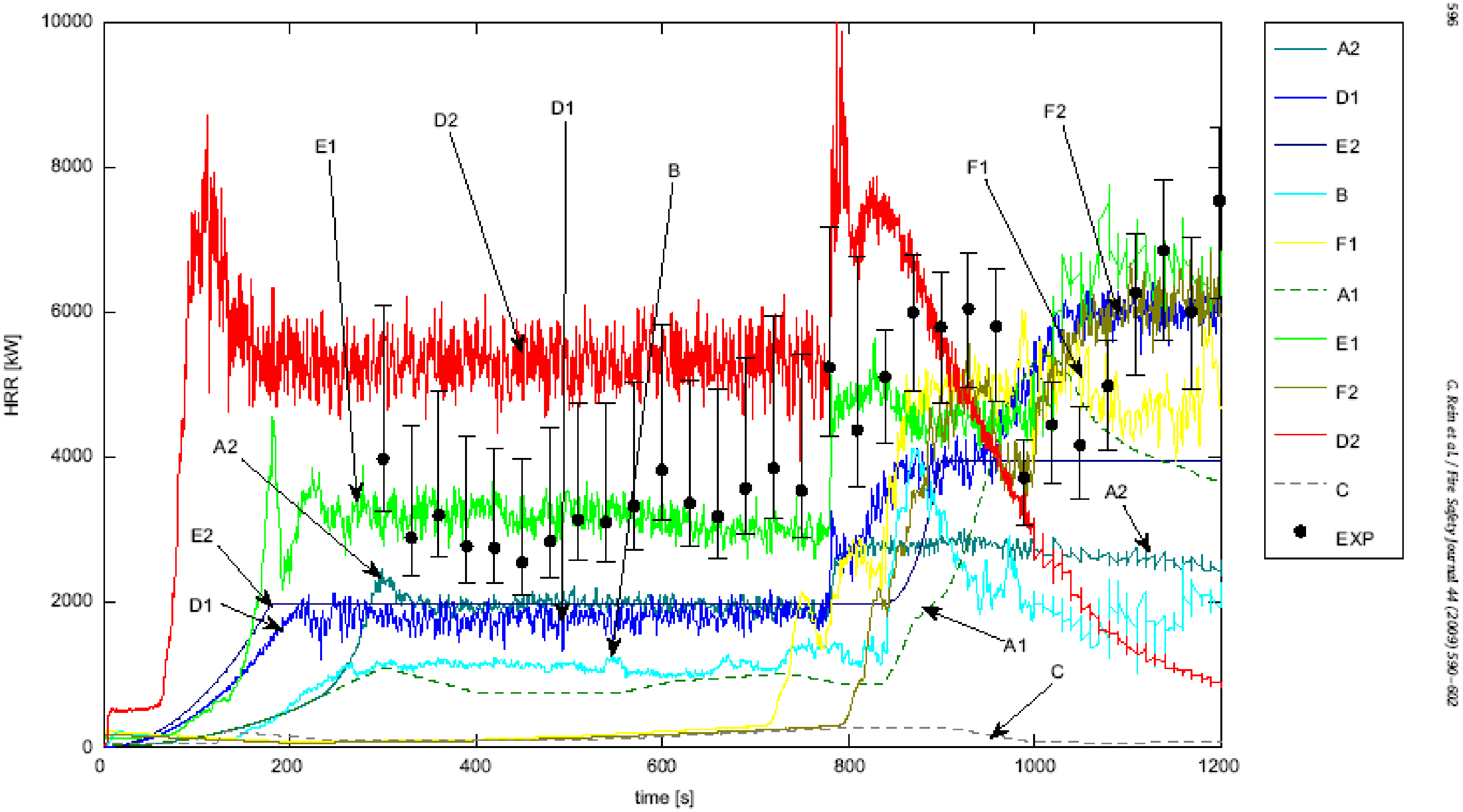

Fig. 6. Evolution of the global heat release rate within the compartment. Legend for the different curves: continuous line for CFD simulations; dashed line for zone model simulations; and dotted for the experimental data with error bars.

a BRE Centre for Fire Safety Engineering, University of Edinburgh, Scotland, UK
b Arup, London, UK
c Packer Engineering Inc., Chicago, USA
d CTICM, Paris, France
e GIDAI, Universidad de Cantabria, Santander, Spain
f Department of Fire Protection Engineering, University of Maryland, USA
g Arup, San Francisco, USA
h Efectis, Paris, France

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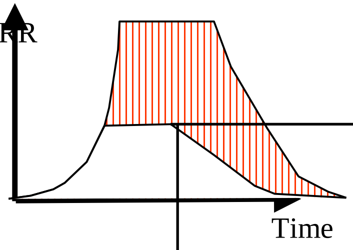

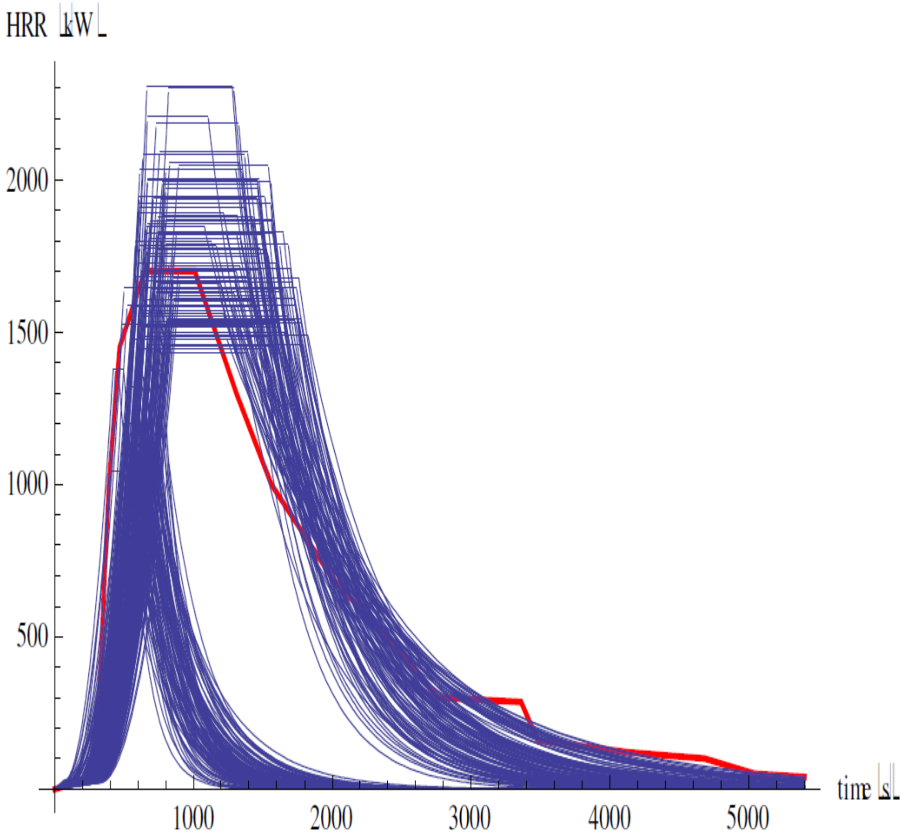

Figure 24: Generated HRR curves and comparison with the experimental one.

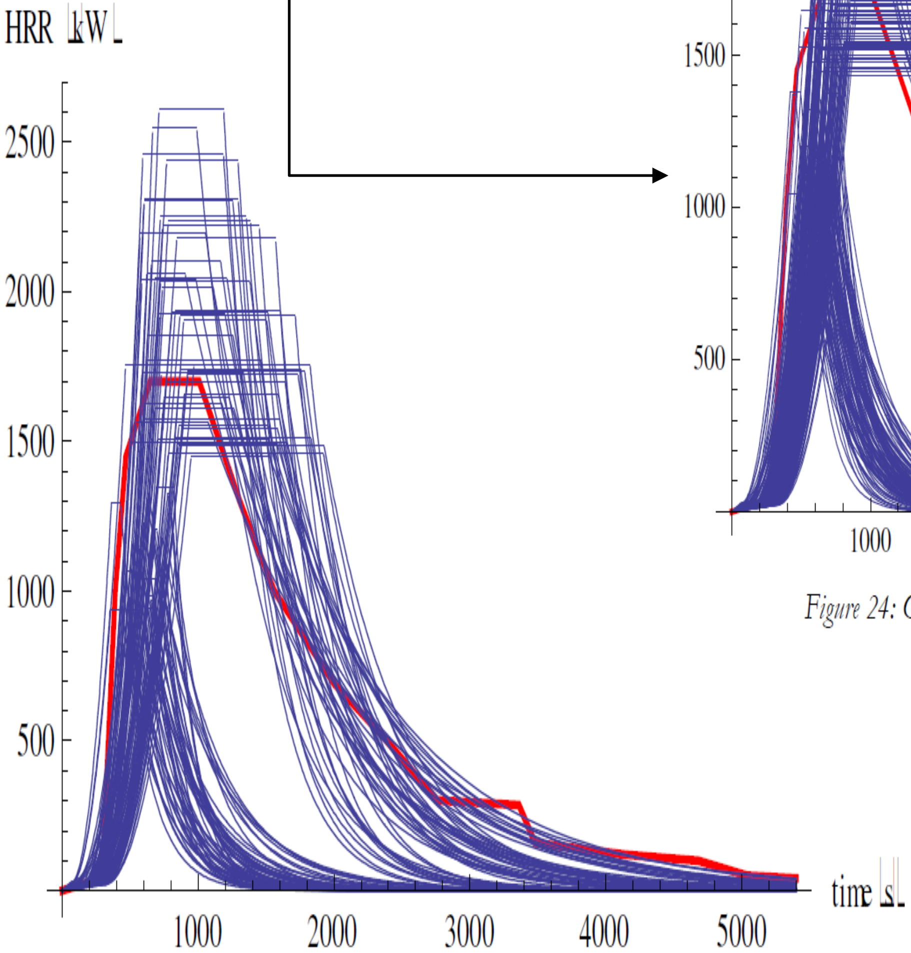

Figure 26: HRR curves generated from the uniform distribution.

Data on fires ?

- **Experiments**
  - **Literature**
  - References must be explicitly cited.

- **Procedure**
  - Eurocodice 1, UNI EN 1991-1-2:2004 Parte 1-2: Azioni in generale - Azioni sulle strutture esposte al fuoco.
  - NFPA 92B “Smoke management systems in malls, atria, and large areas”.
  - NFPA 555 “Guide on methods for evaluating potential for room flash over”.

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NFPA
SFPE

- **NFPA (National Fire Protection Agency)**

Handbook of Fire Protection Engineering

- **SFPE – (Society of Fire Protection Enggineers)**

Handbook of Fire Protection Engineering

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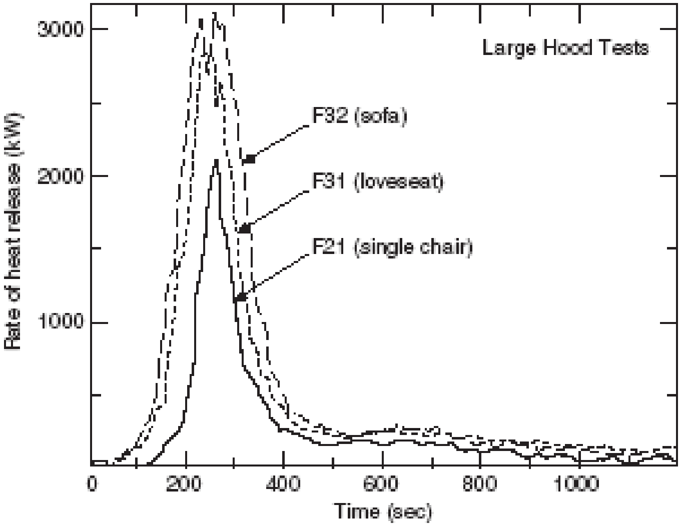
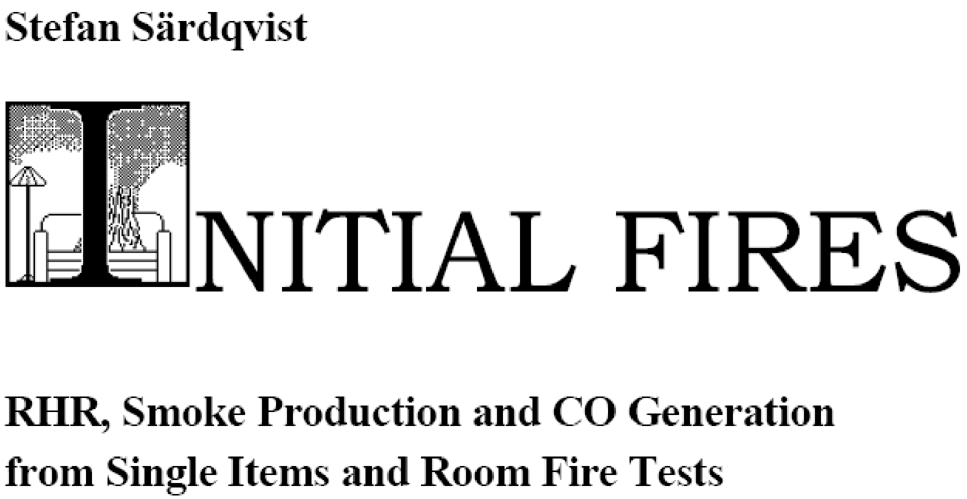


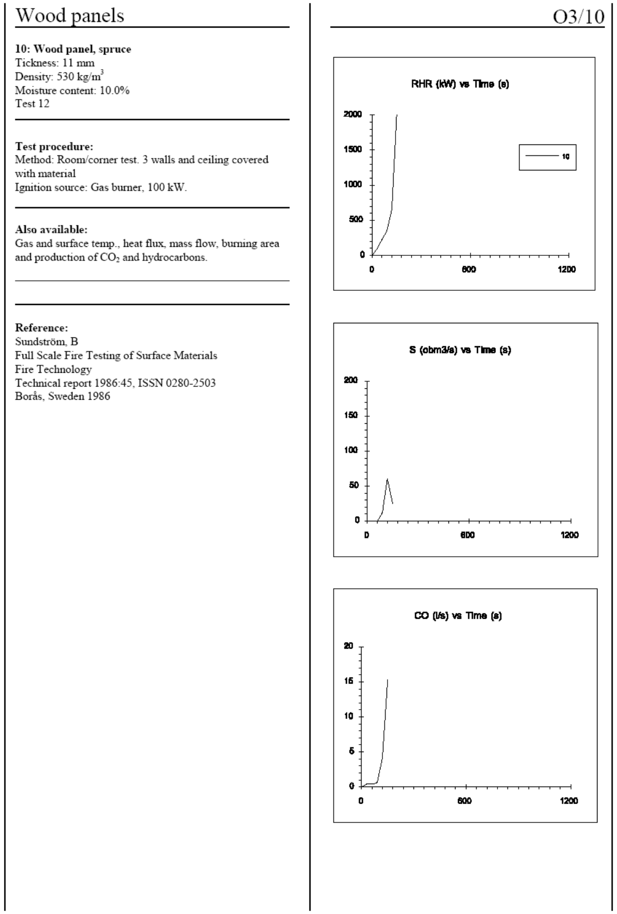
FIGURE 3.6.8 Typical Upholstered Chair Heat Release Rates (Source: Philip J. DiNenno et al. (Eds.), *SFPE Handbook of Fire Protection Engineering*, 2nd ed., National Fire Protection Association, Quincy, MA, 1995. Fig. 3-1.6)



Stefan Särdqvist

INITIAL FIRES

RHR, Smoke Production and CO Generation from Single Items and Room Fire Tests



Wood panels

O3/10

10: Wood panel, spruce
Tickness: 11 mm
Density: 530 kg/m^3
Moisture content: 10.0%
Test 12

Test procedure:
Method: Room/corner test. 3 walls and ceiling covered with material
Ignition source: Gas burner, 100 kW.

Also available:
Gas and surface temp., heat flux, mass flow, burning area and production of CO_2 and hydrocarbons.

Reference:
Sundström, B
Full Scale Fire Testing of Surface Materials
Fire Technology
Technical report 1986:45, ISSN 0280-2503
Borås, Sweden 1986

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Burning rates: woods

Charring Rate [mm/min]	0,45	0,60	0,39	0,76
Density, ρ [Kg/m^3]	447	290	682	400
Soot *[kg/m^2/s]*	0,0034	0,0029	0,0044	0,0051
Potere Calorifico [Kj/Kg]	17000	17000	17000	17000
HRRPUA [kW/ *m^2*]	**56,99**	**49,30**	**75,36**	**86,13**

Data from literature confirm (ISSN 1173-5996 Effects on surface area and thickness on fire load H W Yii pag.41 [6]) HRR lower than 90 Kw/m^2.

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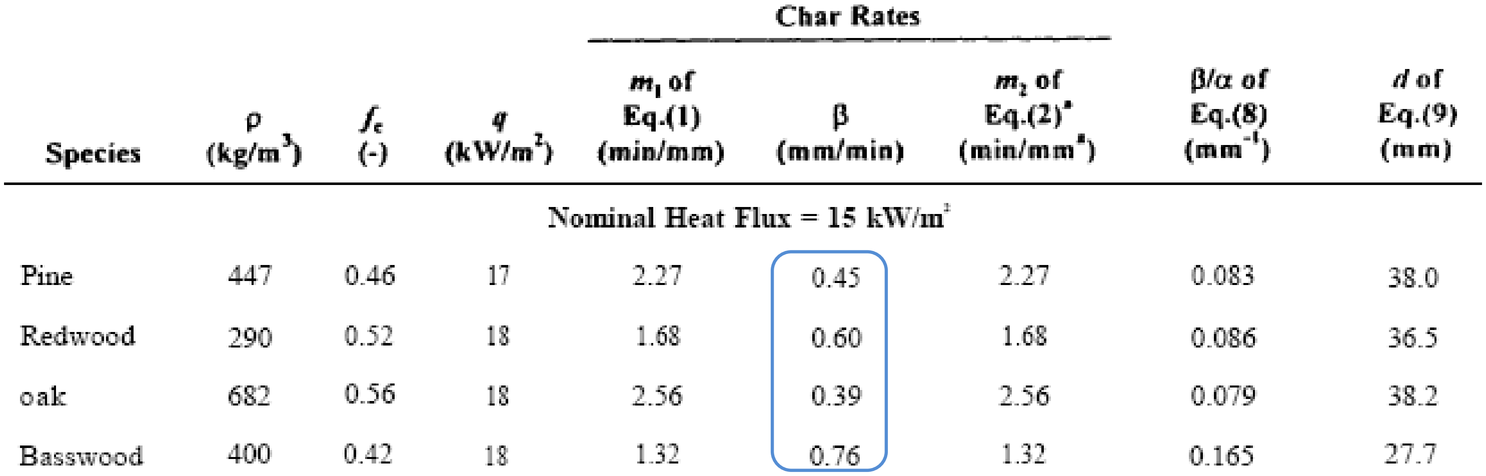
HHR per unit of fuel area: wood



Species	ρ (kg/m^3)	f_c (-)	q (kW/m^2)	Char Rates m_1 of Eq.(1) (min/mm)	β (mm/min)	m_2 of Eq.(2)^a (min/mm^a)	β/α of Eq.(8) (mm^{-1})	d of Eq.(9) (mm)
Nominal Heat Flux = 15 kW/m^2								
Pine	447	0.46	17	2.27	0.45	2.27	0.083	38.0
Redwood	290	0.52	18	1.68	0.60	1.68	0.086	36.5
oak	682	0.56	18	2.56	0.39	2.56	0.079	38.2
Basswood	400	0.42	18	1.32	0.76	1.32	0.165	27.7

	max	*medio*	*min*
Charring Rate [mm/min]	0,80	0,65	0,50
[**ρ**] Densità [Kg/m^3]	600	600	600
kg/m^2/s	0,0080	0,0065	0,0050
Potere Calorifico [Kj/Kg]	16700	16700	16700
HRR [Kw/m^2]	**133,60**	**108,55**	**83,50**

Similar results, although slightly higher, can be obtained using the Italian normative, which is the references for the calculation of the speed of penetration and carbonization in a wooden structure- penetration ranges, indicatively, between 0.5 and 0.8 mm per minute: for reasons of experimental procedures, such values are much easier to measure and, consequentely, to be found in the literature. It should be recalled that in the norm, these values are already reported considering an appropriate safety factor.

