Experimental Verification of a Radiant Heat Exposure Model

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Introduction

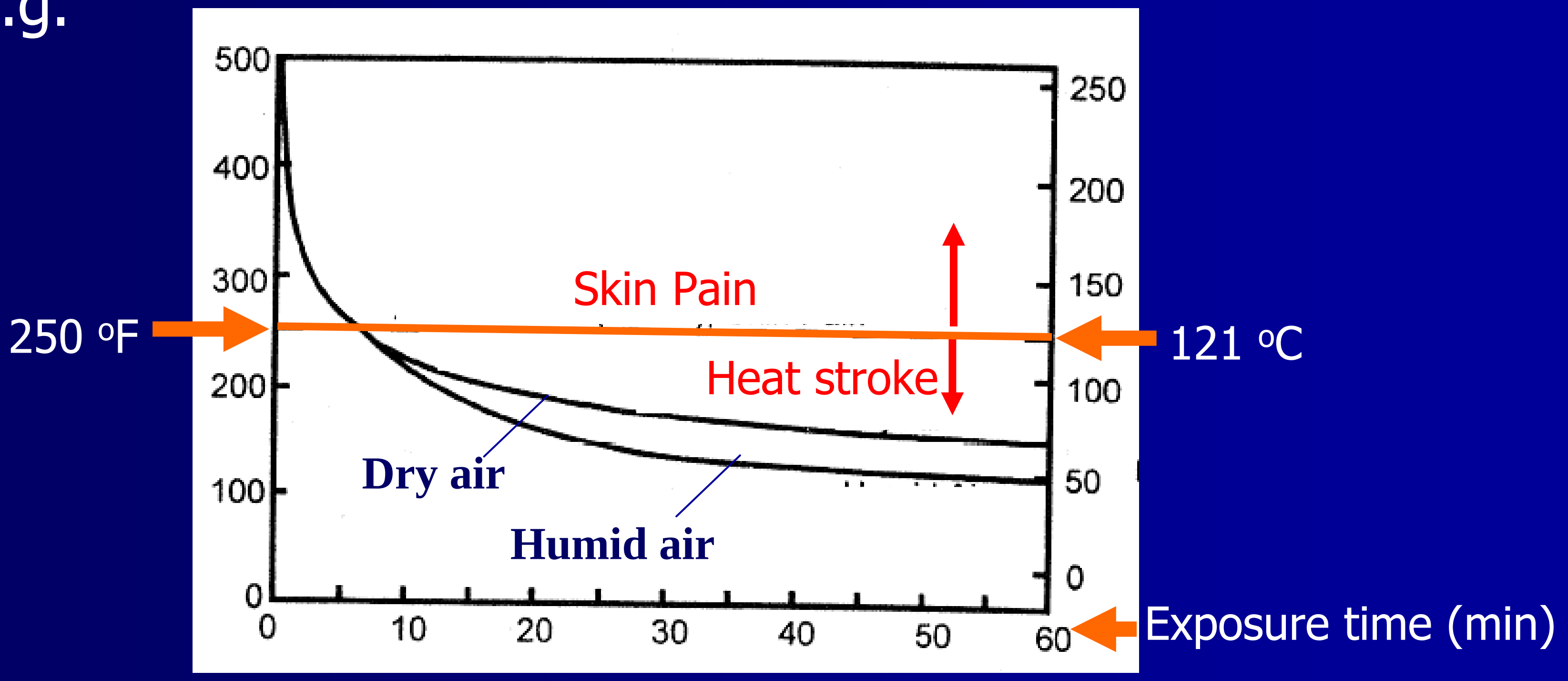
Thermal hazard and heat exposure

Atmospheres at dry air temperature 250^{o}F (121^{o}C)
- Skin burns
- Hyperthermia (Heat stroke): also at a T < 121oC

Thermal radiation
- Pain
- Blistering
- Skin burns

Introduction

Thermal tolerance for humans at rest, naked with low air movement. (Blockley 1973)
e.g.



Introduction

Average time t (min) to incapacitation for exposures to humid air and dry air at an elevated temperature T (^{o}C) (Purser 2002)

$$t = \exp(5.185-0.0273\ T)$$

Introduction

Exposure to Thermal Radiation

Only addressed in some fire scenarios ("Limited" temperature)

Introduction

Why Thermal Radiation is studied?