Suggested for anaylisis

HRRPUA [kW/ *m*^{2}]	**150**

Simplified relation:

-O_2	burnt	(13000 kJ/kg_{o2})~(3600 kJ/kg_{aria})
-CO_2	produced	(18000 kJ/kg_{o2})
-CO	produced	(1/50 di CO_2)

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HRR te T* per m^2 (floor)

prospetto E.5 **Velocità di crescita dell'incendio e *RHR*$_f$ per differenti destinazioni d'uso**

Velocità massima di rilascio di calore *RHR*$_f$			
Destinazione d'uso	Velocità di crescita dell'incendio	t_α [s]	*RHR*$_f$ [kW/m^2]
Alloggio	Media	300	250
Ospedale (stanza)	Media	300	250
Albergo (stanza)	Media	300	250
Biblioteca	Veloce	150	500
Ufficio	Media	300	250
Classe di una scuola	Media	300	250
Centro commerciale	Veloce	150	250
Teatro (cinema)	Veloce	150	500
Trasporti (spazio pubblico)	Lenta	600	250

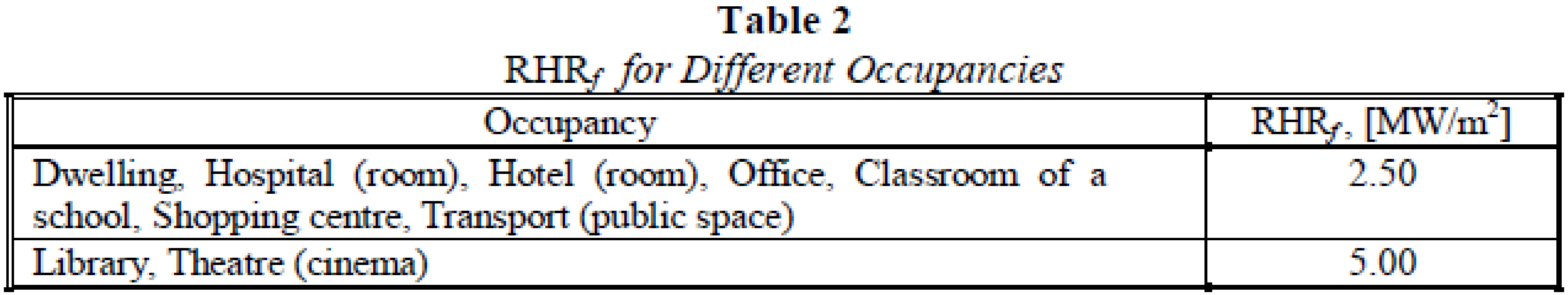

Table 2

RHR$_f$ *for Different Occupancies*

Occupancy	RHR$_f$, [MW/m^2]
Dwelling, Hospital (room), Hotel (room), Office, Classroom of a school, Shopping centre, Transport (public space)	2.50
Library, Theatre (cinema)	5.00

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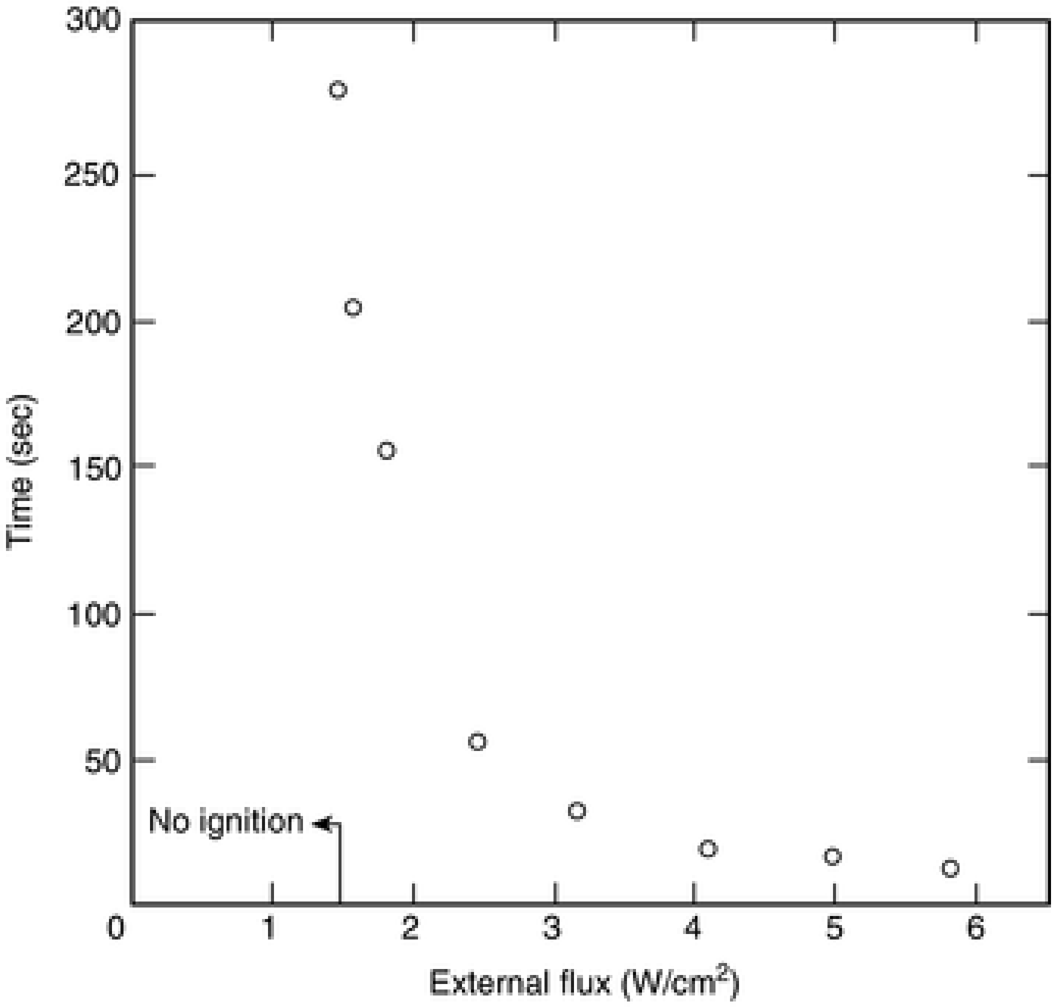
Ignition of Secondary Items by Radiative Heating



Heat flux for ignition: 8, 10, 13 or 20 ????

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Heat flux for ignition: 8, 10, 13 or 20 ????

Will the second item ignite?

- **The concept of using the heat flux to exposed items within the fire room as a criterion for flashover was first suggested in 1974 (Parker and Lee, 1974). It was stated that, at a heat flux of 20 kW/m2 at floor level, cellulosic fuels in the lower part of the room are likely to ignite.**
- **(2) Table A.7.1.3 provides the critical ignition fluxes for some materials for a 60-second exposure (Babrauskas, 1977). The unpiloted values are probably more appropriate for determination of full room involvement, since the distance between the flames and the item to be ignited is considerable. A value of 20 kW/m2 represents, according to W. K. Smith (date unknown), an unpiloted ignition time of approximately 180 seconds for box cardboard and is close to an ultimate asymptotic value.**
- **(3) In one study of a series of room burns, strips of newsprint placed at floor level ignited at fluxes of 17 kW/m2 to 25 kW/m2, while 6.4 mm (¼ in.) thick fir plywood ignited at 21 kW/m2 to 33 kW/m2 (Fang, 1975).**
- **(4) In mobile home tests in which flashover occurred, the minimum total incident heat flux at the center of the floor was 15 kW/m2 (Budnick, 1978).**
- **(5) In submarine compartments, average heat fluxes at floor level of 17 kW/m2 to 30 kW/m2 at flashover were found (Lee and Breese, 1979).**
- **(6) In basement room tests, substantial agreement was found between the time to ignition of newsprint flashover indicators and the time at which the incident heat flux measured at the center of the floor in the burn room reached a level of 20 kW/m2 (Fang and Breese, 1980).**
- **(7) Ignition of filter paper flashover indicators in tests with wood and plastic cribs was observed at a minimum heat flux of 17.7 kW/m2, applied for at least 200 seconds (Quintiere and McCaffrey, 1980). Under more controlled laboratory conditions, with radiant exposure to the same target configuration, the paper was charred black at 25 Copyright NFPA kW/m2 and ripped at 120 seconds but only decomposed to a brown color under 15 kW/m2. Thus, the criterion recommended was a heat flux of 20 kW/m2.**

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Simplified approach

- **correct calculation (accurate) of all terms that can be easily defined with simple models and equations. Eg:**
  - > size and shape of the fire
  - > radiation is about 1/3 total heat flow rate
- **The effect of minor parameter, which are known with greater uncertainty, is accounted in the over-estimation of the main parameters**
  - > Overestimation of HRR

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Movements of fire effluent

- Prevent people being hurt by smoke, heat, toxic effluents

✓ Early detection
✓ Suppression
✓ Smoke and heat extraction
✓ Egress improvement
✓ Reduction of load on structures
✓ Help action of the Fire Brigade
✓ ….

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Newton's second law of dynamic F=ma

- **For Fluid: Momentum conservation:**
  - **Navier Stokes Equations**

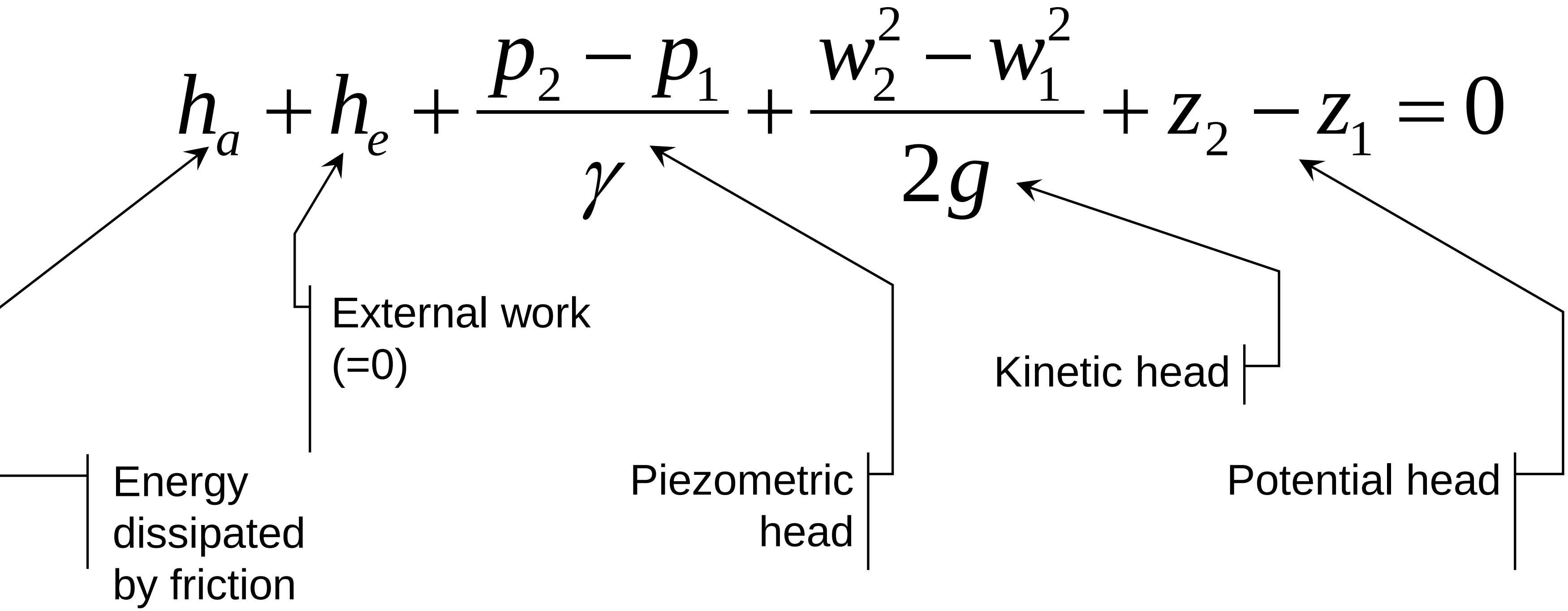
$$\begin{cases} \dfrac{\partial(\rho u)}{\partial\tau}+\nabla\left(\rho u\,\vec{v}\right)=-\dfrac{\partial\left(P-\rho g_{x}x\right)}{\partial x}+\mu\nabla^{2}\vec{v}+\left(\mu+\lambda\right)\dfrac{d}{dx}\left(\nabla\cdot\vec{v}\right) \\ \dfrac{\partial(\rho v)}{\partial\tau}+\nabla\left(\rho v\,\vec{v}\right)=-\dfrac{\partial\left(P-\rho g_{y}y\right)}{\partial y}+\mu\nabla^{2}\vec{v}+\left(\mu+\lambda\right)\dfrac{d}{dy}\left(\nabla\cdot\vec{v}\right) \\ \dfrac{\partial(\rho w)}{\partial\tau}+\nabla\left(\rho w\,\vec{v}\right)=-\dfrac{\partial\left(P-\rho g_{z}z\right)}{\partial z}+\mu\nabla^{2}\vec{v}+\left(\mu+\lambda\right)\dfrac{d}{dz}\left(\nabla\cdot\vec{v}\right) \end{cases}$$

The integration on NS equation a (possible) fluid path (trajectory) gives Bernoulli Equation (dL=f ds)

$$h_{a}+h_{e}+\frac{p_{2}-p_{1}}{\gamma}+\frac{w_{2}^{2}-w_{1}^{2}}{2g}+z_{2}-z_{1}=0 \qquad [m]$$

Equazione di Bernoulli

Bernoulli is valid of a trajectory (possible) inside the fluid domain



$$h_a + h_e + \frac{p_2 - p_1}{\gamma} + \frac{w_2^2 - w_1^2}{2g} + z_2 - z_1 = 0$$

Energy dissipated by friction

External work (=0)

Piezometric head

Kinetic head

Potential head

γ=Specific weight [N/m]; p=Pressure[Pa]; w=velocity [m/s];
g= gravity =9.81[m/s^2]; z = height [m]

Bernoulli

$$h_a + h_e + \int_1^2 \frac{dp}{\rho g} + \frac{w_2^2 - w_1^2}{2g} + z_2 - z_1 = 0 \qquad [m]$$

along a constant density path:

$$\boxed{h_a + h_e + \frac{p_2 - p_1}{\rho g} + \frac{w_2^2 - w_1^2}{2g} + z_2 - z_1 = 0 \qquad [m]}$$

Various form of Bernoulli

$$\frac{p_1}{\rho g} + \frac{w_1^2}{2g} + z_1 + h_{a1\rightarrow} = C \qquad [m]$$

$$\frac{p_1}{\rho} + \frac{w_1^2}{2} + gz_1 + gh_{a1\rightarrow} = C \qquad \left[\frac{J}{kg}\right]$$

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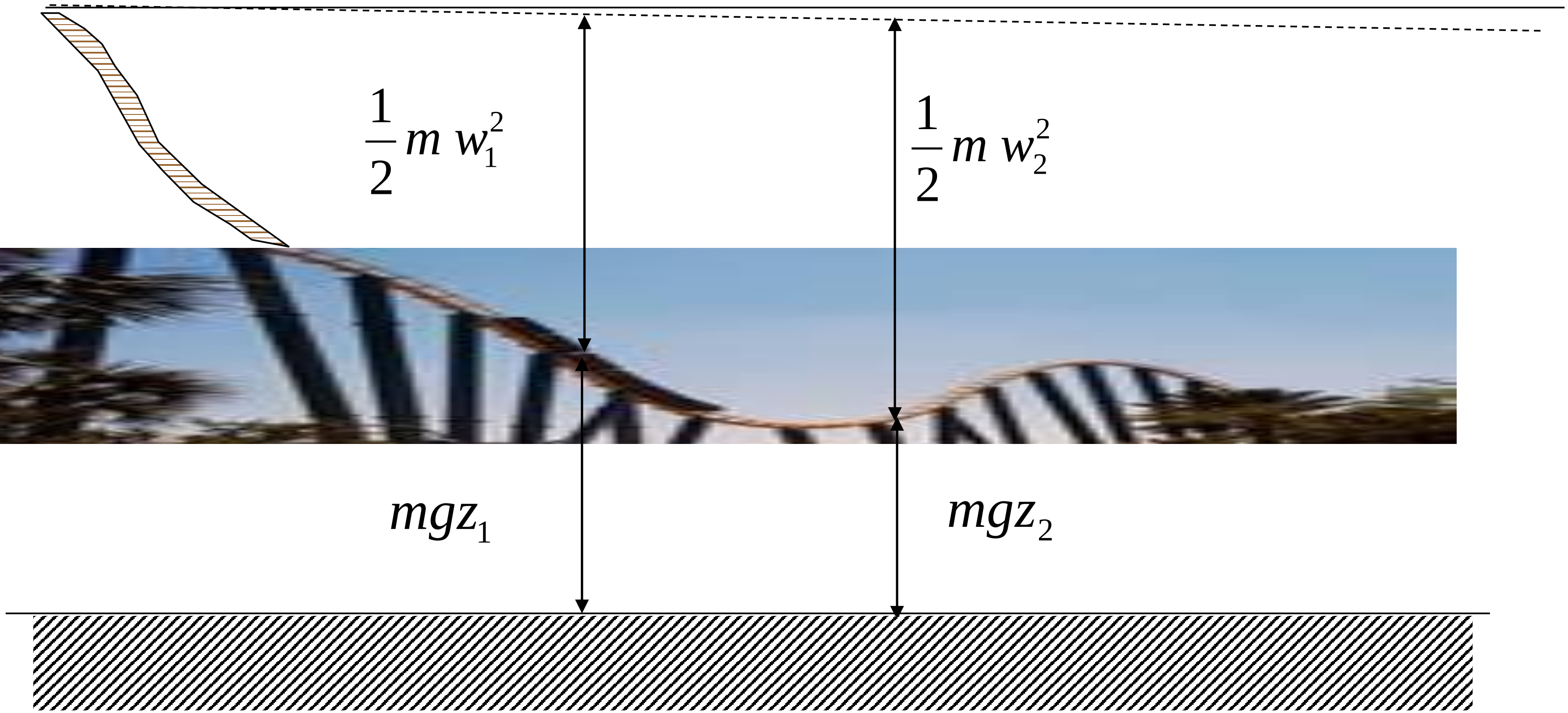
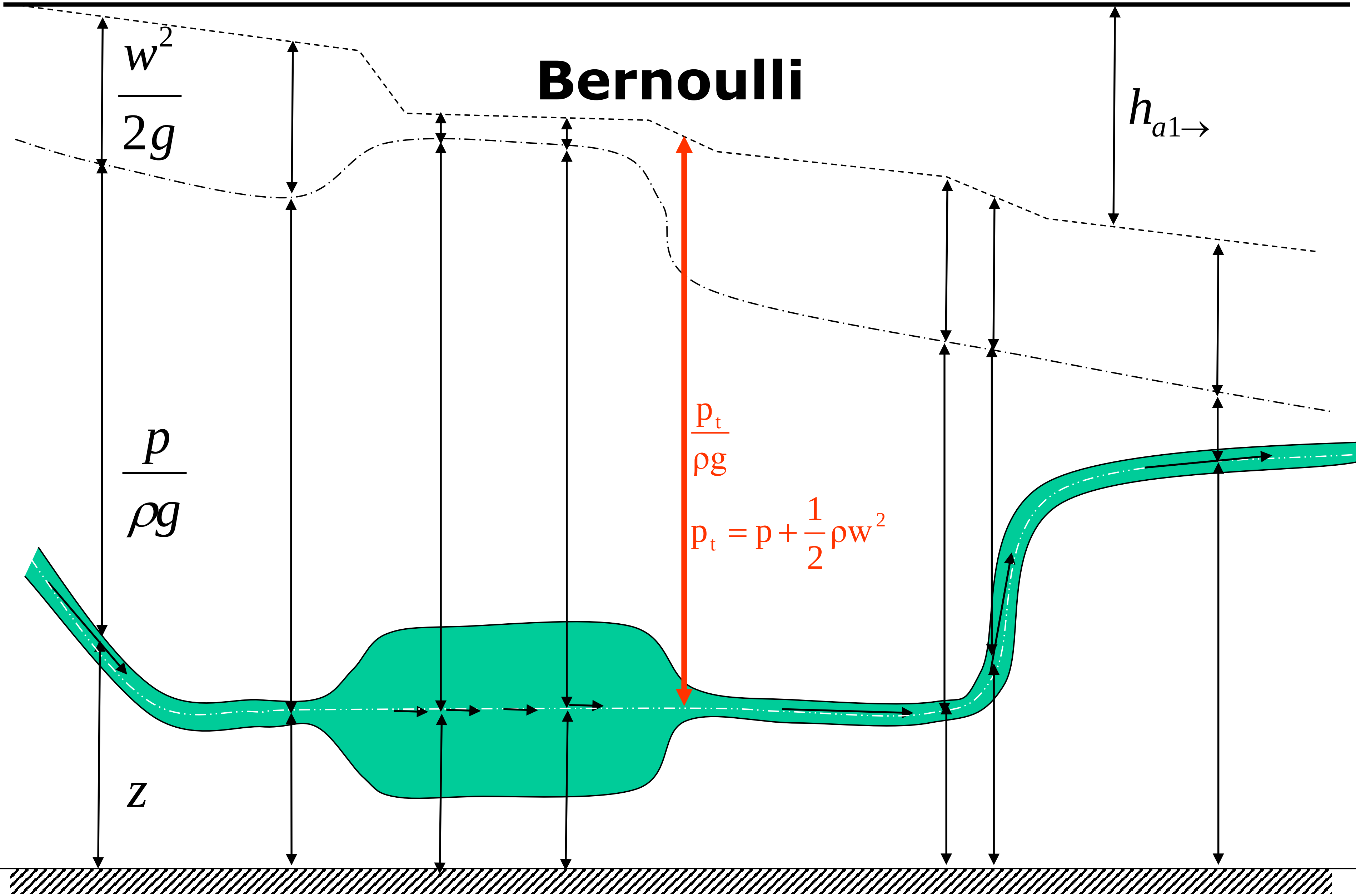
Bilancio dell’energia (meccanica)

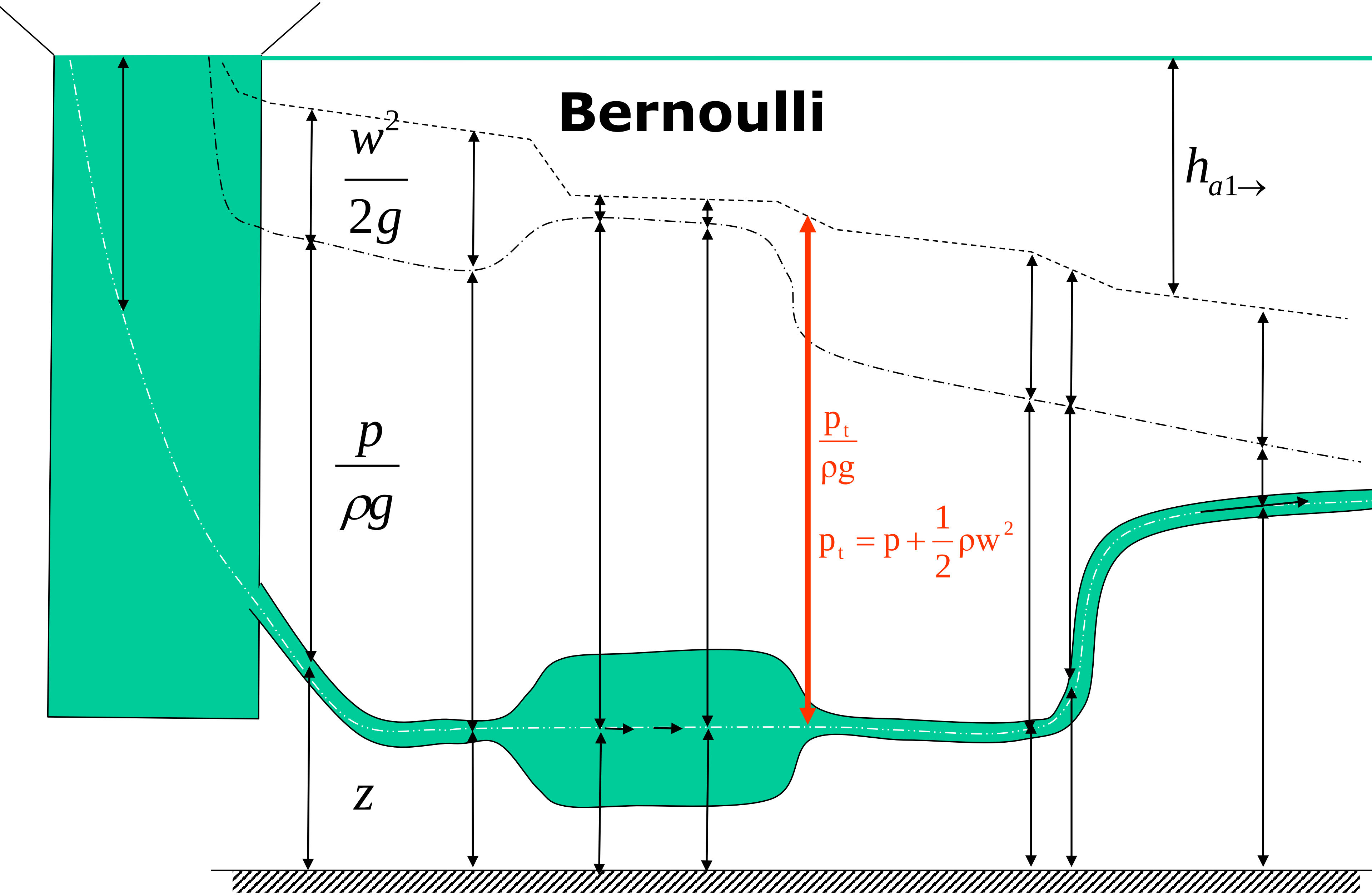


Bernoulli



$$p_t = p + \frac{1}{2}\rho w^2$$

Bernoulli



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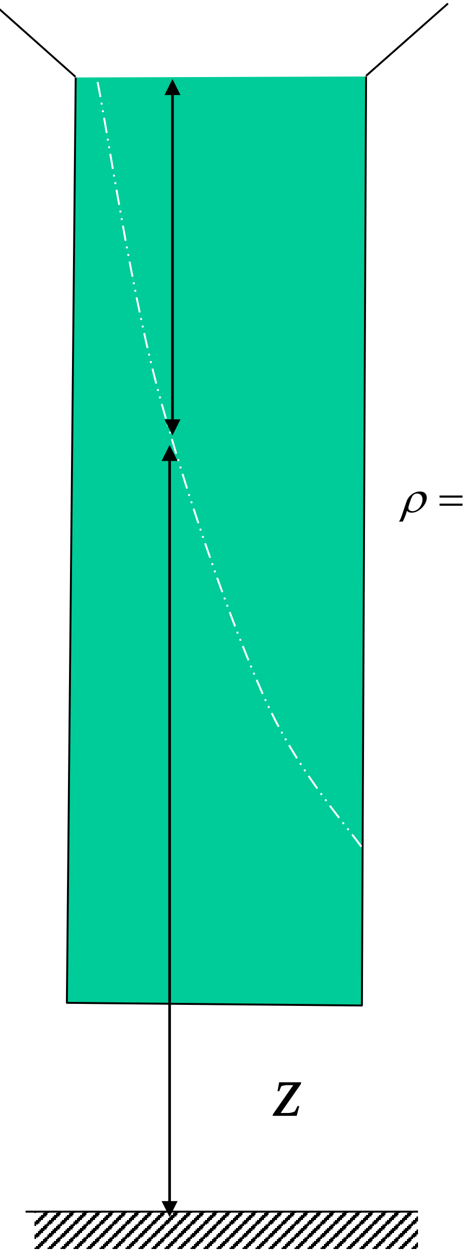
Hydrostatic Distribution



$$\underbrace{\cancel{h_a}}_{=0} + \underbrace{\cancel{h_e}}_{=0} + \int_1^2 \frac{dp}{\rho g} + \underbrace{\cancel{\frac{w_2^2 - w_1^2}{2g}}}_{=0} + z_2 - z_1 = 0 \qquad [m]$$

$$\rho = const \rightarrow p = p_0 + \rho g\left(z_0 - z_1\right) \qquad \left[Pa\right]$$

Water density ρ = 1000 kg/m^3

Pressure gradient ≈10000 Pa/m

Pressure gradient ≈ 0.1 Bar/m

Air density ρ = 1.2 kg/m^3

Pressure gradient ≈12 Pa/m

For Air, in a small domain, (small height) variation can be neglected and pressure can be considered as constant

Height 100 m, 12 Pa/m,

→ we obtain ΔP < 1200 Pa.

ΔP/ P =1200 /100 000 ≈ 1 %.

Which value for pressure?

At sea level P_0= 101325 Pa

Air density ρ = 101325/ (287 T) = 353/T

$$\boxed{\rho = 353/T}$$

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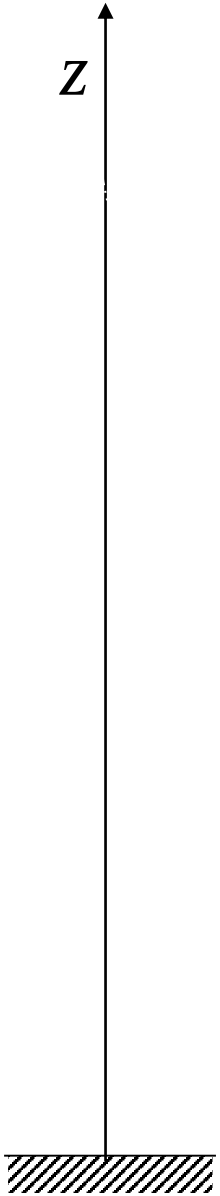

Hydrostatic Distribution - 2

$$h_a + h_e + \int_1^2 \frac{dp}{\rho g} + \frac{w_2^2 - w_1^2}{2g} + z_2 - z_1 = 0 \qquad [m]$$

$$\rho \neq Cost$$

$$g.p. \rightarrow \rho = \frac{P}{R_1 T} = \frac{P}{287 \cdot T}$$

$$\int_{P_0}^{P} \frac{dp}{\rho} = -\int_{z_0}^{z} g dz$$

$$\boxed{\int_{P_0}^{P} \frac{dp}{\rho} = -g\left(z - z_0\right)}$$

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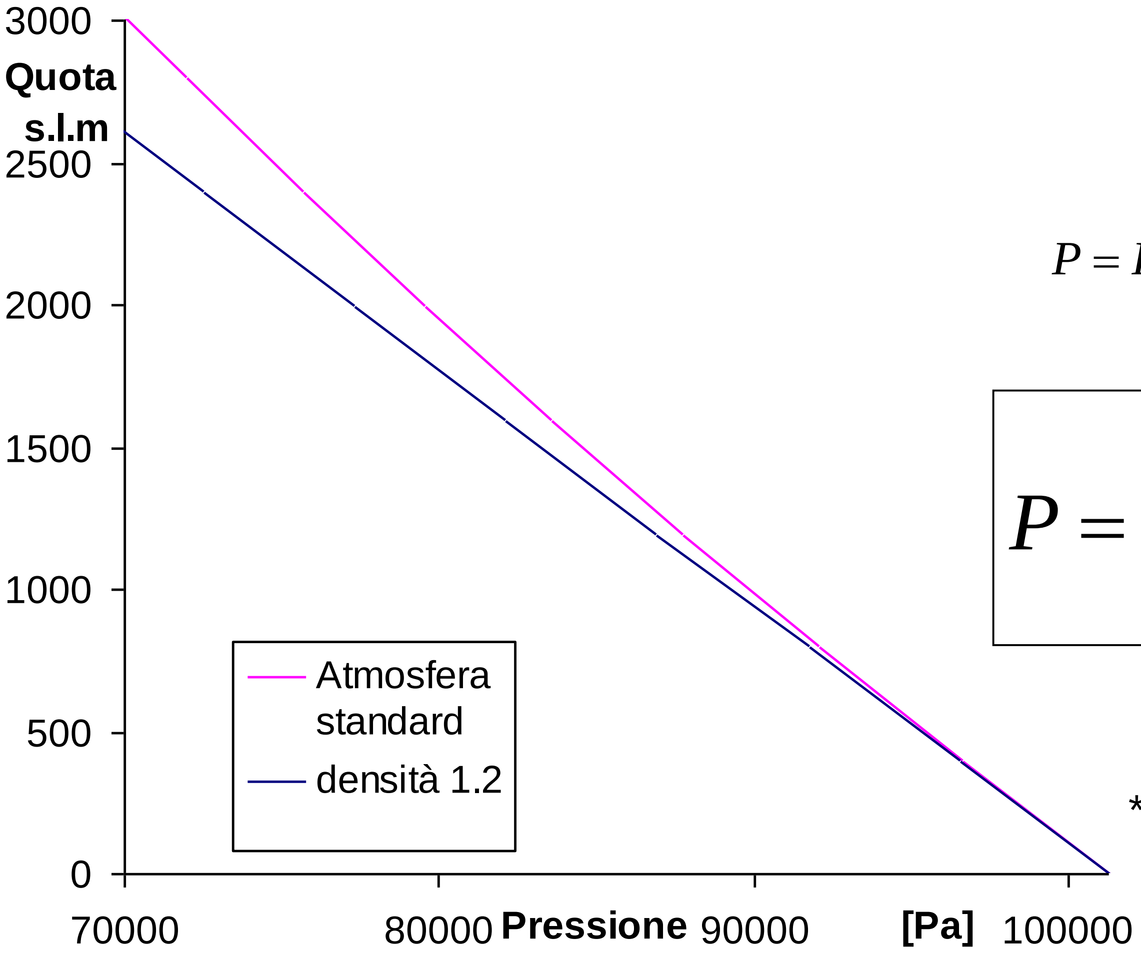
Atmospheric pressure
Air Standard



$$P = P_0\left(1 - \frac{z}{153.8\cdot\left(t + 273.15\right)}\right)^{5.2559}$$

$$\boxed{P = P_0\left(1 - \frac{z}{44308}\right)^{5.2559}}$$

* (adiabatic gradient 6.6°C/km)

Air

Air density depends on reference pressure Prif

A 500 m (above mean sea level, AMSL) presusre is Prif = 95460 Pa

Mean temperature is T = 15 – 6.6·0.5 = 11.7 °C = 284.85 K

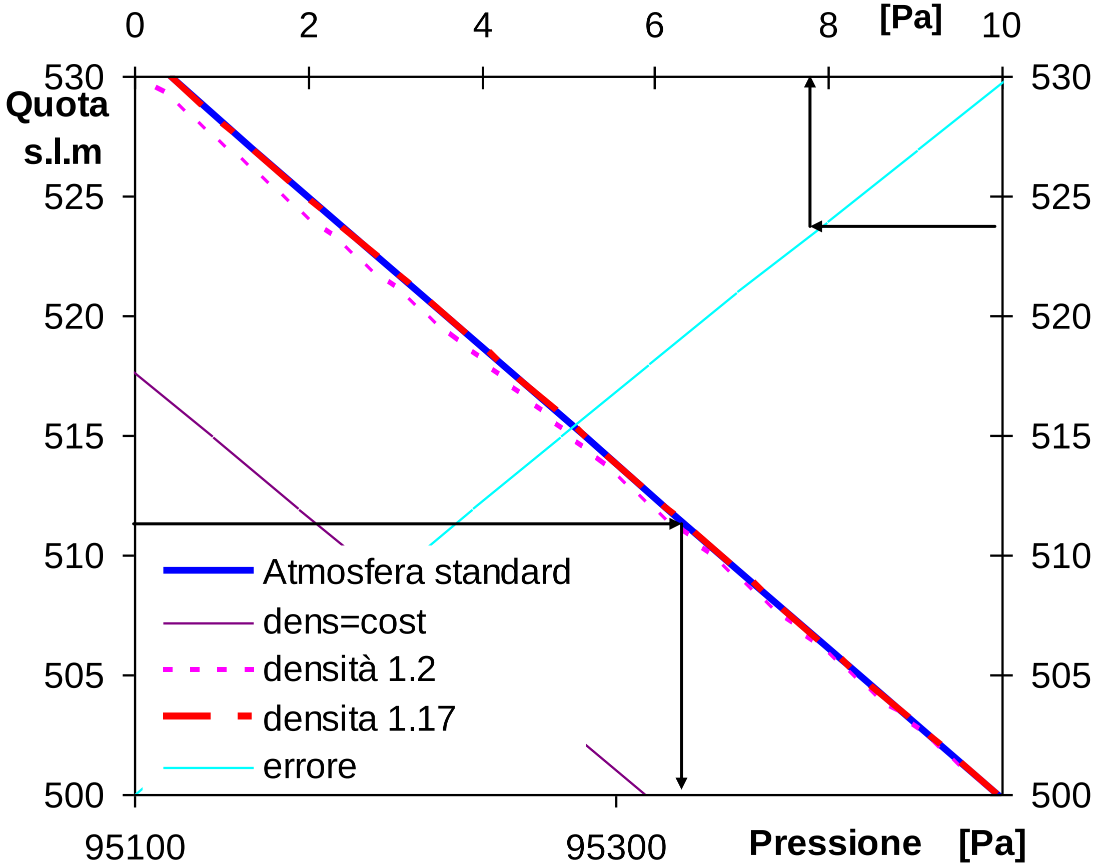
$$\rho = \frac{P_{RIF}}{R_1 T} = \frac{95460}{287 \cdot 284.75} = 1.168$$

Density is $\rho_{RIF} = 1.17\ kg/m^3$

In a small domain (less than 100m height), Density can be considered as a constant.

For instance at 500 m

$$p = p_{500} - \rho * g\left(z - 500\right)$$



P_{rif} e t_{rif} a 500 m can be used to calculate ρ*

Effect of
small error on pressure
on velocity

$$\Delta P = \frac{1}{2}\rho w^2$$

$$\rightarrow w = \sqrt{\frac{2\Delta P}{\rho}}$$

$$w = \sqrt{\frac{2 \cdot 10}{1.2}} \cong 4\, m/s$$

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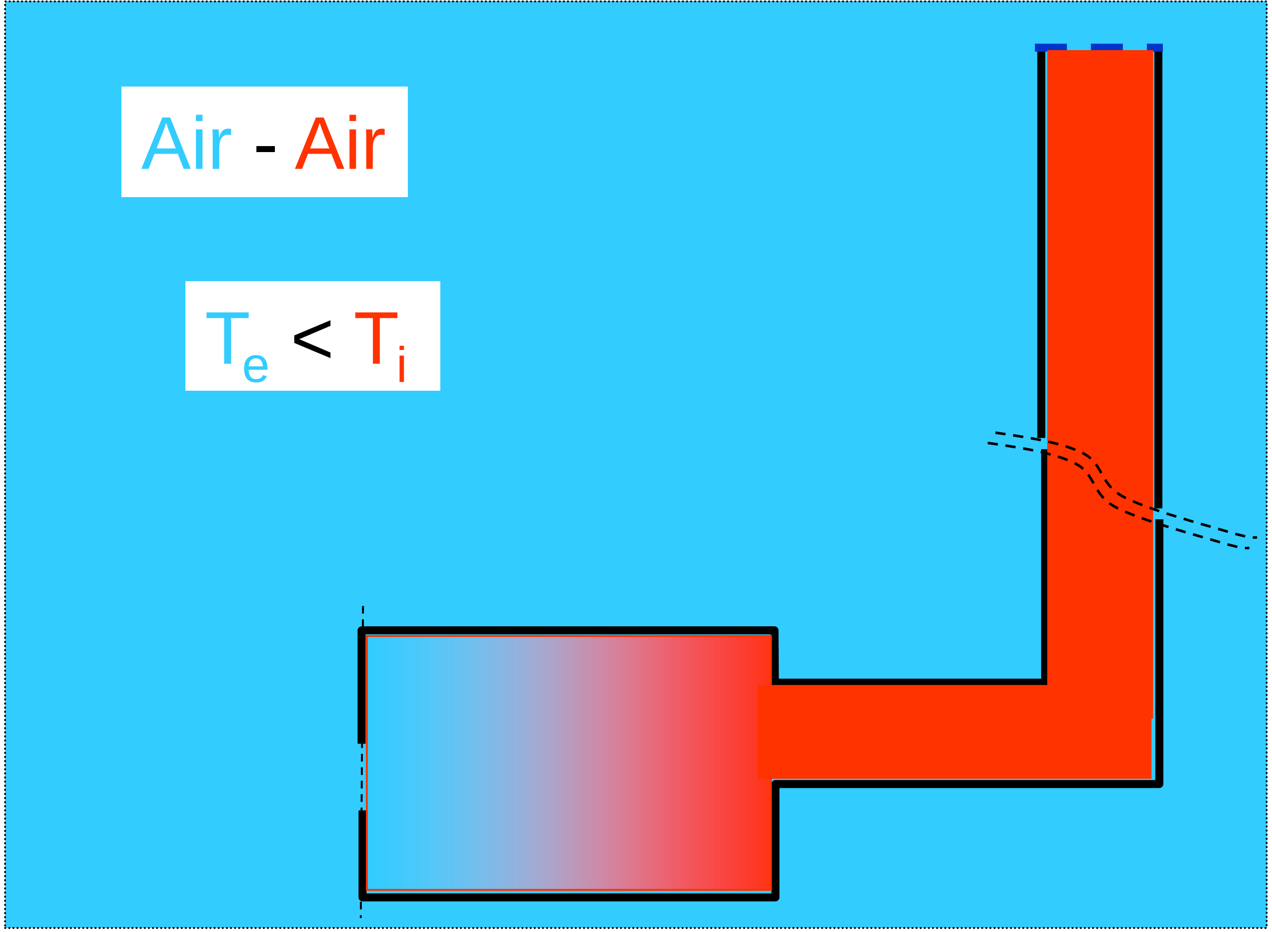
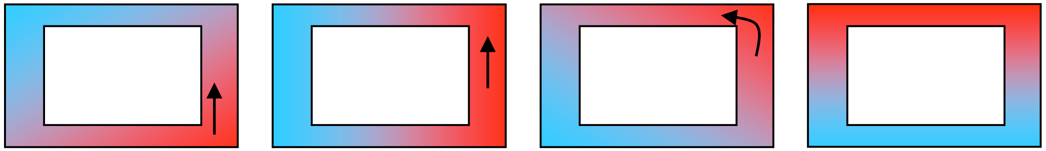
Chimney effect

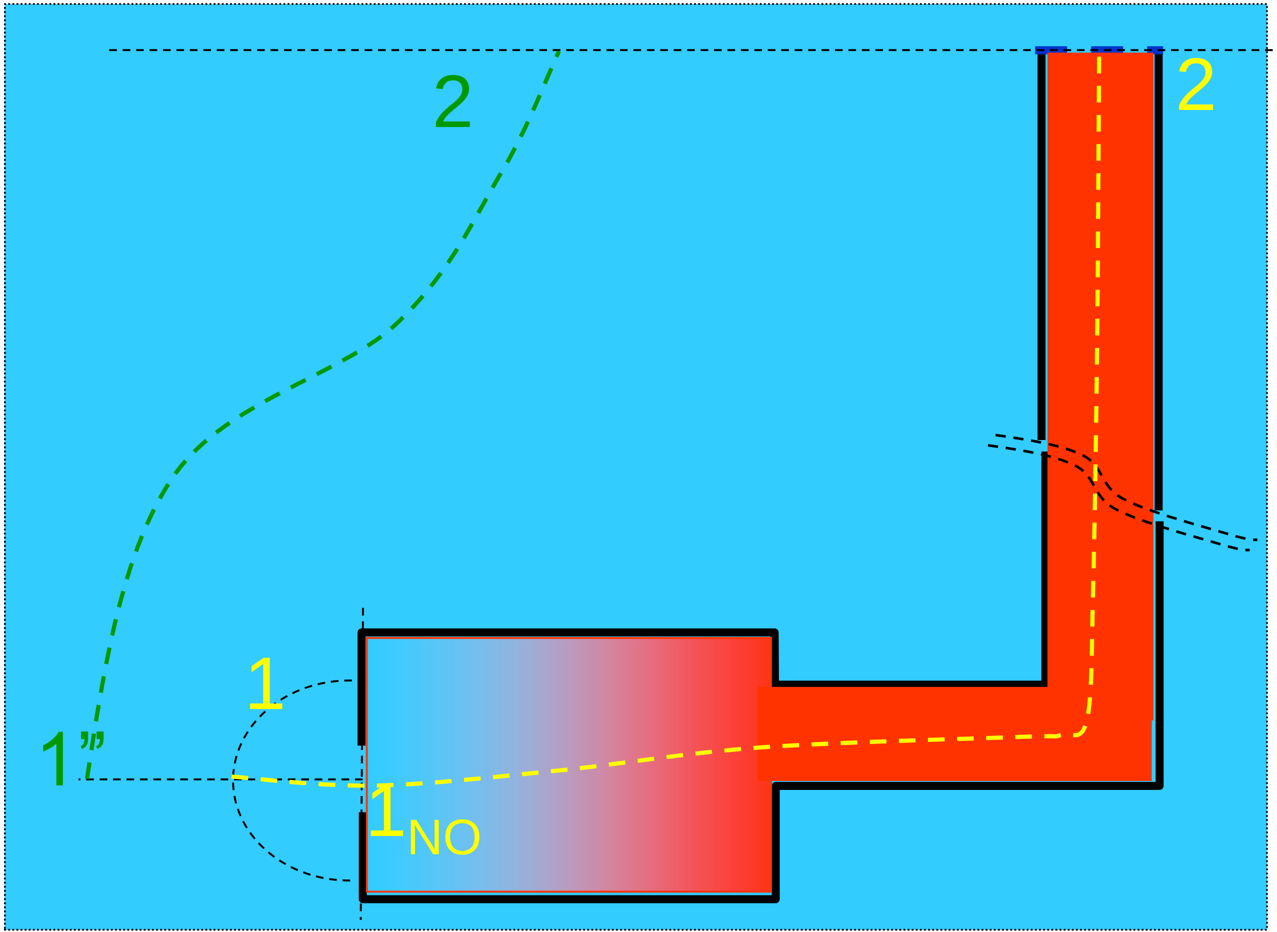


Communicating vessels:



Bernoulli is valid, inside the fluid domain, along (any) trajectory

Chimney effect



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Density depends on temperature

$$h_a + h_e + \int_1^2 \frac{dp}{\rho g} + \frac{w_2^2 - w_1^2}{2g} + z_2 - z_1 = 0 \qquad [m]$$

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Density depends on temperature

Inside chimney, if temperature is constant, density can be held as a constant: ρ_i

$$h_a + h_e + \frac{p_2 - p_1}{\rho_i g} + \frac{w_2^2 - w_1^2}{2g} + z_2 - z_1 = 0 \qquad [m]$$