- Direct hazard – case dependent; Skin pain, skin burns
- Psychological effects – would affect occupant's decision

Example: A large high-rise building fire in 1996

Some building occupants would decide not to use an escape corridor with hot smoke; stayed in the rooms adjacent to the corridor for hours before they used the building windows for evacuation

Skin damage

Exposure Time: t at the Skin Temperature: T > 44ºC

Sensation ∝ t (T > 44ºC)

Pain → Burns → Injury

Classifying skin burns by Degree

First Degree burns: minor and result only in a mild inflammation of the skin. E.g. Sunburn

Second Degree burns: →blisters on the skin.
Superficial: heal with little/no scarring
Deeper 2^{nd} burn: forming thin layer of coagulated and dead cells, feel leathery to the touch

Third Degree burns: penetrates through both epidermis and the dermis; or body tissue (deep burn)

Exposure models

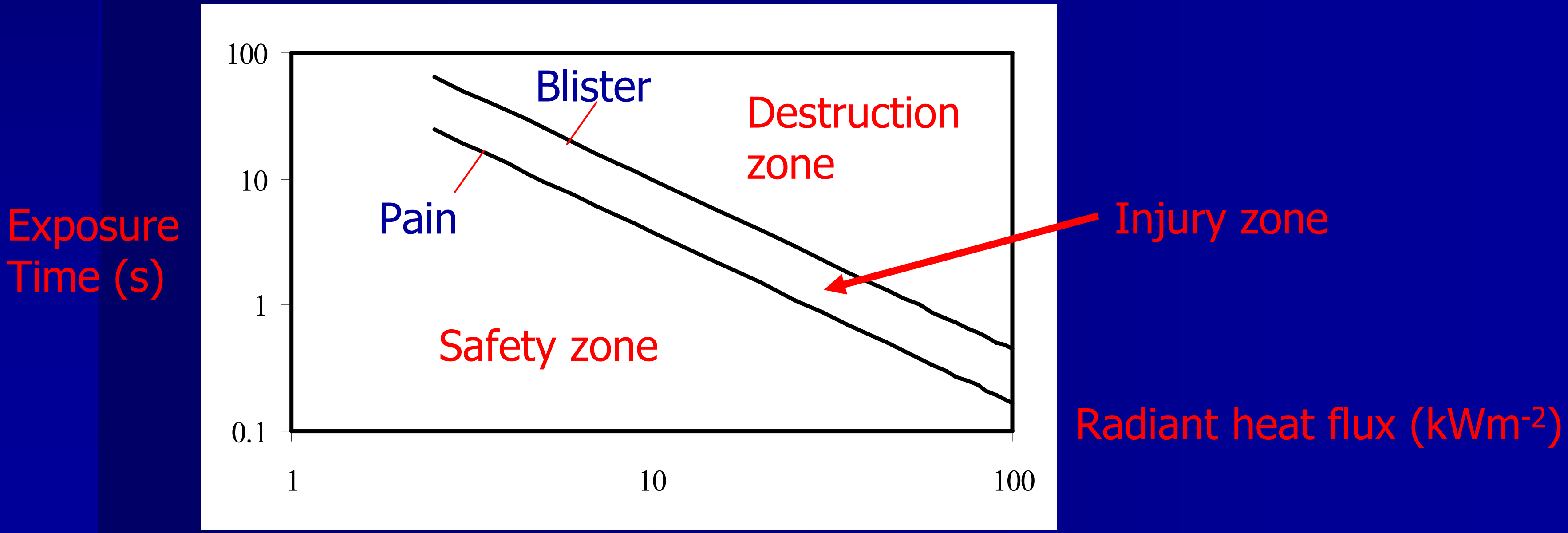
Some examples:

Stoll and Chianata (1969)

Radiant heat flux (kWm^{-2})