- **T_i**
- **Mean pressure is constant P_{RIF}, for calculation of density**
- **Pressure drops, both localized and distributed ones, linearly depends on the square of velocity.**

$$\boxed{\left(c_1 \frac{L}{D} + c_2\right)\frac{w_2^2}{2g} + \frac{p_2 - p_1}{\rho_i g} + \frac{w_2^2}{2g} + z_2 - z_1 = 0 \qquad [m]}$$

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Density depends on temperature

Also outside density can be considered as a constant, ρ_e

$$h_a + h_e + \frac{p_2 - p_1}{\rho_e g} + \frac{w_2^2 - w_1^2}{2g} + z_2 - z_1 = 0 \qquad [m]$$

- **T_e**
- **Mean pressure is constant PRIF, for calculation of density**
- **Density ρ_e = 353/T_e**
- **Velocity is nearly zero.**

$$\frac{p_2 - p_1}{\rho_e g} + z_2 - z_1 = 0 \qquad [m]$$

$$p_2 - p_1 = -\rho_e g(z_2 - z_1)$$

$$** \; p_1 + \rho_e g z_1 = p_2 + \rho_e g z_2$$

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Velocity: w=f(H, di T_i , T_e)

$$h_a + h_e + \frac{p_2 - p_1}{\rho g} + \frac{w_2^2 - w_1^2}{2g} + z_2 - z_1 = 0$$

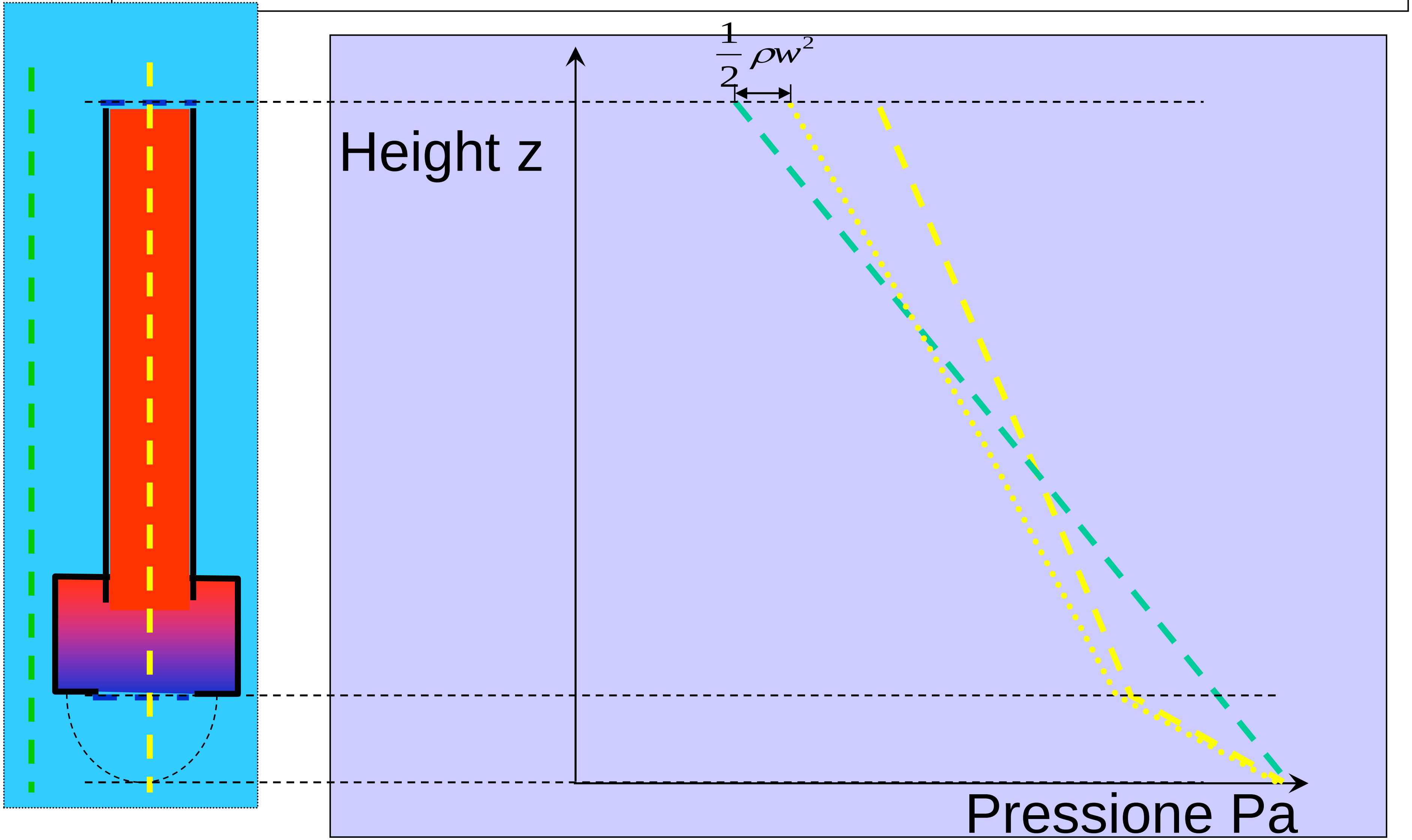
$$L \cong H = z_2 - z_1$$

$$\left(c_1 \frac{H}{D} + c_2 + 1 \right) \frac{w_2^2}{2g} + \frac{-\rho_e g H}{\rho_i g} + H = 0$$

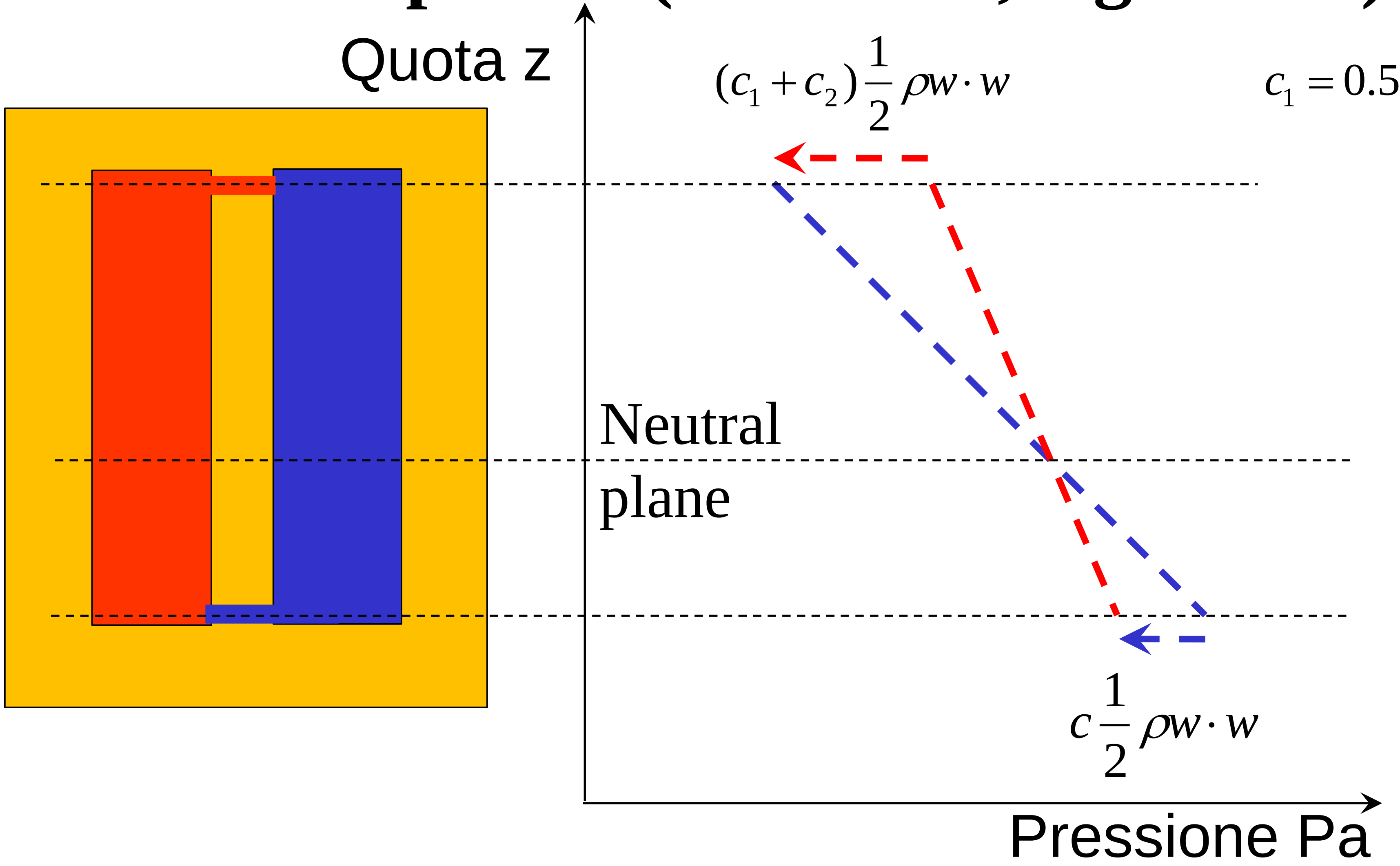
$$w_2^2 = \frac{2g}{\left(c_1 H/D + c_2 + 1 \right)} \left(\frac{\rho_e}{\rho_i} - 1 \right) H = \frac{2g}{\left(c_1 H/D + c_2 + 1 \right)} \left(\frac{T_i}{T_e} - 1 \right) H$$

$$w = \sqrt{\frac{2gH}{\left(c_1 H/D + c_2 + 1 \right)} \left(\frac{T_i}{T_e} - 1 \right)}$$

Pressure profile



Pressure profile (left warm, right cold)



Distribution di p+ρgz

$$\rho\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)=\boxed{-\frac{\partial(P)}{\partial z}}+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)\boxed{+Z}$$

$$Z=-\rho g \qquad -\frac{\partial(\rho g z)}{\partial z}=-\rho g \qquad \frac{\partial(P+\rho g z)}{\partial z}=\frac{\partial(P)}{\partial z}+\frac{\partial(\rho g z)}{\partial z}$$

$$\rho\left(\frac{\partial w}{\partial t}+u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}\right)=-\frac{\partial(P+\rho g z)}{\partial z}+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)$$

Commonly, softwares solve THIS equation for pressure

Reference pressure P^*

is calculated by means of reference density ρ_{RIF}

Software usually calculate and show P*

$$\boxed{P^* = p + \rho_{RIF} g z}$$

where ρ_{RIF} is an user input (explicit or implicit)

Explicit – direct input of reference density
Implicit – input of reference temperature and reference pressure

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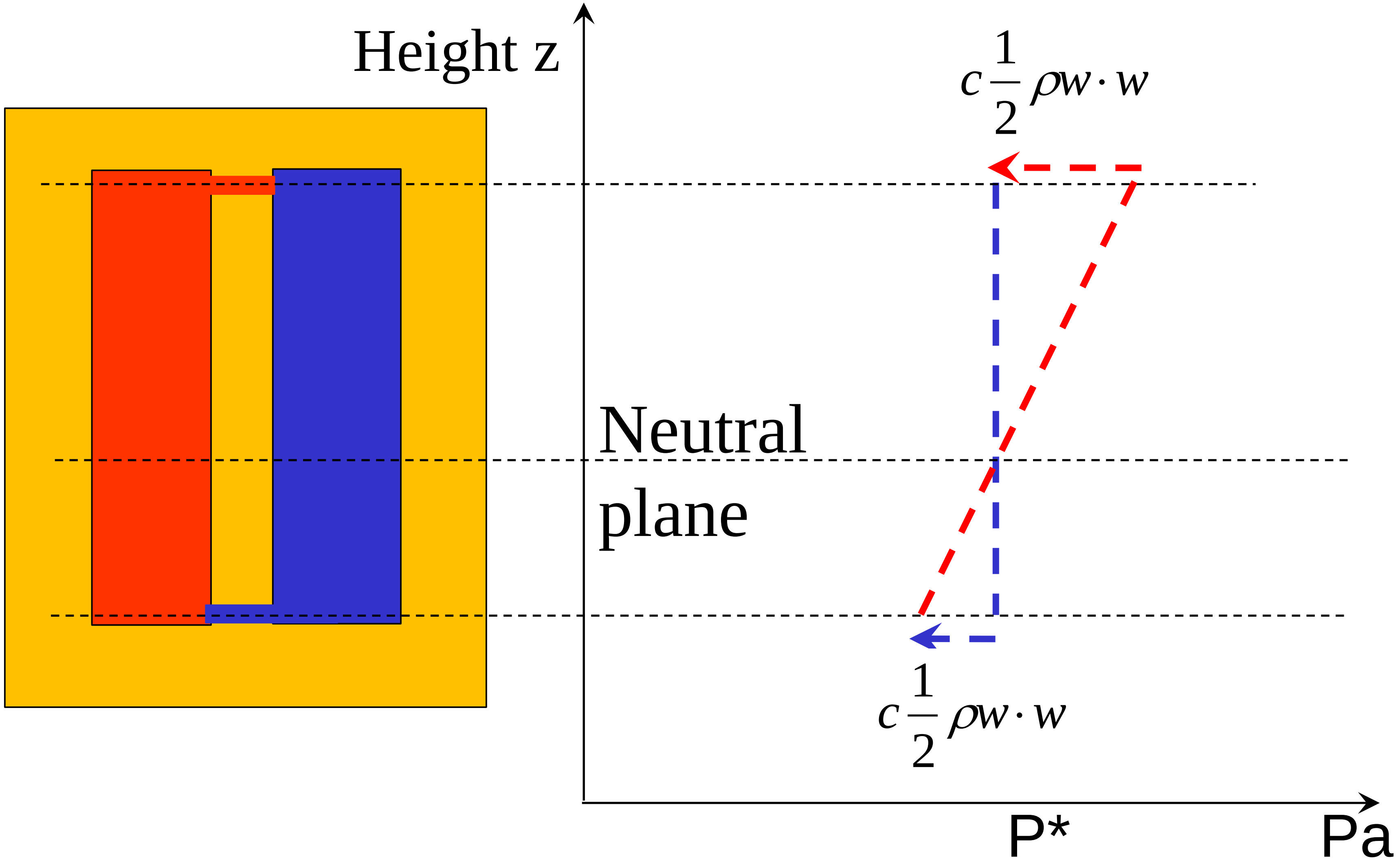
$\rho_{RIF} = \rho_{BLU}$



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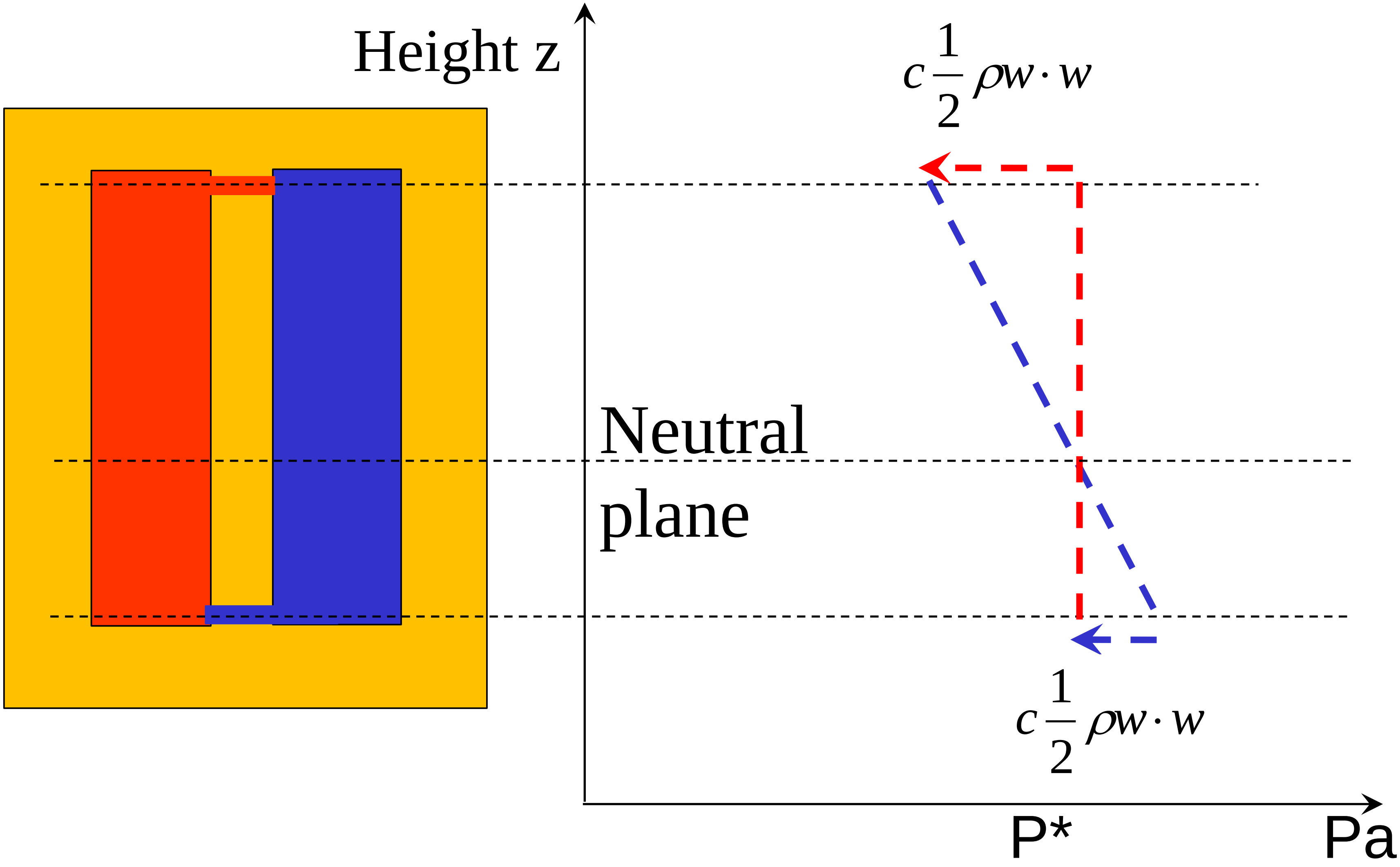
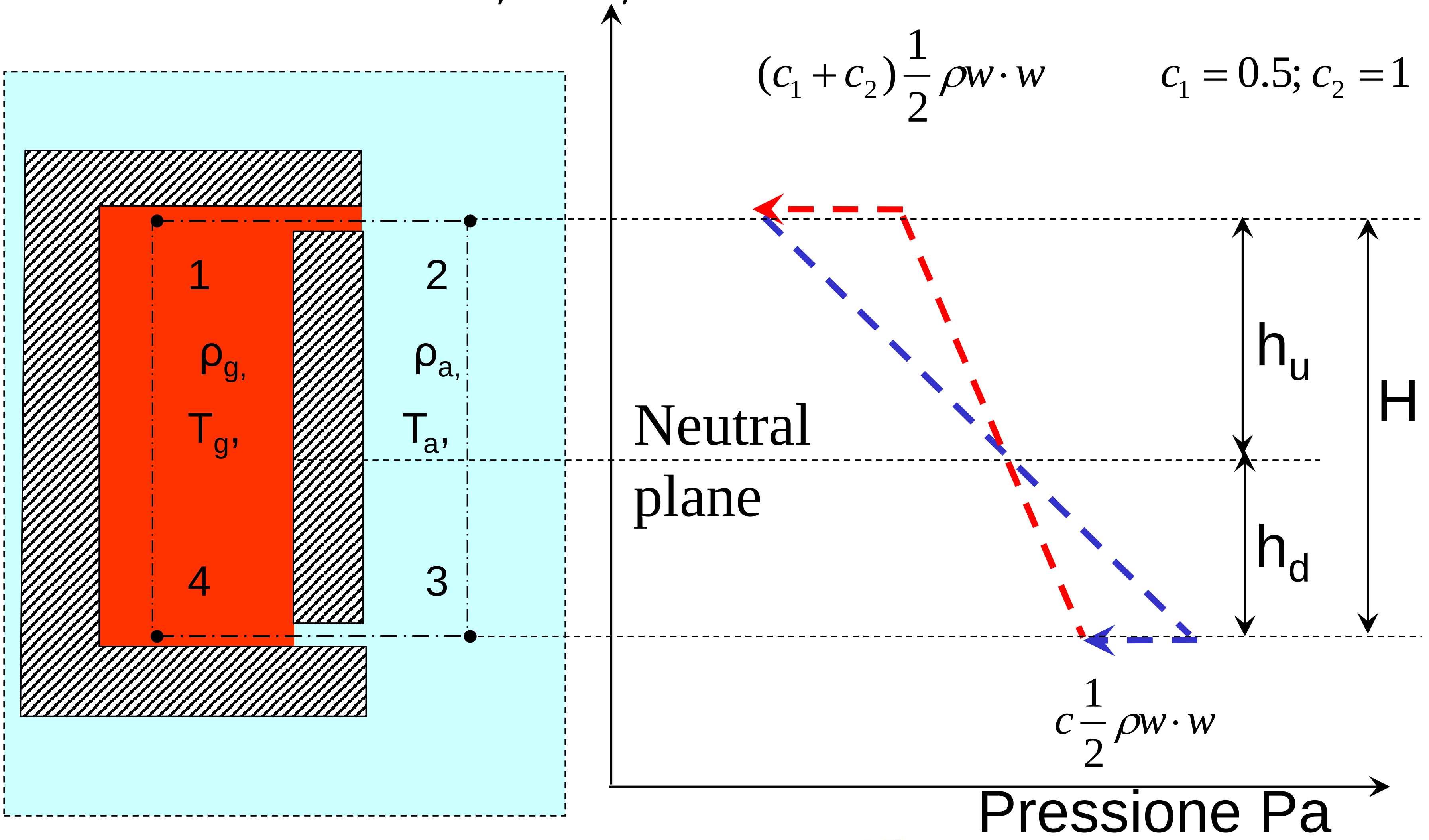
$\rho_{RIF} = \rho_{Rosso}$



Height of neutral plane

P. Karlsson, J. Quinitere, *Enclosure Fire Dynamics* ,
CRC Press, 2000, ISBN 0-8493-1300-7



$$(c_1 + c_2)\frac{1}{2}\rho w \cdot w$$

$$c_1 = 0.5; c_2 = 1$$

$$c\frac{1}{2}\rho w \cdot w$$

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Bernoulli from point 1 to point 2

$$\int dh_a + \int \frac{dp}{\rho g} + \int d\left(\frac{w}{2g}\right) + \int dz = 0$$

$$\int_{inizio}^{fine} dh_a + \int_{inizio}^{fine} \frac{dp}{\rho g} + \frac{w_{fine}^2 - w_{inzio}^2}{2g} + z_{fine} - z_{inizio} = 0$$

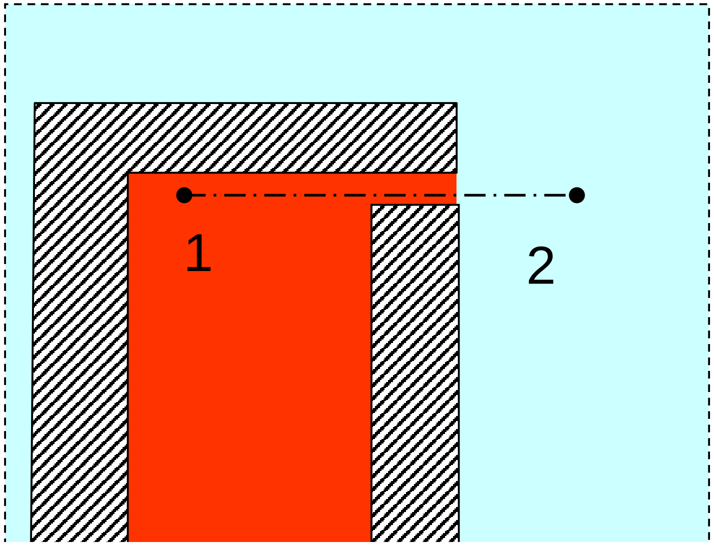
We evaluate Bernoulli eq. twice:

form 1 to 2

from 3 to 4

From point 1 to point 2

(through upper opening)



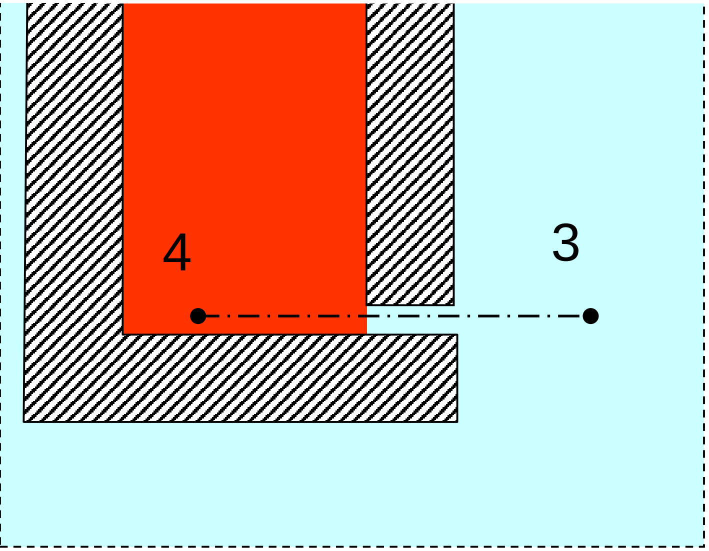
- $z_1=z_2$;
- $w_1=w_2=0$;
- $\rho = \rho_g$;
- The pressure drop across the opening are proportional to w^2_u

$$\int_1^2 dh_a + \int_1^2 \frac{dp}{\rho_g g} + \cancel{\frac{w_2^2 - w_1^2}{2g}} + \cancel{z_2 - z_1} = 0$$

$$P_1 - P_2 = c\rho_g \frac{w_u^2}{2}$$

From 3 to 4

(through the lower opening)

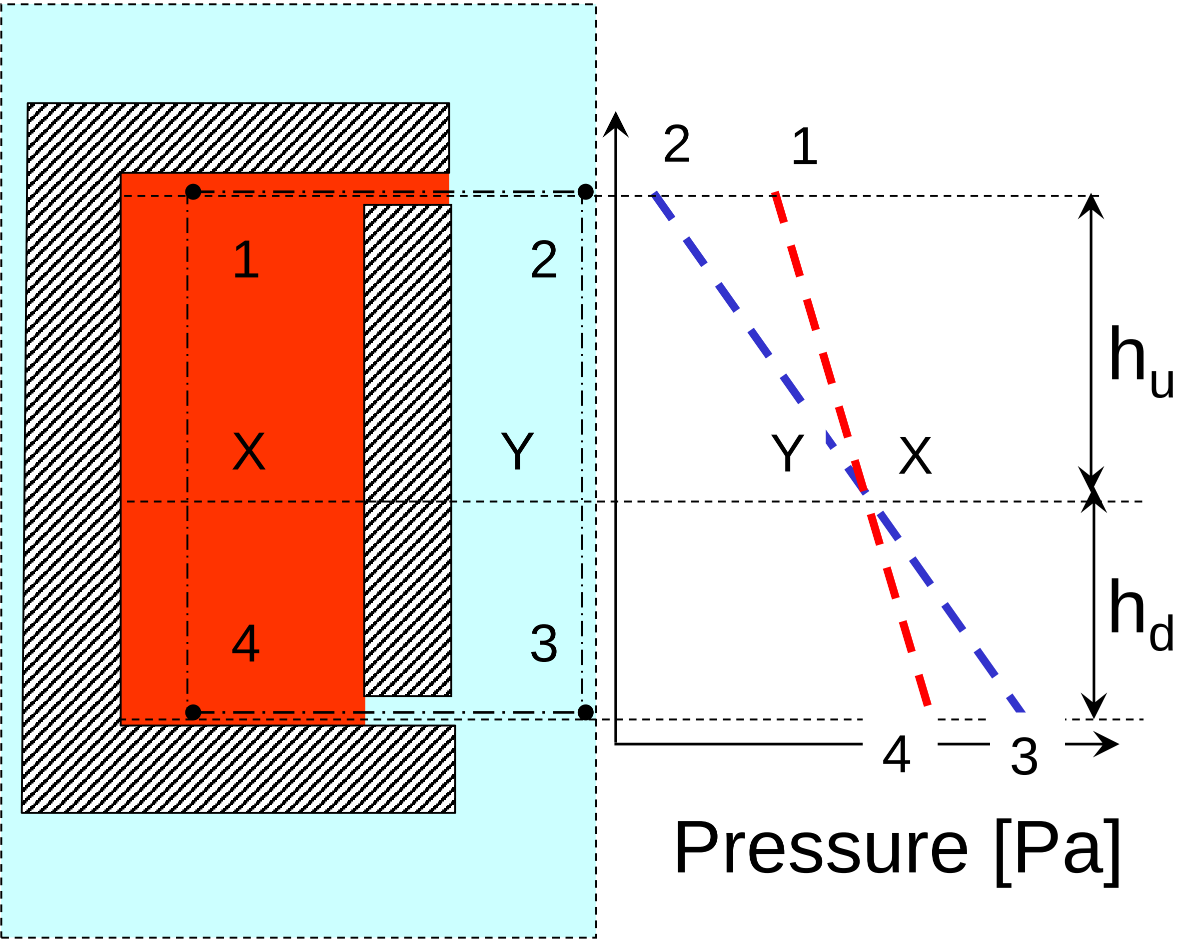


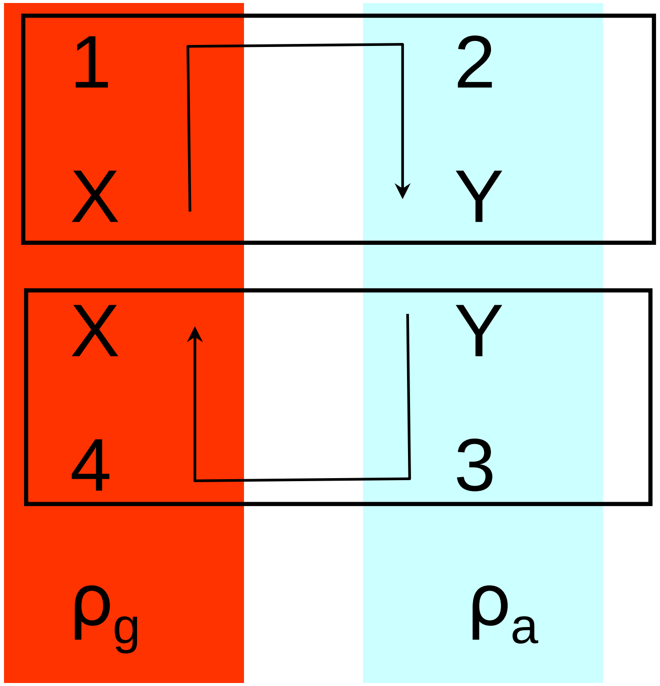
- $z_3=z_4$;
- $w_3=w_4=0$;
- $\rho= \rho_a$;
- The pressure drop across the opening are proportional to w^2_i

$$\int_3^4 dh_a + \int_3^4 \frac{dp}{\rho_a g} + \cancel{\frac{w_4^2 - w_3^2}{2g}} + \cancel{z_4 - z_3} = 0$$

$$P_4 - P_3 = c\rho_a \frac{w_i^2}{2}$$

Calculation of the pressure, starting from the neutral plane





$P_{X=}P_Y$

$$P_1 - P_2 = (\rho_a - \rho_g) g h_u$$

$$P_3 - P_4 = (\rho_a - \rho_g) g h_d$$

Inlet and outlet velocity

$$\begin{cases} P_1 - P_2 = c\rho_g \dfrac{w_u^2}{2} \\ P_1 - P_2 = (\rho_a - \rho_g) g h_u \end{cases}$$

$$\begin{cases} P_4 - P_3 = c\rho_a \dfrac{w_i^2}{2} \\ P_3 - P_4 = (\rho_a - \rho_g) g h_d \end{cases}$$

$$c\rho_g \frac{w_u^2}{2} = (\rho_a - \rho_g) g h_u$$

$$c\rho_a \frac{w_i^2}{2} = (\rho_a - \rho_g) g h_d$$

$$w_u = \sqrt{2 g h_u \frac{(\rho_a - \rho_g)}{c\rho_g}}$$

$$w_i = \sqrt{2 g h_d \frac{(\rho_a - \rho_g)}{c\rho_a}}$$

The ratio between the upper and lower heights, h$_u$ e h$_d$

is obtained by means of continuity equation

Mass flow rate $\dot{m} = \rho w A \qquad [kg/s]$

$$\dot{m}_{in} = \rho_a w_i A_i \qquad \dot{m}_{out} = \rho_g w_u A_u$$

$$\dot{m}_{in} = \rho_a A_i \sqrt{2gh_d \frac{(\rho_a - \rho_g)}{c\rho_a}} \qquad \dot{m}_{out} = \rho_g A_u \sqrt{2gh_u \frac{(\rho_a - \rho_g)}{c\rho_g}}$$

$$\rho_g A_u \sqrt{2gh_u \frac{(\rho_a - \rho_g)}{c\rho_g}} = \rho_a A_i \sqrt{2gh_d \frac{(\rho_a - \rho_g)}{c\rho_a}}$$

$$A_u \sqrt{\rho_g h_u} = A_i \sqrt{\rho_a h_d}$$

h_u e h_d RATIO

$$\frac{h_d}{h_u}=\left(\frac{A_u}{A_i}\right)^2\frac{\rho_g}{\rho_a}\qquad\Rightarrow\qquad\frac{h_d}{h_u}=\left(\frac{A_u}{A_i}\right)^2\frac{T_a}{T_g}$$

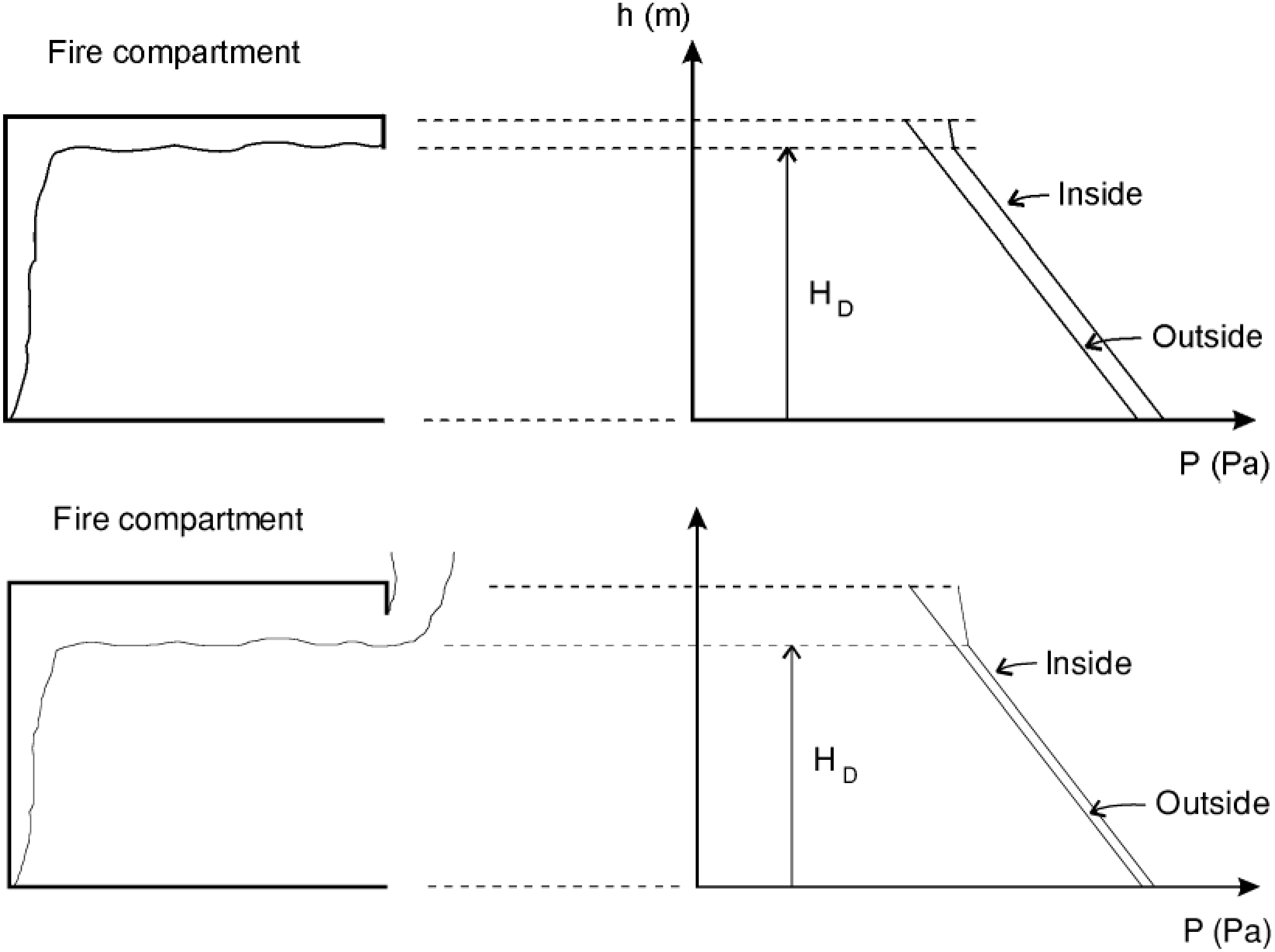
Since $H=h_d(1+h_u/h_d)$

$$h_d=\frac{H}{1+\left(\frac{A_i}{A_u}\right)^2\frac{T_a}{T_g}}$$

$$\dot{m}_{out}=A_u\sqrt{2gh_u\,c_D\,\rho_g\left(\rho_a-\rho_g\right)}=A_u\sqrt{2g\left(H-h_d\right)c_D\,\rho_g\left(\rho_a-\rho_g\right)}$$

Room with large opening

(istanti iniziali e pochi istanti successivi)



Stratification of smoke

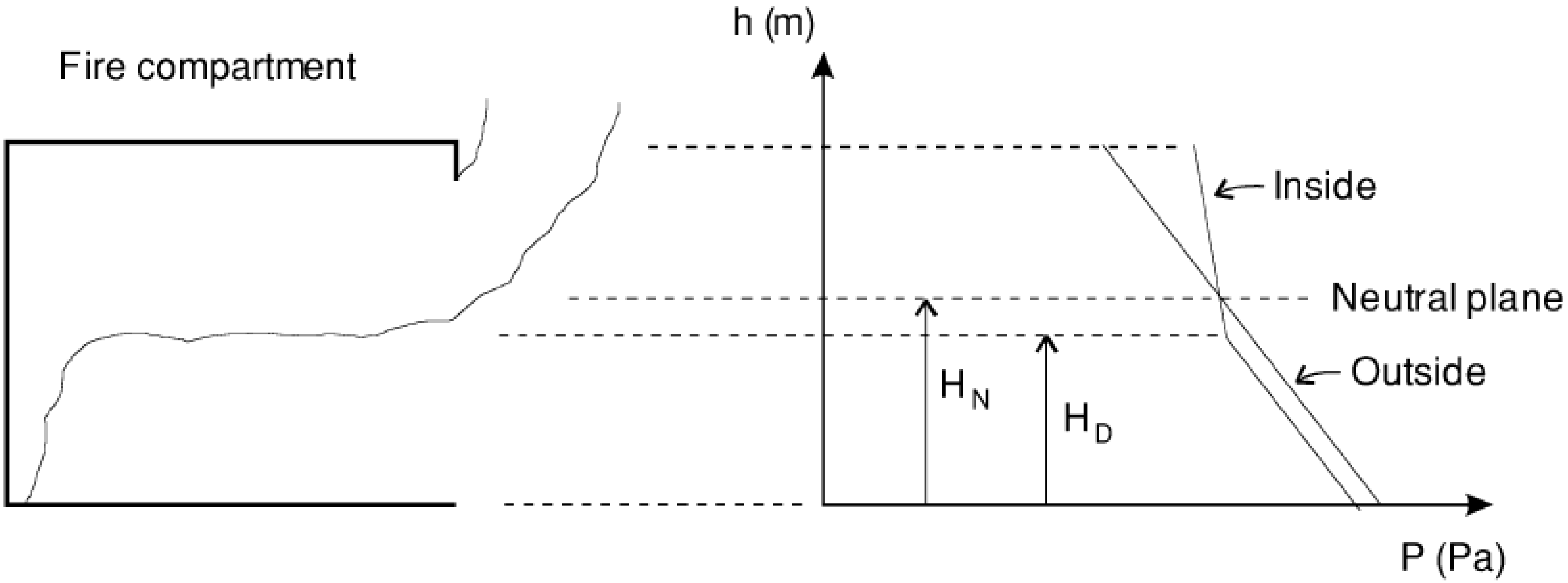
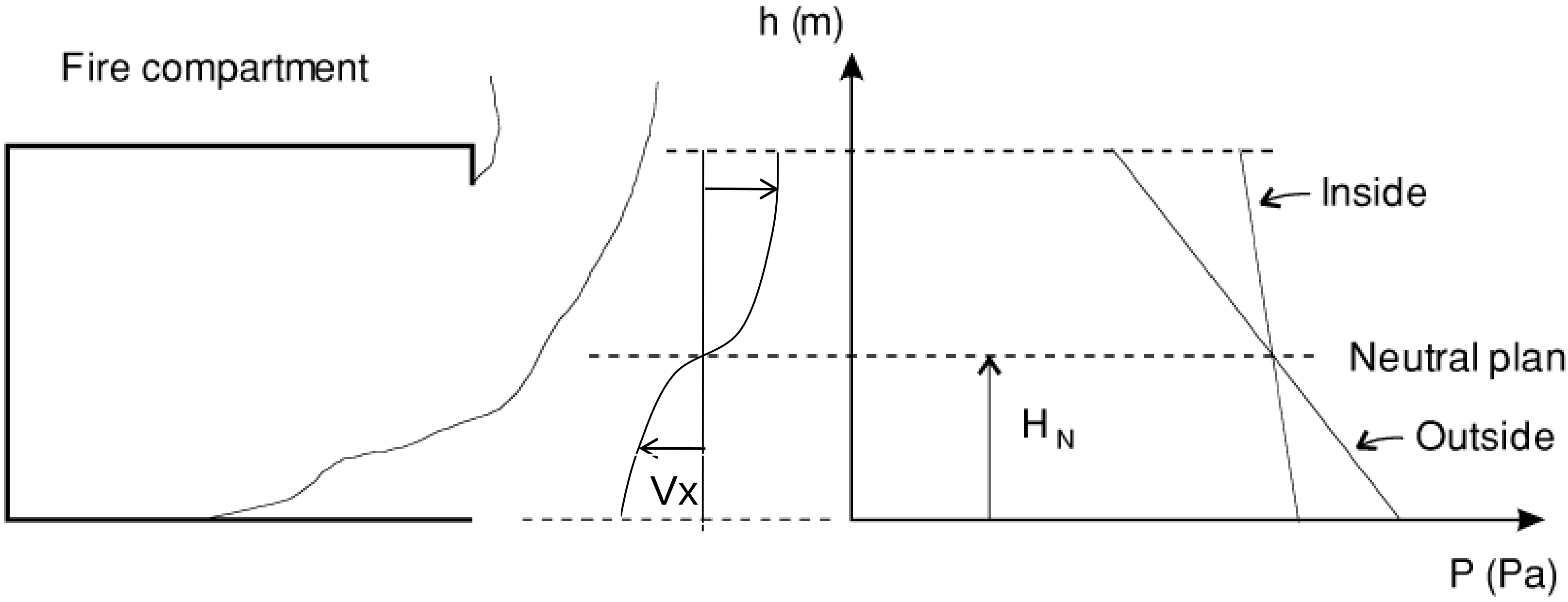


FIGURE 5.10 Pressure difference in a room with two layers, termed the stratified case.