Exposure time to pain (s): $t_{r,p} = 85\ q_r^{-1.35}$

Exposure time to blister (s): $t_{r,b} = 223\ q_r^{-1.35}$



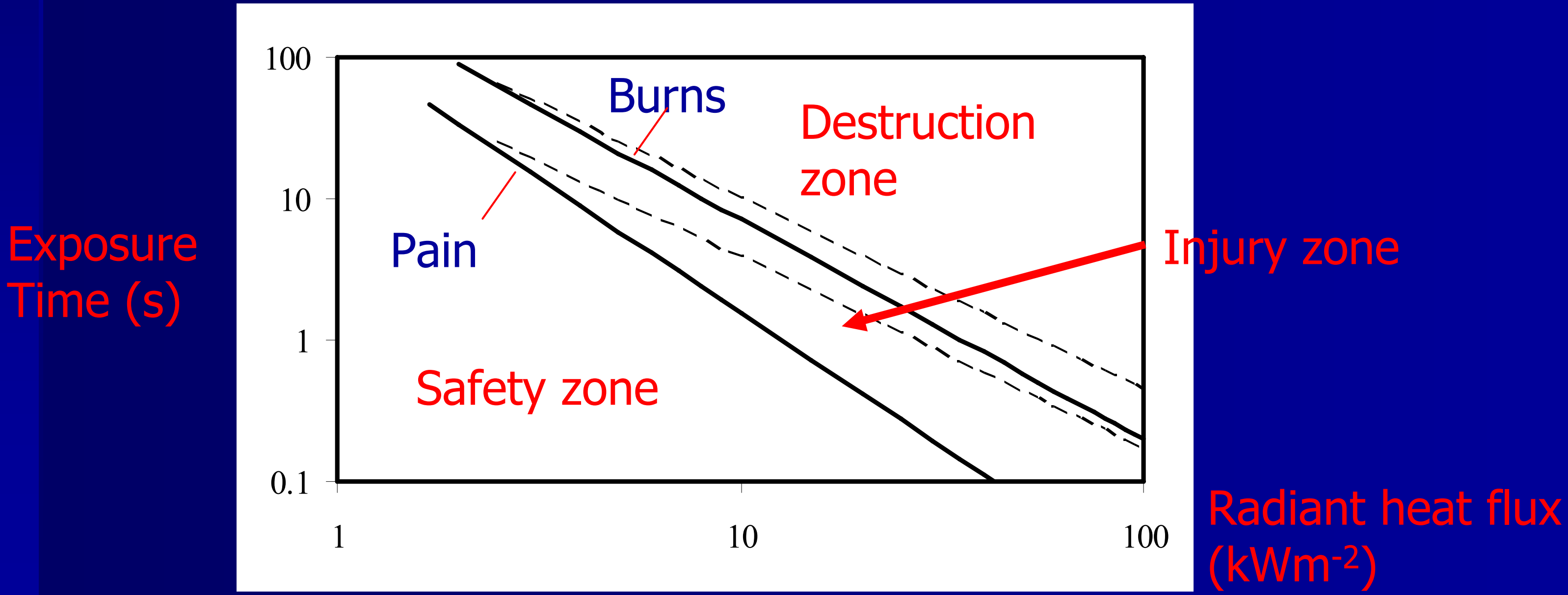
Exposure models

Some examples:

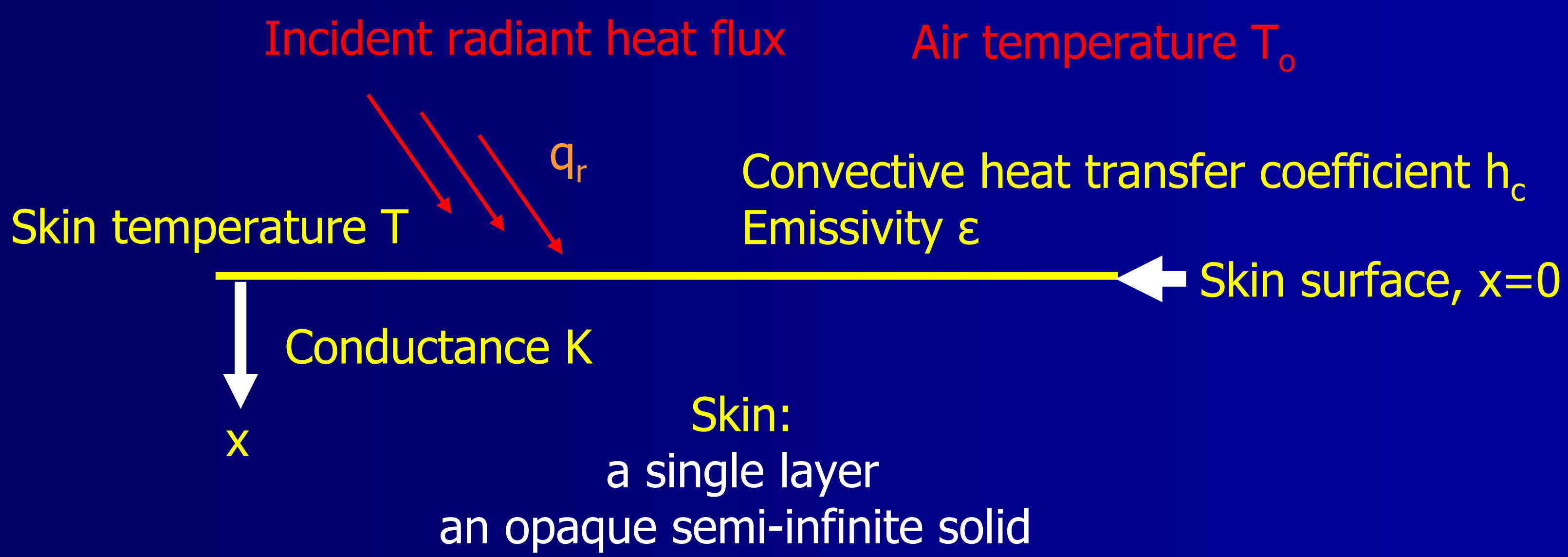
SFPE Model (Wieczorek and Dembsey 2001)