* P. Karlsson, J. Quinitere, *Enclosure Fire Dynamics* , CRC Press, 2000, ISBN 0-8493-1300-7

Fully developed fire

Il fumo ha invaso completamente la stanza e la temperatura, all’interno, può essere considerata uniforme. Welll mixed , Post flashover, One-zone. Anche nel caso di incendio di bassa intensità e ventilazione elevata (caratterizzato da temperature più basse)



* P. Karlsson, J. Quinitere, *Enclosure Fire Dynamics* , CRC Press, 2000, ISBN 0-8493-1300-7

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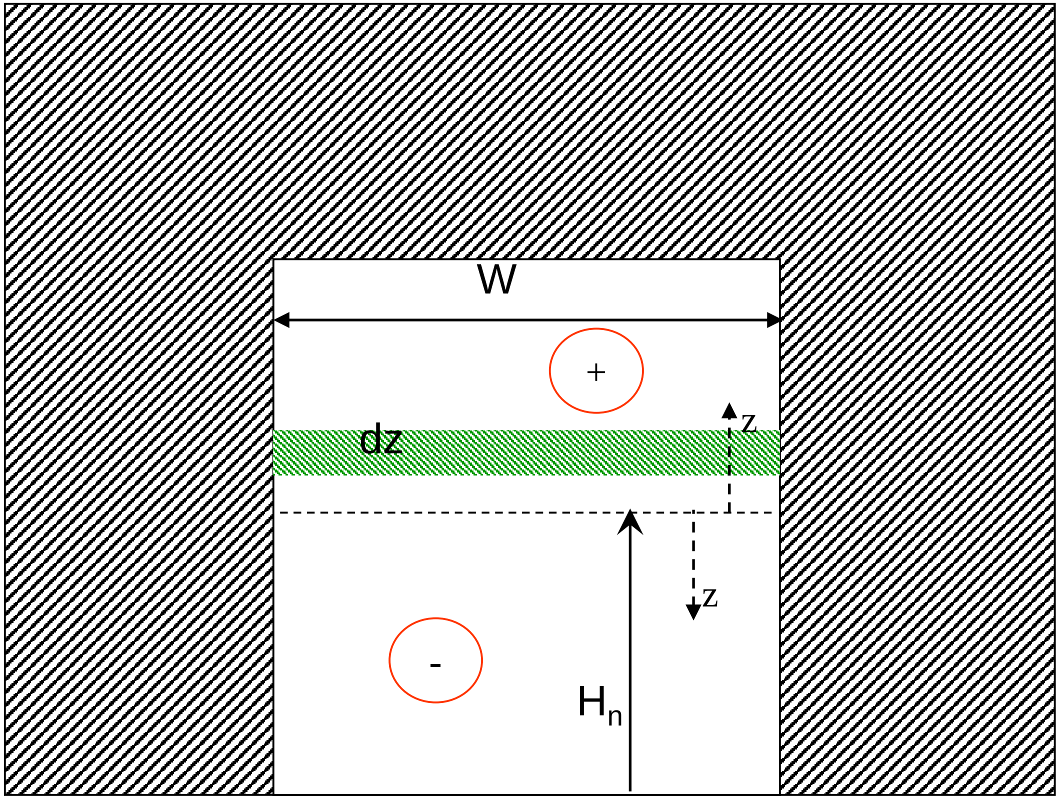
Height of neutral plane H_n

(from continuity)

La portata è $$\dot{m} = \int_A \rho\, w(z)\, dA \qquad [kg/s]$$

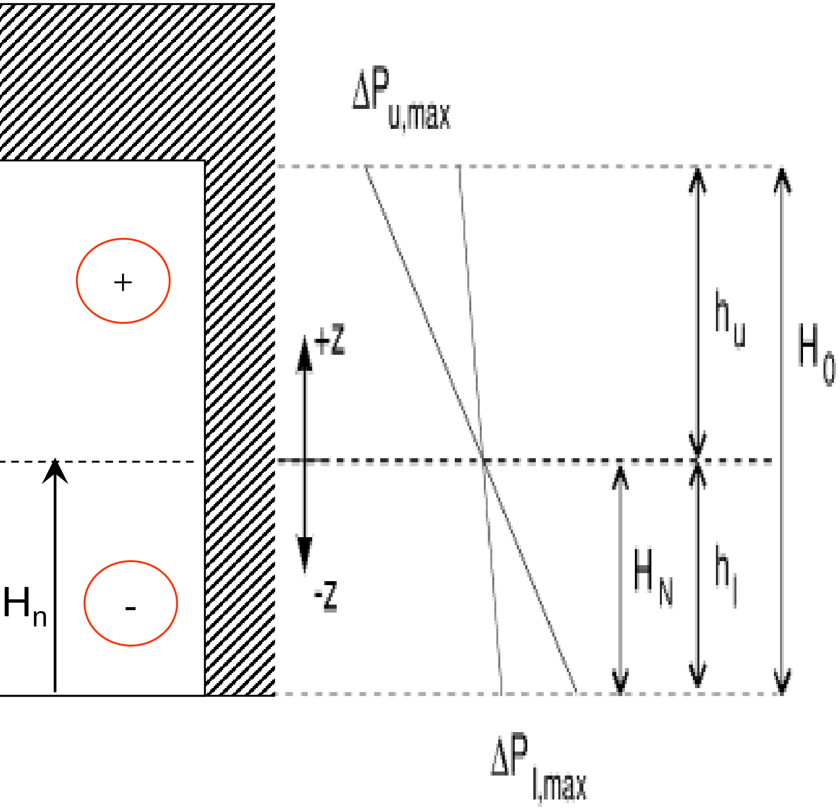


$$dA = W dz$$

$$\dot{m} = W \int_H \rho\, w(z)\, dz$$

$$w(z) = ?$$

The velocity profile depends on pressure difference which, in turn, depends upon height.



$$\Delta P_{u,Max} = \left(\rho_a - \rho_g\right) g h_u$$

$$\Delta P_{l,Max} = \left(\rho_a - \rho_g\right) g h_l$$

$$\Delta P_z = \left(\rho_a - \rho_g\right) g z$$

$$w_u = \sqrt{2g \frac{\left(\rho_a - \rho_g\right)}{c \rho_g} z}$$

$$w_i = -\sqrt{2g \frac{\left(\rho_a - \rho_g\right)}{c \rho_a} \left| z \right|}$$

Mass (flow rate) balance

Substituting velocity

$$\dot{m}_u = C_D W \sqrt{2g \frac{\left(\rho_a - \rho_g\right)}{\rho_g}} \int_0^{h_u} \sqrt{z}\, dz$$

$$\boxed{\dot{m}_u = C_D \rho_g W \sqrt{2g \frac{\left(\rho_a - \rho_g\right)}{\rho_g}} \frac{2}{3} h_u^{3/2}}$$

$$\boxed{\dot{m}_i = C_D \rho_a W \sqrt{2g \frac{\left(\rho_a - \rho_g\right)}{\rho_a}} \frac{2}{3} h_l^{3/2}}$$

$$\dot{m}_u = \dot{m}_i \rightarrow \left(\frac{h_u}{h_l}\right)^{3/2} = \left(\frac{\rho_a}{\rho_g}\right)^{1/2}$$

$$\boxed{\frac{H - h_l}{h_l} = \left(\frac{\rho_a}{\rho_g}\right)^{1/3} = \left(\frac{T_g}{T_a}\right)^{1/3}}$$

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The heigh of the neutral plane is H_n

$$h_l = H_N$$

$$\boxed{H_n = H\frac{1}{1+\left(T_g/T_a\right)^{1/3}}}$$

$$\dot{m}_i = \frac{2}{3}C_D\rho_a W\sqrt{2g\frac{\left(\rho_a-\rho_g\right)}{\rho_a}}\left(\frac{H}{1+\left(\rho_a/\rho_g\right)^{1/3}}\right)^{3/2}$$

$$\dot{m}_i = \frac{2}{3}C_D\rho_a HW\sqrt{2gH}\sqrt{\frac{\left(1-\rho_g/\rho_a\right)}{\left(1+\left(\rho_a/\rho_g\right)^{1/3}\right)^3}}$$

$$\boxed{\dot{m}_i = \frac{2}{3}C_D\rho_a A\sqrt{2gH}\sqrt{\frac{\left(1-T_a/T_g\right)}{\left(1+\left(T_g/T_a\right)^{1/3}\right)^3}}}$$

$$\sqrt{\frac{\left(1-T_a/T_g\right)}{\left(1+\left(T_g/T_a\right)^{1/3}\right)^3}}$$

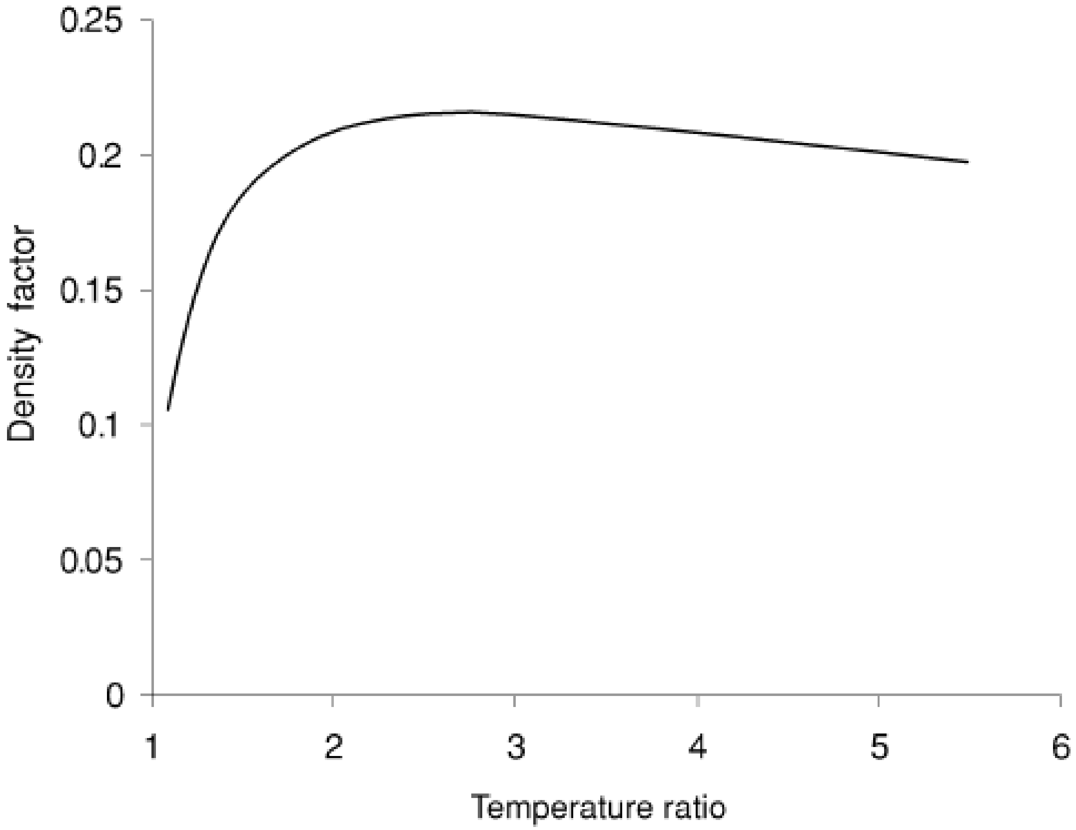

FIGURE 5.13 Density factor in Eq. (5.23) as a function of temperature ratio, T_g/T_a.

Equation (5.23) can then be rewritten as

$$\dot{m}_a = \frac{2}{3} C_d A \sqrt{H_o} \sqrt{2g} \rho_a 0.214$$

* P. Karlsson, J. Quinitere, *Enclosure Fire Dynamics* , CRC Press, 2000, ISBN 0-8493-1300-7

Simplified equation for smoke mass flow rate

$$\dot{m}_a = \frac{2}{3} C_d A \sqrt{H_o} \sqrt{2 g \rho_a} 0.214$$

$$\boxed{\dot{m}_i = 0.5 A \sqrt{H} \quad [kg / s]}$$

~~**Burning rate m”$_b$**~~

~~**Specific mass flow rate of [kg/m$_2$s]**~~

$$\dot{m}_u = \dot{m}_i + \dot{m}_b$$

$$\dot{m}_b'' = 0.01 \div 0.05 \; kg / s \qquad 1\% \dot{m}_i < \dot{m}_b < 7\% \dot{m}_i$$

$$h_1 = \frac{H_o}{1 + \left(\frac{1 + \dot{m}_b / \dot{m}_a}{\sqrt{\rho_g / \rho_a}} \right)^{2/3}} \qquad \dot{m}_a = \frac{2.1 \cdot A \sqrt{H_o}}{\left[1 + 1.6 \cdot (1 + \dot{m}_b / \dot{m}_a)^{2/3} \right]^{3/2}}$$

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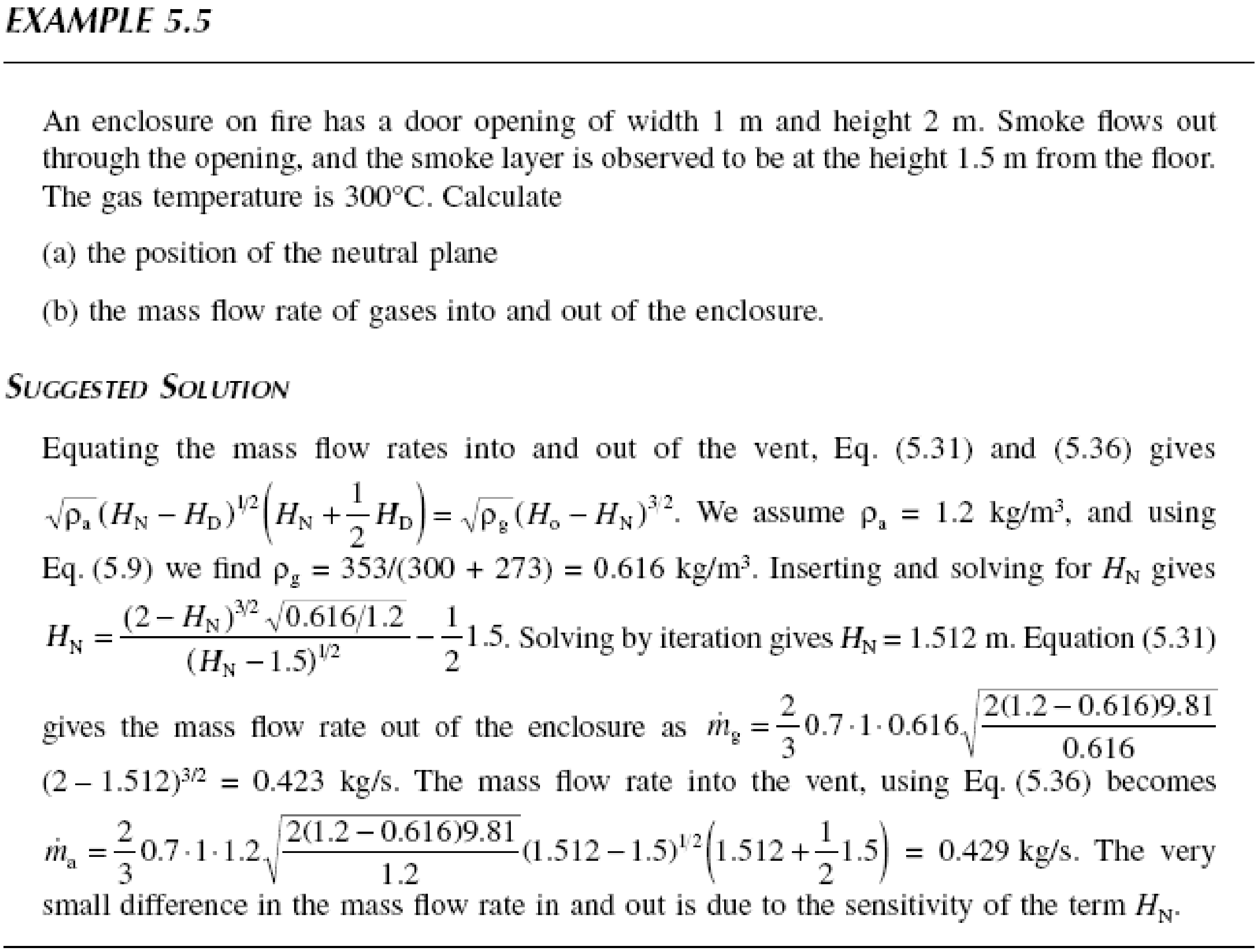


EXAMPLE 5.5

An enclosure on fire has a door opening of width 1 m and height 2 m. Smoke flows out through the opening, and the smoke layer is observed to be at the height 1.5 m from the floor. The gas temperature is 300°C. Calculate

(a) the position of the neutral plane

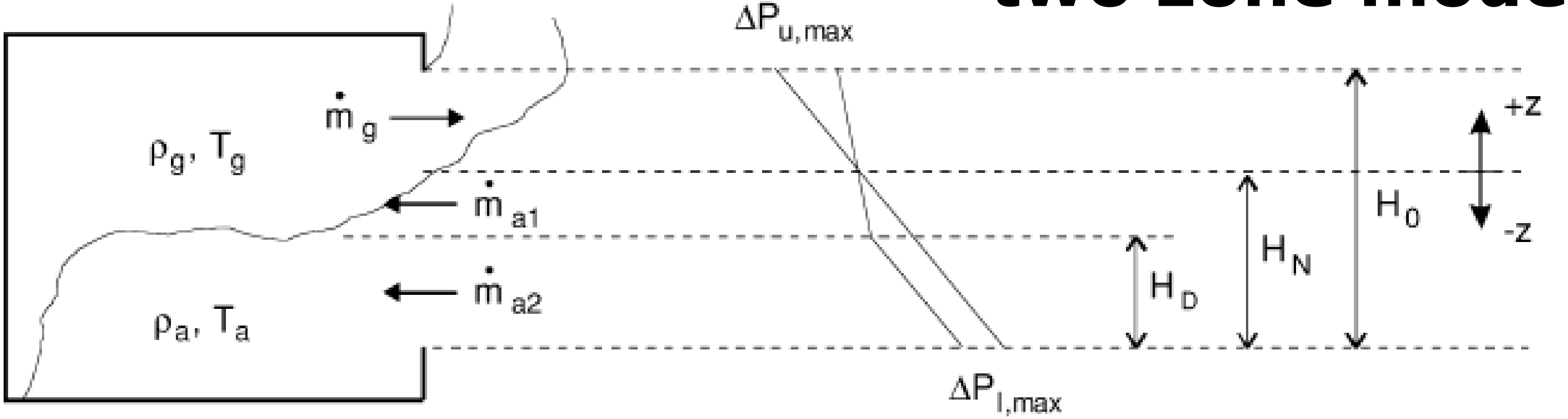
(b) the mass flow rate of gases into and out of the enclosure.

SUGGESTED SOLUTION

Equating the mass flow rates into and out of the vent, Eq. (5.31) and (5.36) gives $\sqrt{\rho_a}(H_N - H_D)^{1/2}\left(H_N + \frac{1}{2}H_D\right) = \sqrt{\rho_g}(H_o - H_N)^{3/2}$. We assume ρ_a = 1.2 kg/m³, and using Eq. (5.9) we find ρ_g = 353/(300 + 273) = 0.616 kg/m³. Inserting and solving for H_N gives $H_N = \frac{(2 - H_N)^{3/2}\sqrt{0.616/1.2}}{(H_N - 1.5)^{1/2}} - \frac{1}{2}1.5$. Solving by iteration gives $H_N = 1.512$ m. Equation (5.31) gives the mass flow rate out of the enclosure as $\dot{m}_g = \frac{2}{3}0.7 \cdot 1 \cdot 0.616\sqrt{\frac{2(1.2 - 0.616)9.81}{0.616}}$ $(2 - 1.512)^{3/2}$ = 0.423 kg/s. The mass flow rate into the vent, using Eq. (5.36) becomes $\dot{m}_a = \frac{2}{3}0.7 \cdot 1 \cdot 1.2\sqrt{\frac{2(1.2 - 0.616)9.81}{1.2}}(1.512 - 1.5)^{1/2}\left(1.512 + \frac{1}{2}1.5\right)$ = 0.429 kg/s. The very small difference in the mass flow rate in and out is due to the sensitivity of the term H_N.