Exposure time to pain (s): $t_{r,p} = 125\, q_r^{-1.9}$

Exposure time to burns (s): $t_{r,b} = 260\, q_r^{-1.56}$



A simple model: Heat balance at the skin surface



Radiant heat gain

Temperature

$$k\frac{\partial T}{\partial x}+\varepsilon_b q_R = h_c\left(T - T_0\right)$$

Convective heat loss

One-dimensional heat conduction equation

(Modest, 1993; Siegel and Howell, 2002; Tien *et al.*, 2002)

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2}$$

temperature

time

skin depth

thermal diffusivity
of the skin

One-dimensional heat conduction equation: solution

Solved for the temperature at the depth of x (m) below skin surface (Tien *et al.* 2002, Wieczorek and Dembsey, 2001)

$$T = T_0 + \frac{q_R}{k}\left[\frac{2\sqrt{\alpha(st)}}{\sqrt{\pi}}\exp\left(-\frac{x^2}{4\alpha(st)}\right) - x\,\mathrm{erfc}\left(\frac{x}{2\sqrt{\alpha(st)}}\right)\right]$$

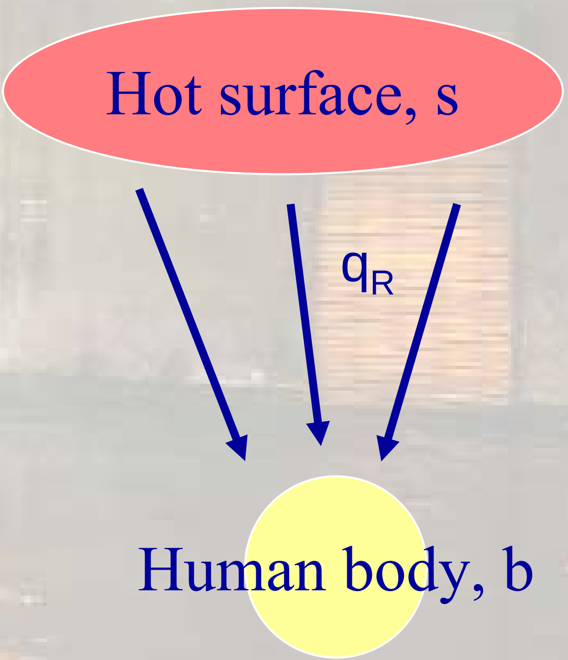
Safety factor (S = 2) for Human variability

(SFPE, 2000; Wieczorek and Dembsey, 2001).

Thermal radiant heat flux

Galbraith G. H., McLean R. C. and Stewart D. (1989). Occupational hot exposures: a review of heat and mass transfer theory. *Journal of Engineering in Medicine* **203:3,** 123-131.

$$q_R = \sigma \frac{A_s}{A_b} \zeta \left(T_s{}^4 - T_b{}^4 \right)$$

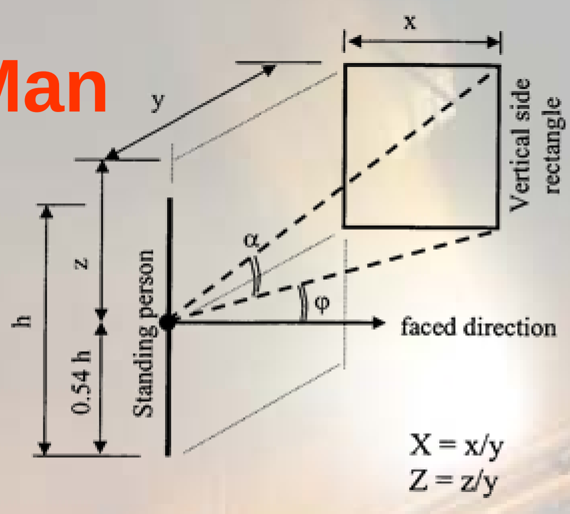


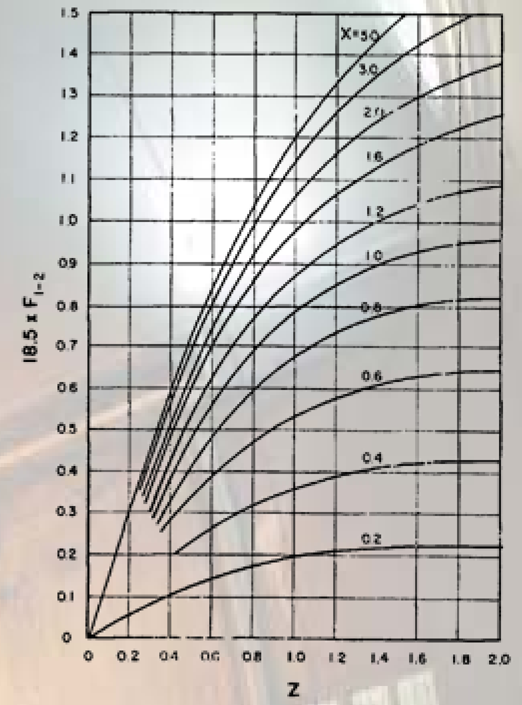
$$\zeta = \left[\left(\frac{1}{\varepsilon_s} - 1 \right) + \frac{1}{F_{sb}} + \frac{A_s}{A_b} \left(\frac{1}{\varepsilon_b} - 1 \right) \right]^{-1}$$

$$F_{sb} = F_{bs} \frac{A_b}{A_s}$$

$$A_s = W_R \times H_R$$

The Standard Man





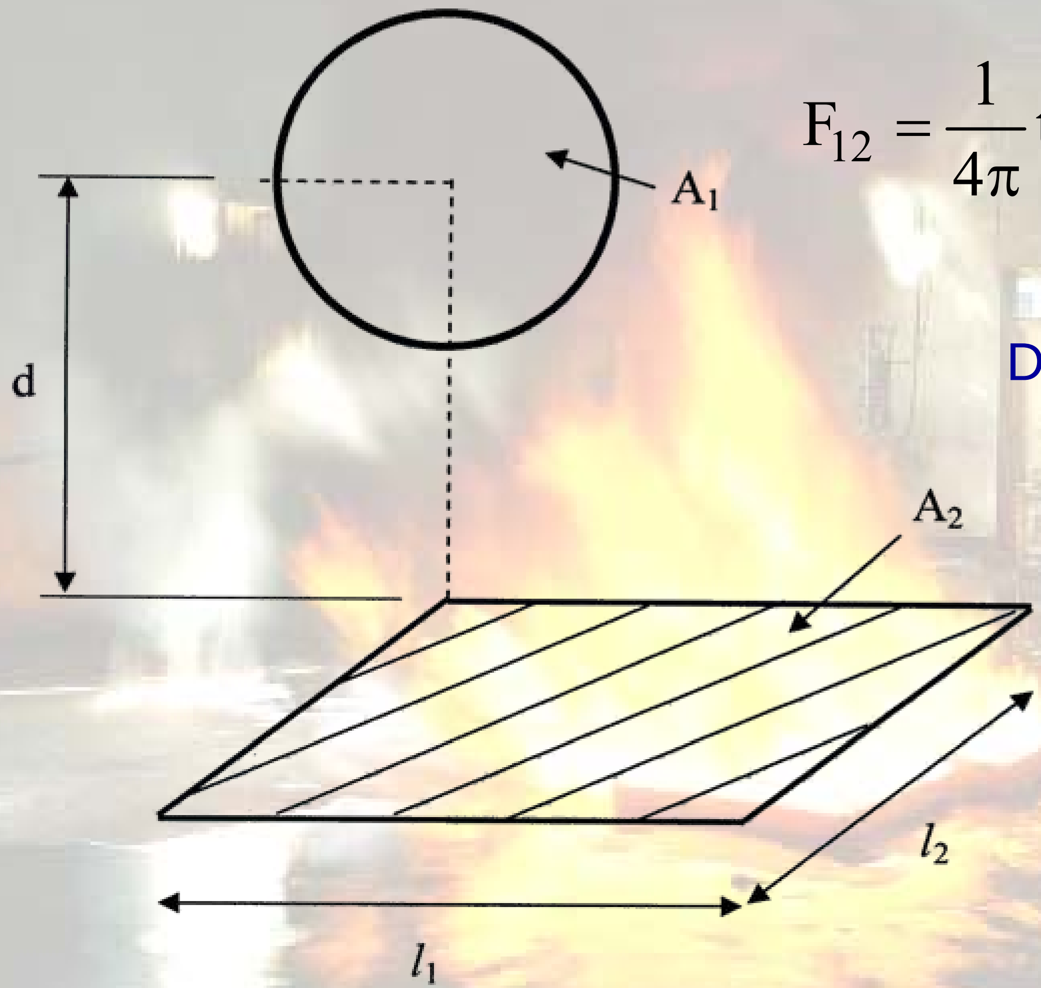
standard object (H_b = 1.73 m and w = 72.7 kg) with an orientation of $\alpha = \varphi = 0$

Ref: Dunkle R. V. (1963). Configuration factors for radiant heat transfer calculations involving people. *Journal of Heat Transfer* **85:1,** 71-76.

$$R_b^2 = \frac{H_b w_b^{1/3}}{7.21} R^2$$

$$R^2 = 0.0929\left[0.65 + \cos\alpha\left(7.15 + 0.52\left|\cos\varphi\right|\right)\right]$$

view factor



$$F_{12} = \frac{1}{4\pi}\tan^{-1}\left(\frac{1}{D_1^2 + D_2^2 + D_1^2 D_2^2}\right)^{\frac{1}{2}}$$