* P. Karlsson, J. Quinitere, *Enclosure Fire Dynamics* , CRC Press, 2000, ISBN 0-8493-1300-7

Stratified smoke: two zone model



$$\dot{m}_a = \frac{2}{3} C_d W \rho_a \cdot \sqrt{\frac{2 \cdot (\rho_a - \rho_g) g}{\rho_a}} (H_N - H_D)^{1/2} \left(H_N + \frac{1}{2} H_D \right)$$

$$\dot{m}_g = \frac{2}{3} C_d W \rho_g \sqrt{\frac{2(\rho_a - \rho_g) g}{\rho_g}} (H_o - H_N)^{3/2}$$

$$\frac{H_N + 0.5 H_D}{H - H_N} = \left(\frac{\rho_g}{\rho_a} \right)^{1/2} = \left(\frac{T_a}{T_g} \right)^{1/2}$$

to solve the equation, the mass flow rate of smoke must be assumed a-priori (iterative solution)

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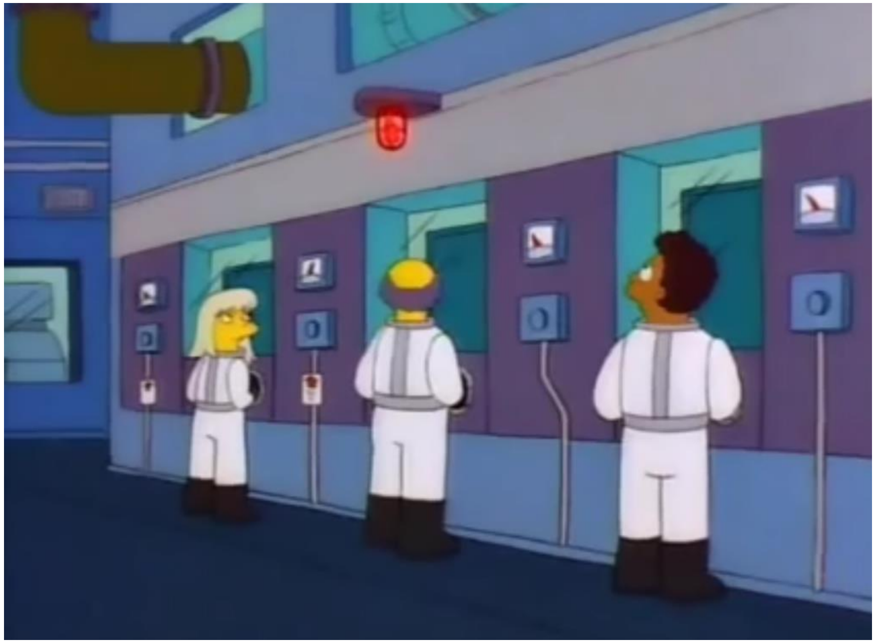
softwares

- **Zone models (CFAST, BRANZfire…)**

- **CFD Model**
  - **General purpose (Fluent, StarCCM+ , …..)**
  - **FDS**

In any case, easier than moving people

Simpson – Egress to a safe place



Safe egress

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Example of
FSE approach
in an Historical building

The library of Albergo dei Poveri

Wikipedia…

https://en.wikipedia.org/wiki/List_of_destroyed_libraries

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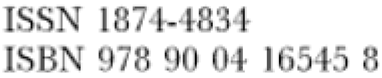
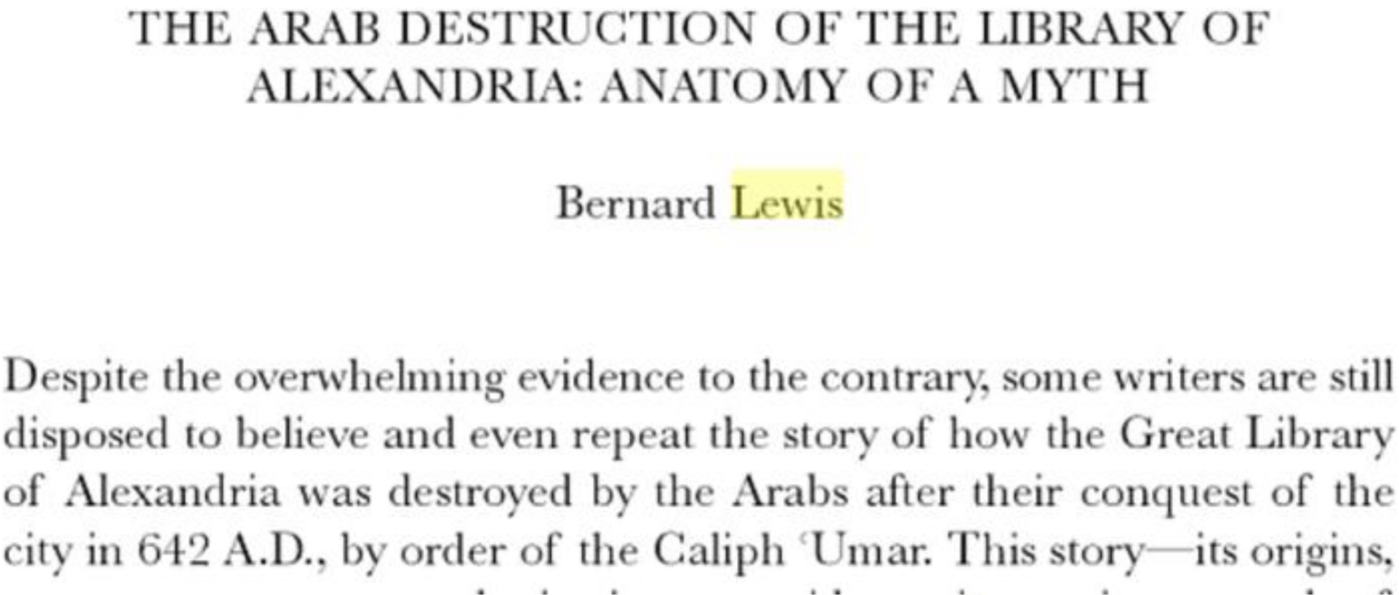
What Happened to the Ancient Library of Alexandria?



ISSN 1874-4834
ISBN 978 90 04 16545 8

Giulio Cesare 47 a.C. ???



THE ARAB DESTRUCTION OF THE LIBRARY OF ALEXANDRIA: ANATOMY OF A MYTH

Bernard Lewis

Despite the overwhelming evidence to the contrary, some writers are still disposed to believe and even repeat the story of how the Great Library of Alexandria was destroyed by the Arabs after their conquest of the city in 642 A.D., by order of the Caliph 'Umar. This story—its origins,

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Biblioteca Nazionale Universitaria di Torino (1904)

National University Library in Turin

http://www.unito.it/unitoWAR/ShowBinary/FSRepo/M009/Allegati/Percorsi_fonti/Incendio/articolo_Novaria.pdf
http://cinquantamila.corriere.it/storyTellerArticolo.php?storyId=4dcacc491d38c

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National Library - Sarajevo

(1992)

http://www.biblio-map.com/2012/04/02/sarajevo-il-4-aprile-di-venti-anni-fa-iniziava-lassedio-pochi-mesi-dopo-il-rogo-della-biblioteca-nazionale-reportage/

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Anna Amalia Weimar Library 2004

http://www.viaggio-in-germania.de/weimar-anna-amalia.html
http://www.anna-amalia-bibliothek.de/de/

2008 - Fire of Architecture Building, Delft

Fire spread out starting from a coffee vending machine !!!

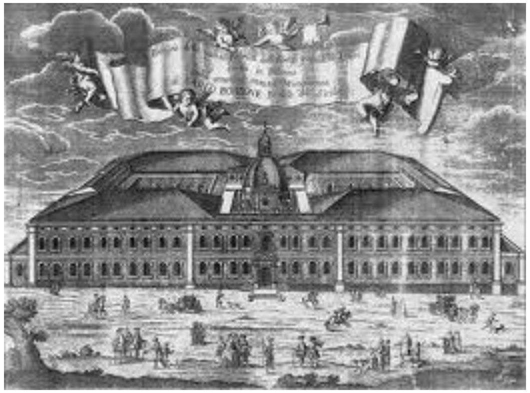
https://www.flickr.com/photos/stylos/2958066460/

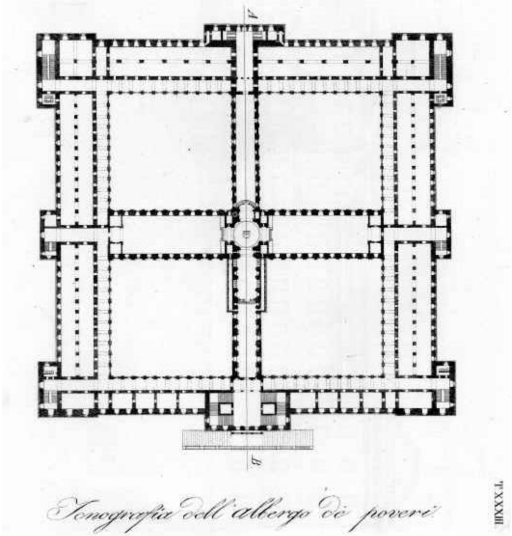
Library of the ‘L'Institut d’Egypte’ - Cairo (2011)

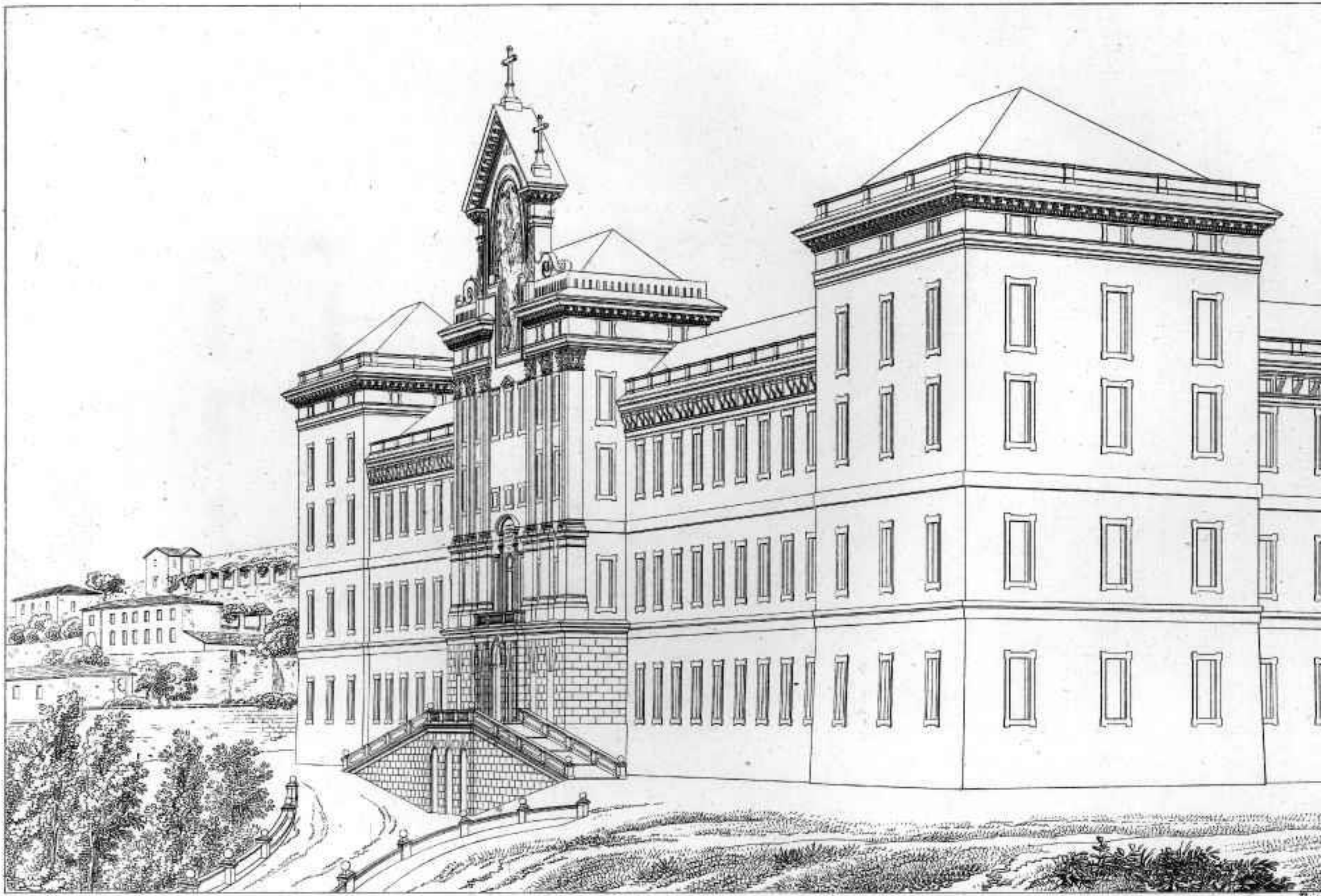
The Egyptian Scientific Institute, in Cairo, was established in 1798 by Napoleon Bonaparte (in 1798 as L'Institut d’Egypte)

Albergo dei Poveri

L'Albergo dei Poveri

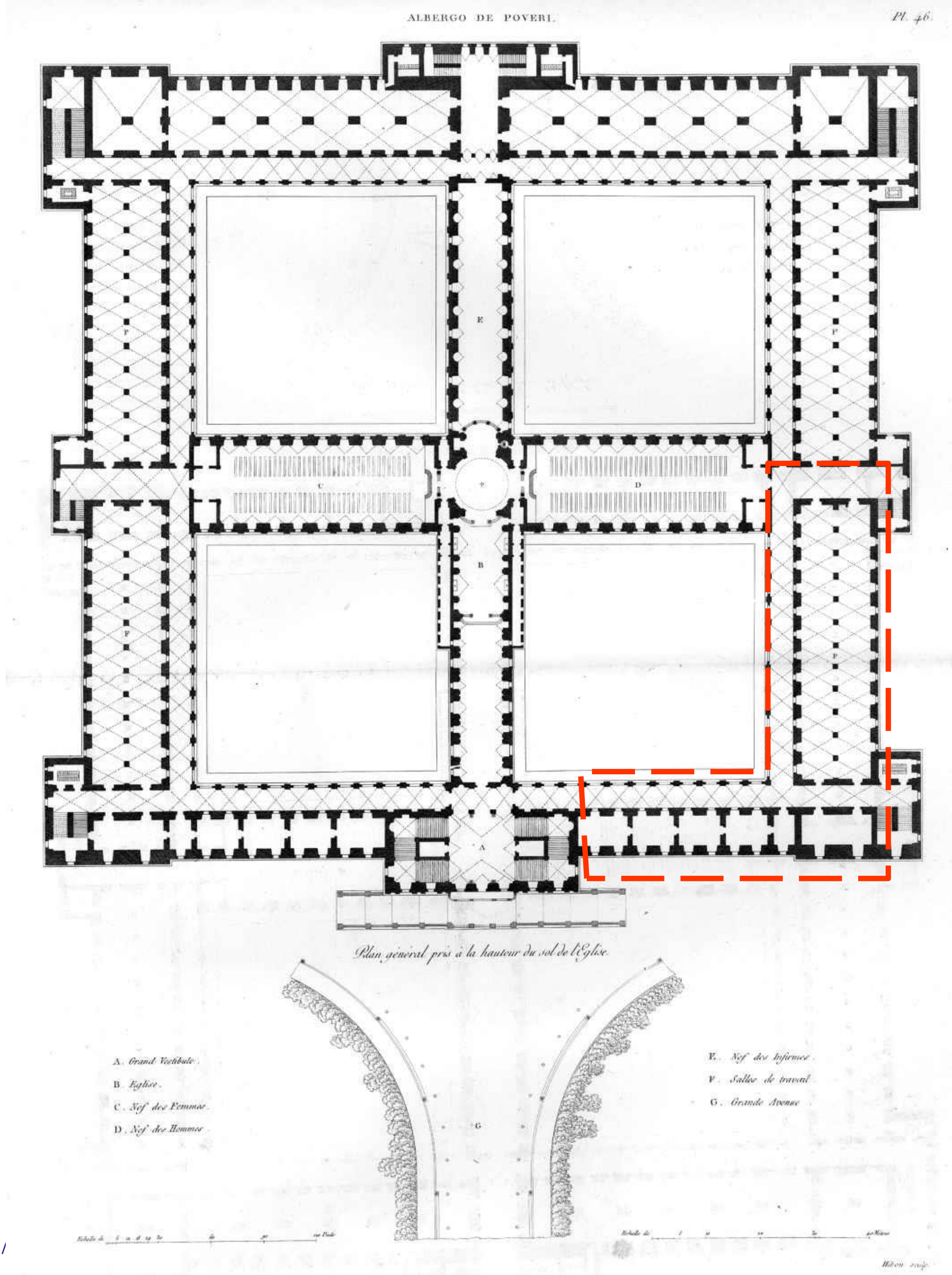






Vue Extérieure.

The building plan (3rd floor)



Plan général pris à la hauteur du sol de l'Eglise.

A. Grand Vestibule.
B. Eglise.
C. Nef des Femmes.
D. Nef des Hommes.
E. Nef des Infirmes.
F. Salles de travail.
G. Grande Avenue.

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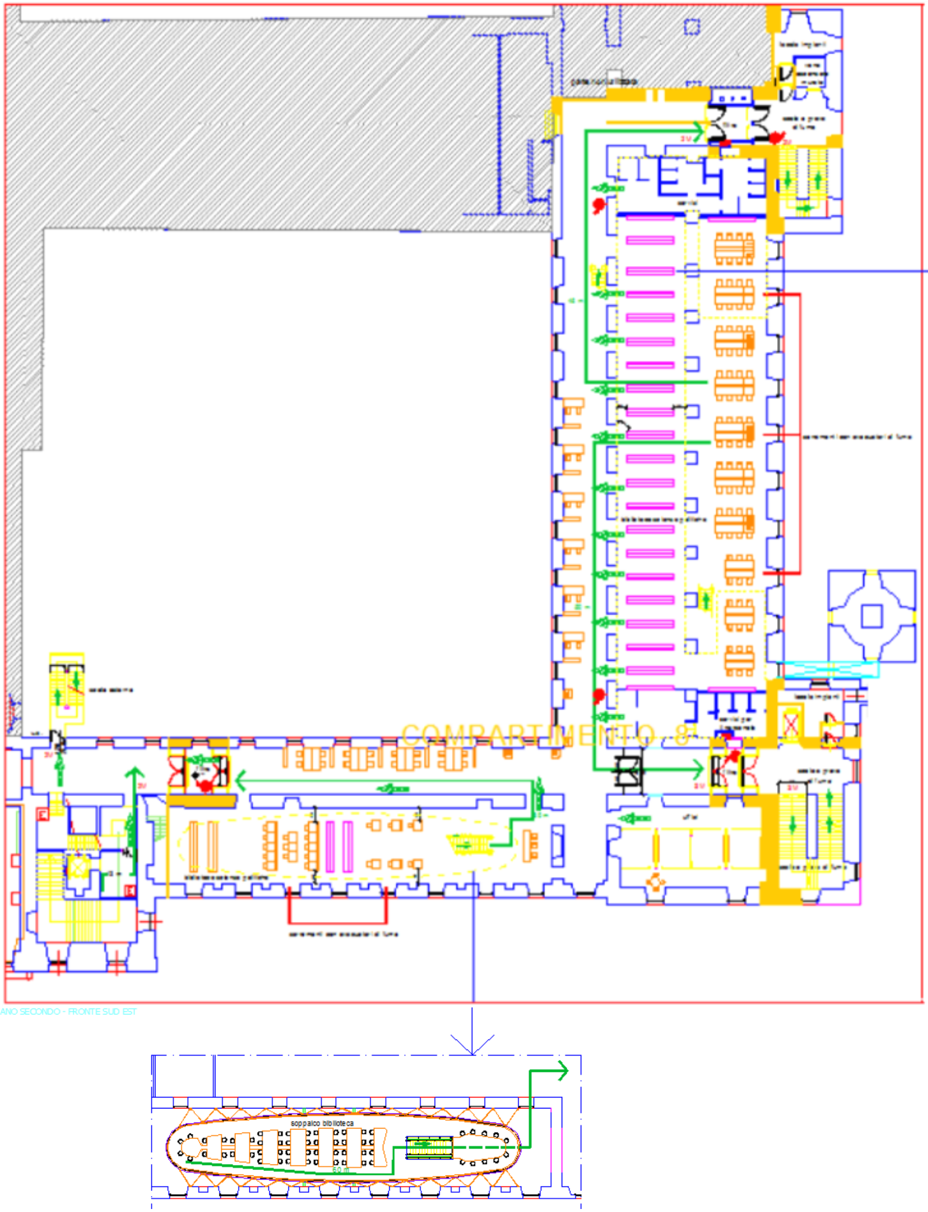
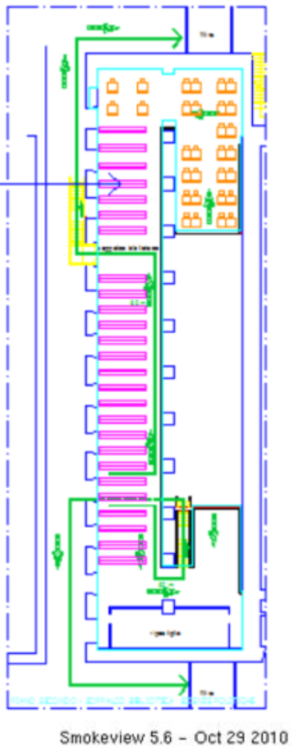
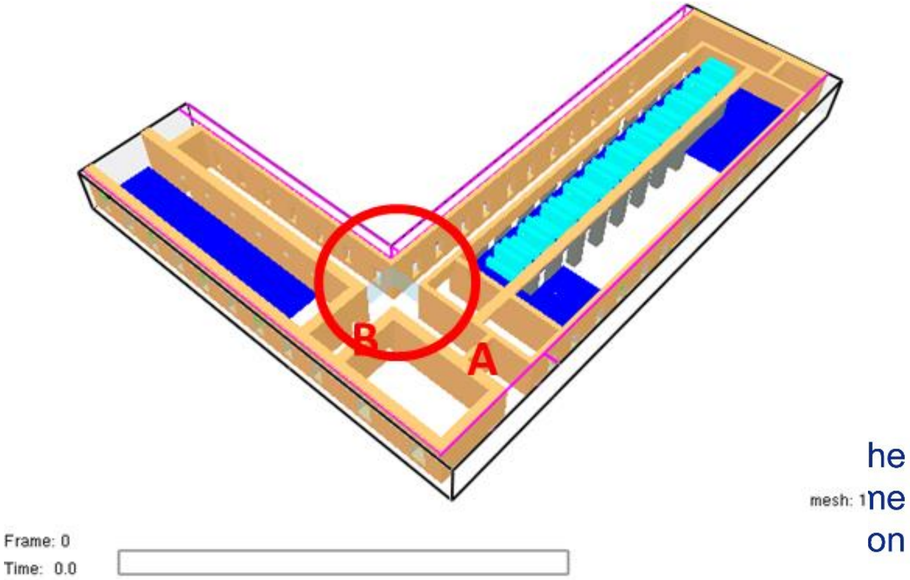
The library today







Premise 2:

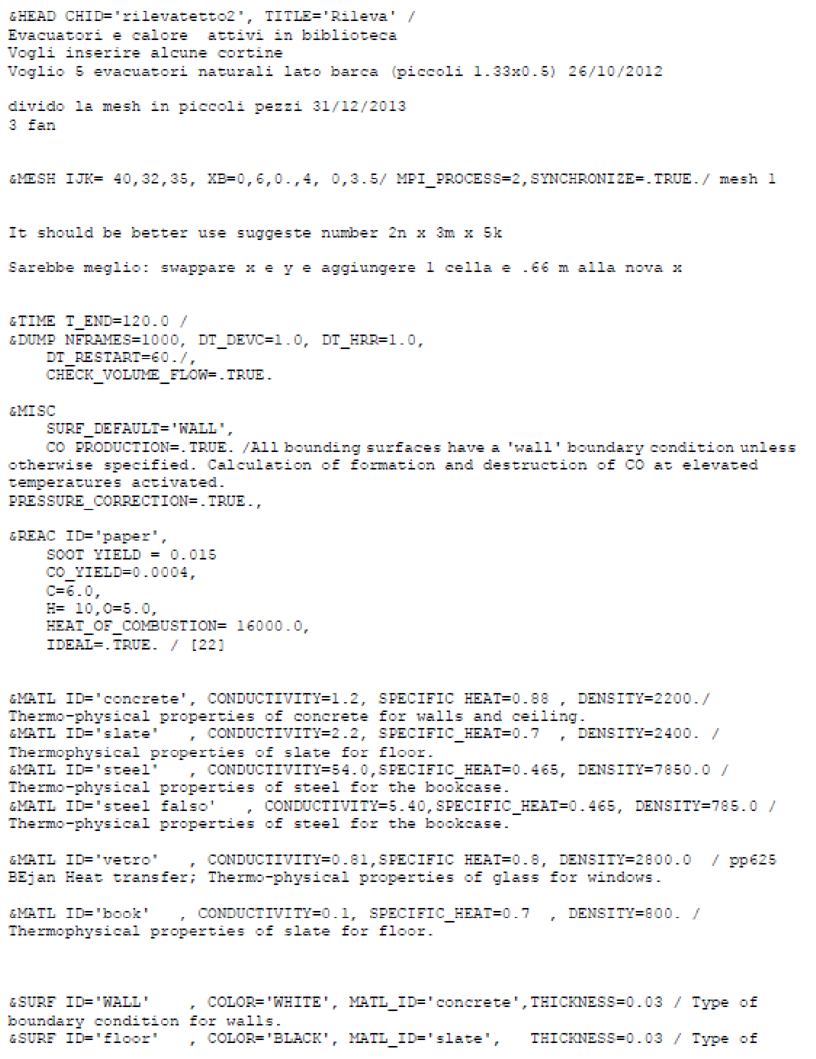
In our case…

Because of some refurbishment of other parts of the building, a compartment…
….didn’t match the prescriptive rules, anymore.