D1 = d/l_1 and D2 = d/l_2

Assumptions

Human shape and variability,
values of emissivity, diffusivity, conductivity
depth of basal layer
single layer skin, 1D heat conduction …

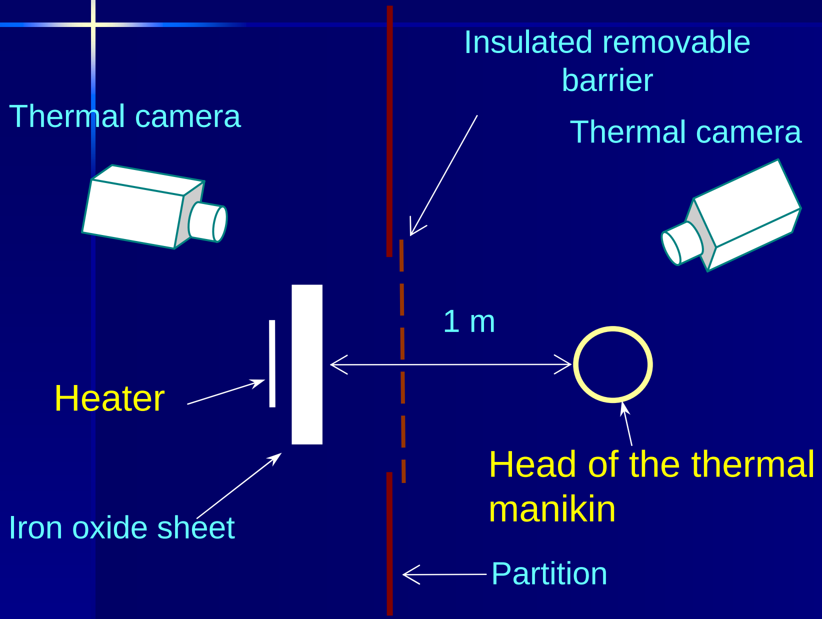
Verification: accidental skin burn statistics or sample tests

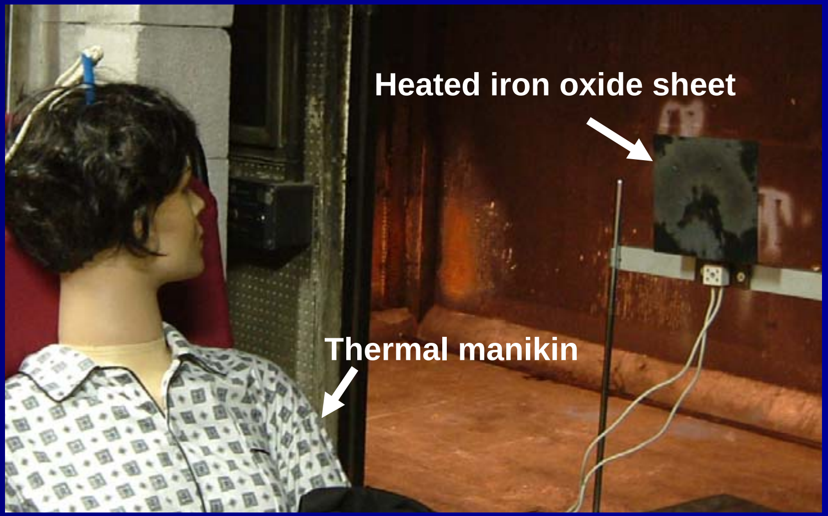
This study

Measure the temperature T on the thermal manikin skin layer when being exposed to different radiation fluxes

Compare with the calculations for the estimated temperature rise at the head portion of the thermal manikin

Skin temperature measurement





(a) Schematic

(b) Photo

Experimental setup

Thermal manikin (Bjorn, E., Nielsen, P. V. 2002)

Shape:

- accurate geometrical likeness to a real person
- 1.7 m tall average-sized woman
- body surface area of 1.47 m^2

Construction of for skin temperature measurements:

- 4 mm glass fibre-armed polyester shell wounded round with 0.3 mm diameter nickel wire at a spacing of 2 mm
- The wiring covered by a protective coating of about 0.1 mm in thickness
- maintain a body temperature (individual control of temperature of 16 body parts of the manikin)

Experimental set-up

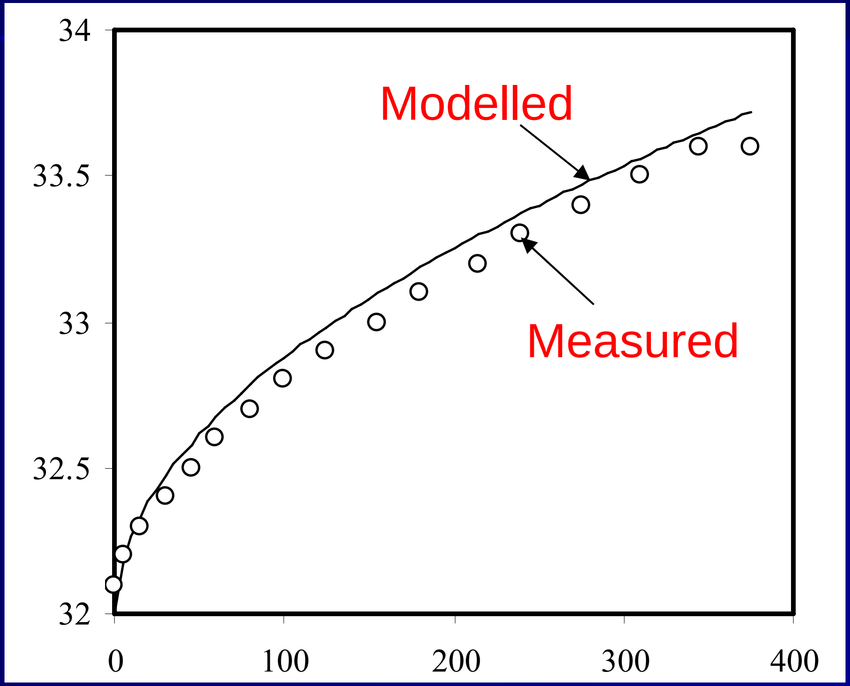
- The thermal manikin in BSE Fire chambers (PolyU)
- Heated iron oxide plate (180 mm × 180 mm thickness 3 mm)
- 1.7 kW electric heater; steady state surface temperature = 426°C (699K)
- Thermocouples and thermal cameras were used to monitor the surface temperatures.

Measured results: Skin surface temperature

By thermal camera

Measured results: Skin temperature

By thermal manikin



Skin temperature T (°C)

Exposure time t (s)