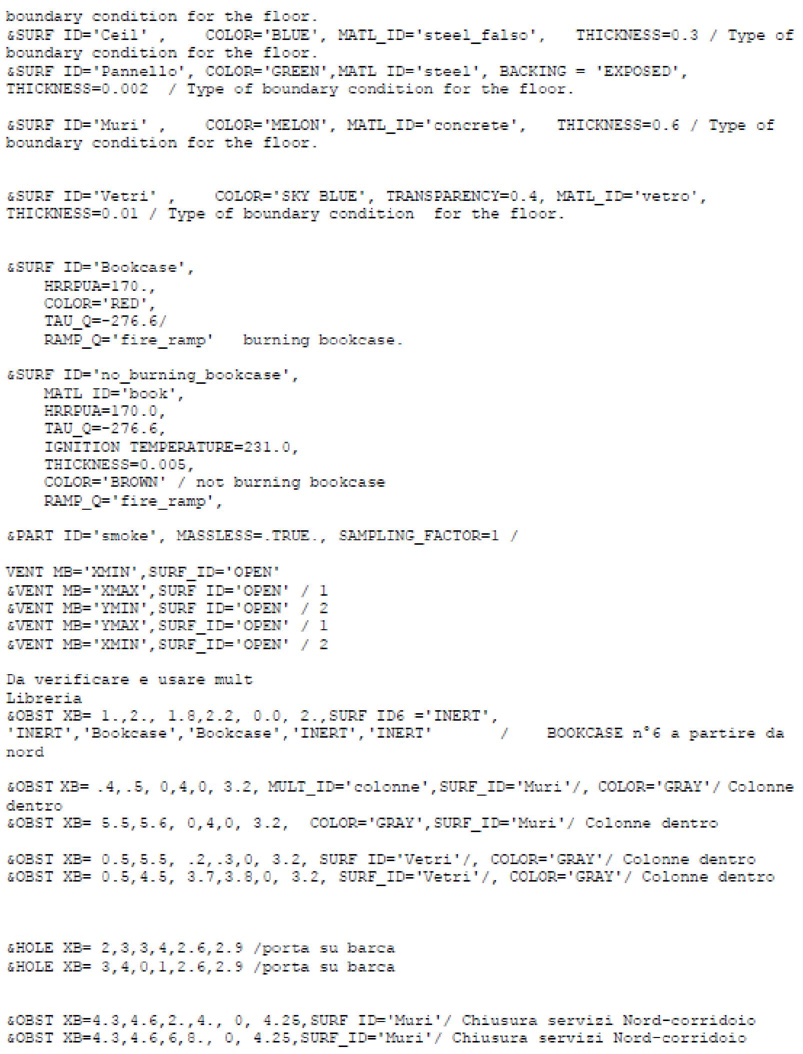
SOLUTION

- Reduce the size of the compartment
- Create a fluid-dynamic compartment

2 pages of .fds input file (of 6)

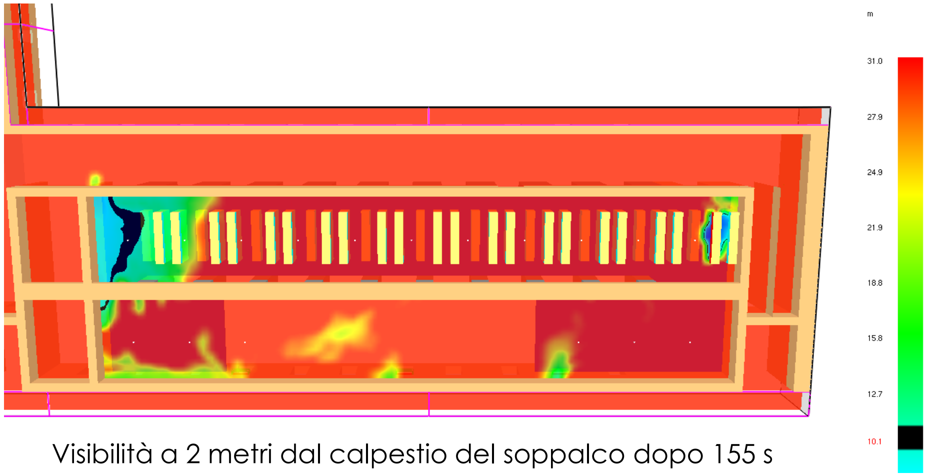


```
&HEAD CHID='rilevatetto2', TITLE='Rileva' /
Evacuatori e calore  attivi in biblioteca
Vogli inserire alcune cortine
Voglio 5 evacuatori naturali lato barca (piccoli 1.33x0.5) 26/10/2012

divido la mesh in piccoli pezzi 31/12/2013
3 fan


&MESH IJK= 40,32,35, XB=0,6,0.,4, 0,3.5/ MPI_PROCESS=2,SYNCHRONIZE=.TRUE./ mesh 1


It should be better use suggeste number 2n x 3m x 5k

Sarebbe meglio: swappare x e y e aggiungere 1 cella e .66 m alla nova x


&TIME T_END=120.0 /
&DUMP NFRAMES=1000, DT_DEVC=1.0, DT_HRR=1.0,
    DT_RESTART=60./,
    CHECK_VOLUME_FLOW=.TRUE.

&MISC
    SURF_DEFAULT='WALL',
    CO PRODUCTION=.TRUE. /All bounding surfaces have a 'wall' boundary condition unless
otherwise specified. Calculation of formation and destruction of CO at elevated
temperatures activated.
PRESSURE_CORRECTION=.TRUE.,

&REAC ID='paper',
    SOOT YIELD = 0.015
    CO_YIELD=0.0004,
    C=6.0,
    H= 10,O=5.0,
    HEAT_OF_COMBUSTION= 16000.0,
    IDEAL=.TRUE. / [22]


&MATL ID='concrete', CONDUCTIVITY=1.2, SPECIFIC HEAT=0.88 , DENSITY=2200./
Thermo-physical properties of concrete for walls and ceiling.
&MATL ID='slate'   , CONDUCTIVITY=2.2, SPECIFIC_HEAT=0.7  , DENSITY=2400. /
Thermophysical properties of slate for floor.
&MATL ID='steel'   , CONDUCTIVITY=54.0,SPECIFIC_HEAT=0.465, DENSITY=7850.0 /
Thermo-physical properties of steel for the bookcase.
&MATL ID='steel falso'   , CONDUCTIVITY=5.40,SPECIFIC_HEAT=0.465, DENSITY=785.0 /
Thermo-physical properties of steel for the bookcase.

&MATL ID='vetro'   , CONDUCTIVITY=0.81,SPECIFIC HEAT=0.8, DENSITY=2800.0  / pp625
BEjan Heat transfer; Thermo-physical properties of glass for windows.

&MATL ID='book'   , CONDUCTIVITY=0.1, SPECIFIC_HEAT=0.7  , DENSITY=800. /
Thermophysical properties of slate for floor.



&SURF ID='WALL'    , COLOR='WHITE', MATL_ID='concrete',THICKNESS=0.03 / Type of
boundary condition for walls.
&SURF ID='floor'   , COLOR='BLACK', MATL_ID='slate',   THICKNESS=0.03 / Type of
```

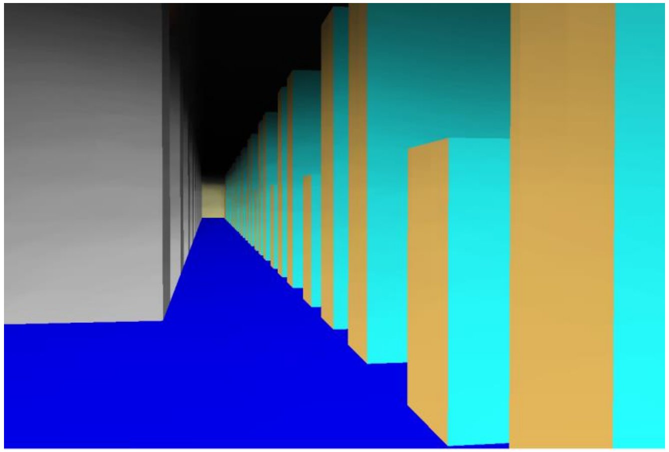


```
boundary condition for the floor.
&SURF ID='Ceil' ,    COLOR='BLUE', MATL_ID='steel_falso',   THICKNESS=0.3 / Type of
boundary condition for the floor.
&SURF ID='Pannello', COLOR='GREEN',MATL ID='steel', BACKING = 'EXPOSED',
THICKNESS=0.002  / Type of boundary condition for the floor.

&SURF ID='Muri' ,    COLOR='MELON', MATL_ID='concrete',   THICKNESS=0.6 / Type of
boundary condition for the floor.


&SURF ID='Vetri' ,    COLOR='SKY BLUE', TRANSPARENCY=0.4, MATL_ID='vetro',
THICKNESS=0.01 / Type of boundary condition  for the floor.


&SURF ID='Bookcase',
    HRRPUA=170.,
    COLOR='RED',
    TAU_Q=-276.6/
    RAMP_Q='fire_ramp'   burning bookcase.

&SURF ID='no_burning_bookcase',
    MATL ID='book',
    HRRPUA=170.0,
    TAU_Q=-276.6,
    IGNITION TEMPERATURE=231.0,
    THICKNESS=0.005,
    COLOR='BROWN' / not burning bookcase
    RAMP_Q='fire_ramp',

&PART ID='smoke', MASSLESS=.TRUE., SAMPLING_FACTOR=1 /

VENT MB='XMIN',SURF_ID='OPEN'
&VENT MB='XMAX',SURF ID='OPEN' / 1
&VENT MB='YMIN',SURF ID='OPEN' / 2
&VENT MB='YMAX',SURF_ID='OPEN' / 1
&VENT MB='XMIN',SURF_ID='OPEN' / 2

Da verificare e usare mult
Libreria
&OBST XB= 1.,2., 1.8,2.2, 0.0, 2.,SURF ID6 ='INERT',
'INERT','Bookcase','Bookcase','INERT','INERT'       /    BOOKCASE n°6 a partire da
nord

&OBST XB= .4,.5, 0,4,0, 3.2, MULT_ID='colonne',SURF_ID='Muri'/, COLOR='GRAY'/ Colonne
dentro
&OBST XB= 5.5,5.6, 0,4,0, 3.2,  COLOR='GRAY',SURF_ID='Muri'/ Colonne dentro

&OBST XB= 0.5,5.5, .2,.3,0, 3.2, SURF ID='Vetri'/, COLOR='GRAY'/ Colonne dentro
&OBST XB= 0.5,4.5, 3.7,3.8,0, 3.2, SURF_ID='Vetri'/, COLOR='GRAY'/ Colonne dentro



&HOLE XB= 2,3,3,4,2.6,2.9 /porta su barca
&HOLE XB= 3,4,0,1,2.6,2.9 /porta su barca


&OBST XB=4.3,4.6,2.,4., 0, 4.25,SURF ID='Muri'/ Chiusura servizi Nord-corridoio
&OBST XB=4.3,4.6,6,8., 0, 4.25,SURF_ID='Muri'/ Chiusura servizi Nord-corridoio
```

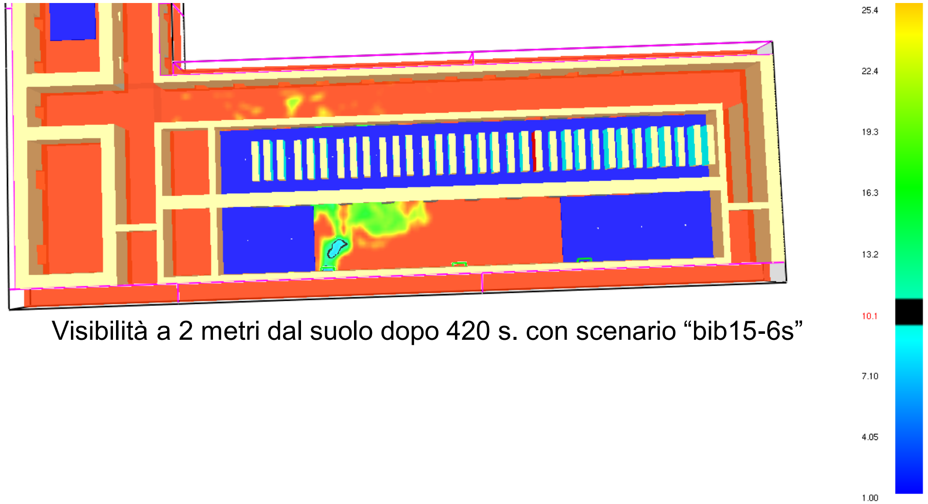
La scelta della soluzione finale è stata effettuata sulla base delle condizioni di visibilità alla quota di due metri dal livello del soppalco (Z=5m) **dopo 155 s e quelle a 2 m dal suolo dopo 420 s**.



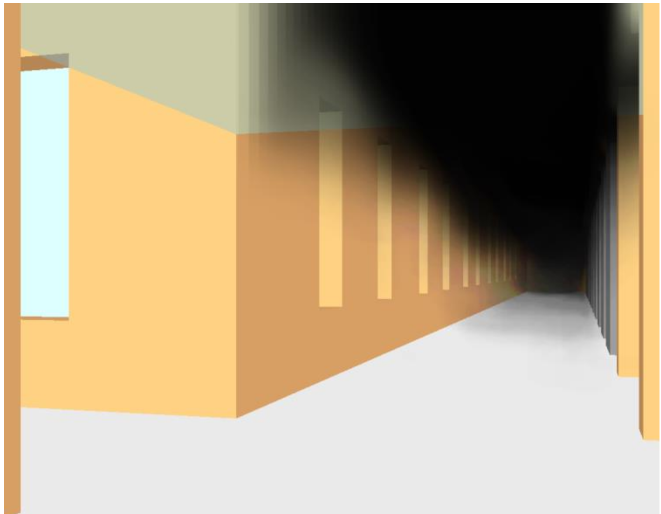
Visibilità a 2 metri dal calpestio del soppalco dopo 155 s



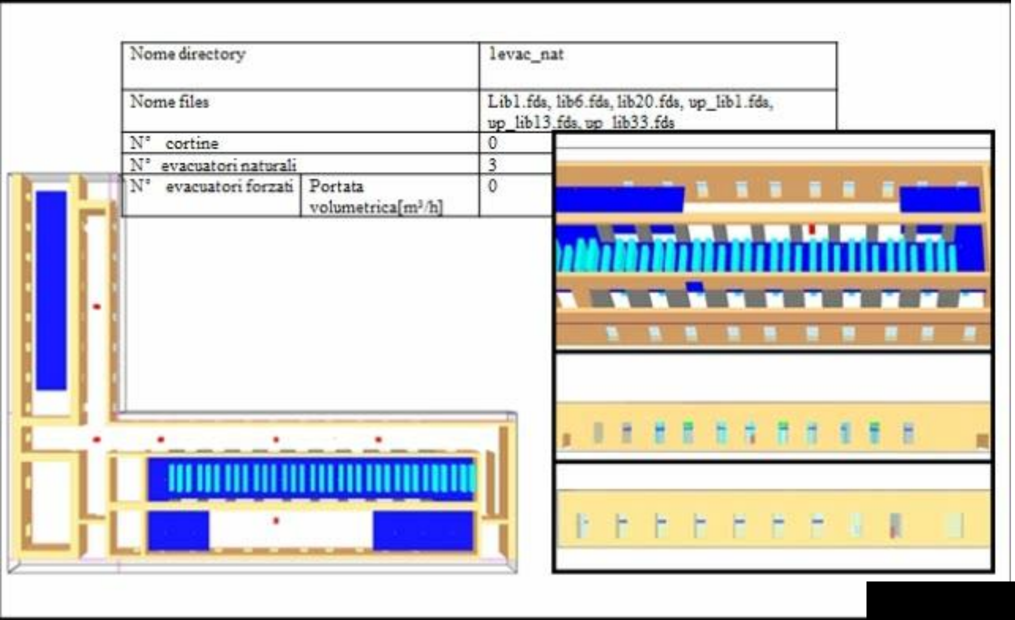
Soot dopo 155 s. (vista da nord del soppalco es.bib15-25s)



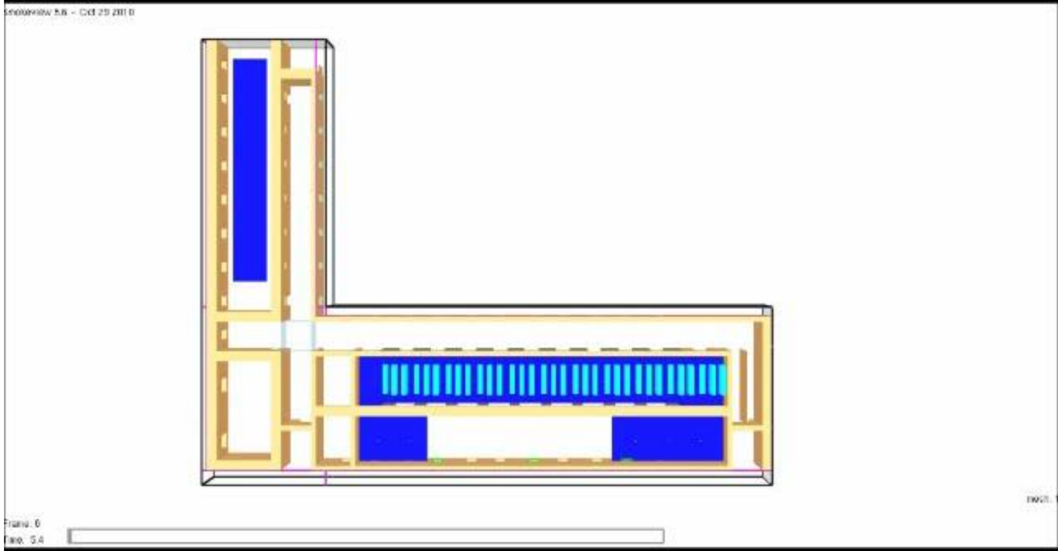
Visibilità a 2 metri dal suolo dopo 420 s. con scenario "bib15-6s"



Soot dopo 420 s. (vista corridoio dall'incrocio es.bib15-25s



Nome directory		1evac_nat
Nome files		Lib1.fds, lib6.fds, lib20.fds, up_lib1.fds, up_lib13.fds, up_lib33.fds
N° cortine		0
N° evacuatori naturali		3
N° evacuatori forzati	Portata volumetrica[m³/h]	0



CONCLUSION

"… is that catastrophes occur more as a rule than as exceptions…“

R.K. Mehra, E.H. Blum

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TENABILITY TO THERMAL RADIATION

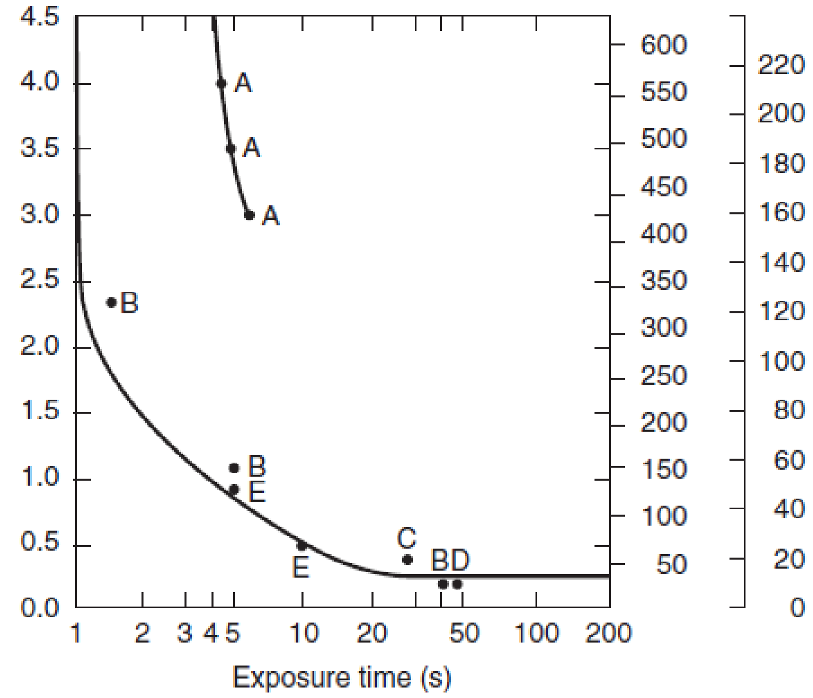

Figure 2-6.28. *Time to severe skin pain from radiant heat. Adapted from Berenson and Robertson.[111] See text and Table 2-6.18 for discussion of data points A to E.*[56,112,115,118,124,125]

Table 2-6.18 ***Data on the Effects of Exposure to Radiant Heat***

Reference Source	Heat Flux W/cm²	Time to Effect(s) Erythema (or pain)	Burn	Full Burn	Letter in Figure 2-6.28
Perkins et al.[124]	15	1	2.5	4	
	10	2	4	6	
	5	4	7	>15	
	4	4.5	9	>15	A
	3.5	5	9.5	>15	A
	3	6	10	>15	A
Buettner[119]	2.35	1.6			B
	1.05	5			B
	0.25	40			B
Veghte[115]			Blisters		
	0.42		30		C
Simms and Hinkley[112]		Unbearable pain			
	0.126	600			
	0.252	30 to 60			D
Dinman[125]	0.24	Lower limit for pain after a long period			
	0.82	5			E
	0.48	10			E
Berenson and Robertson[111]	0.34	Limit for blood to carry away heat			
Babrauskas[56]	0.25	Tenability limit			

the shape of tenability curve show a clear limit **physical limit value at** 0.25 W/cm^2 (**2.5 kW/m^2**) (Babrauskas)

Thank you for your attention…

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