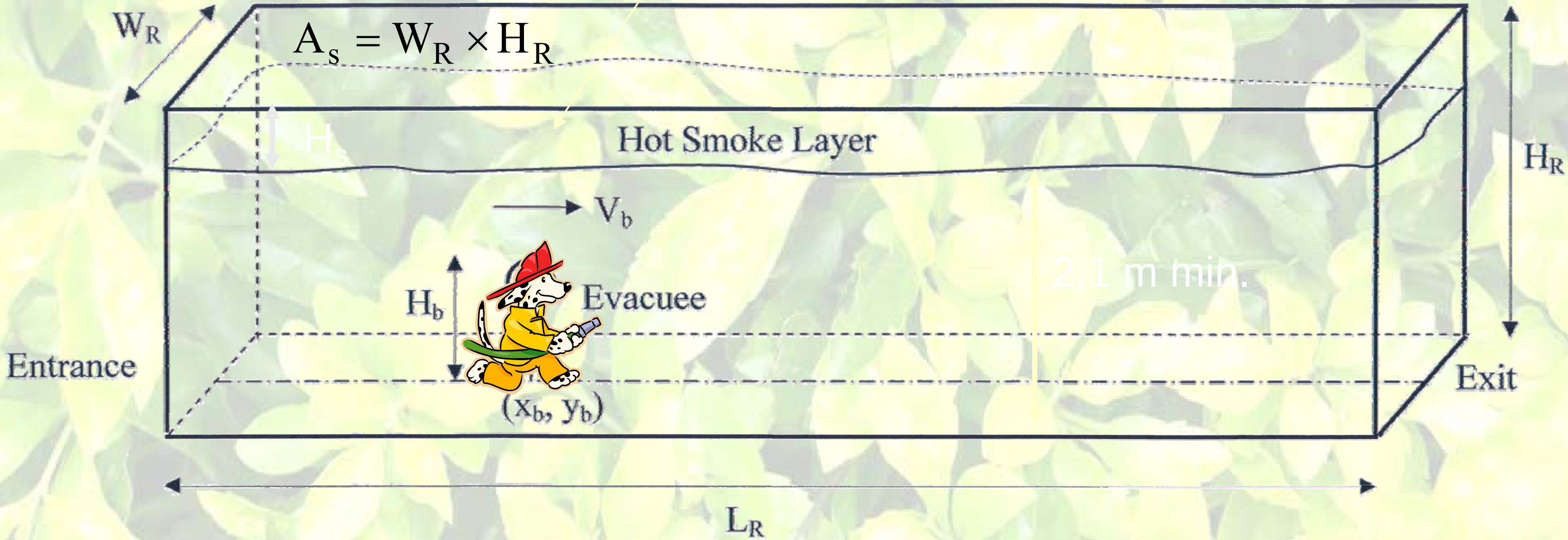
$r = 0.9969$

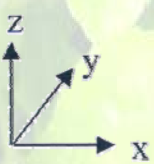
$p \leq 0.0001$

Skin temperature of a head

An example application

Corridor with a hot smoke layer





Room	
Length L_R (m)	5–30
Width W_R (m)	1.5–2.5
Height H_R (m)	2.6
Smoke layer	
Depth H_s (m)	0.2–0.5
Temperature T_s (K)	600–900
Partial pressure of CO_2 and H_2O	0.2, 0.8
Soot volume fraction	0.362×10^{-6}
Mean refractive index n, k at 1000 K	2.4, 1.2

Standing object (A standard man)	
Height H_b (m)	1.73
Weight w_b (kg)	72.6
Equivalent radius R_b (m)	0.25 (body)
	0.08 (head)
Emissivity ε_b	0.95
Temperature T_b (K)	307
Walking speeds V_b ($m\,s^{-1}$)	1–2

Journal of Fire Science 23(2), Wong 2005

Smoke layer properties: considered as gas-soot mixtures

The total emissivities for homogeneous gas-soot mixtures ε_s

Soot

Gas

$$\varepsilon_s = \varepsilon_{soot} + \varepsilon_g \left(1 - \varepsilon_{soot}\right)$$

Ref: Modest M. F. (1993). *Radiative heat transfer*, McGraw-Hill, New York, USA

Emissivity: Soot

$$\varepsilon_{soot} = 1 - e^{\kappa_{soot} L_s}$$

L_s (m) is physical path length

$$\kappa_{soot} = 3.72 \frac{C_0}{C_2} f_v T$$

κ_{soot} is the Planck mean absorption coefficient of the soot for entire range of optical thickness

f_v is the soot volume fraction, C_2 is Planck's second constant (1.4388×10^{-2} mK) and C_0, is a constant between 2 and 6 dependent on the complex index of refraction m = n – ik,

$$C_0 = \frac{36\pi nk}{\left(n^2 - k^2 + 2\right)^2 + 4n^2k^2}$$

Ref: Modest M. F. (1993). *Radiative heat transfer*, McGraw-Hill, New York, USA

Emissivity: Gas mixture

ε_g is the total emissivity of the gas mixture of CO_2 ε_{CO2} and water vapour ε_{H2O}

$$\varepsilon_g = \varepsilon_{H2O} + \frac{1}{2}\varepsilon_{CO2}$$

The emittance of CO_2 and water vapour can be found from emissivity charts or by exponential wide-band model

Ref: Modest M. F. (1993). *Radiative heat transfer*, McGraw-Hill, New York, USA

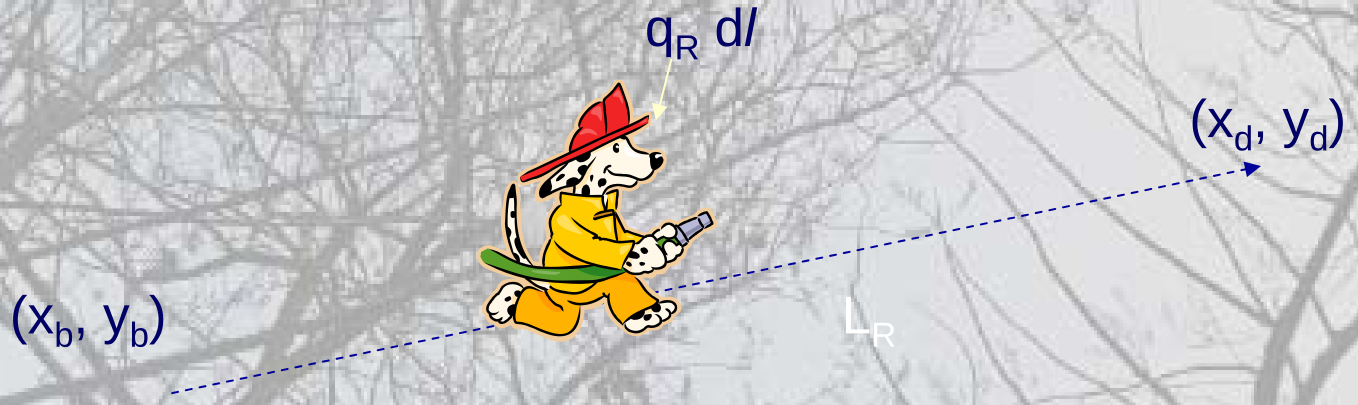
Average heat flux

(Wong, L. T., Yuen, W. W. 2004; Appl. Fire Science)

The average radiative flux a person is exposed to during the evaluation

$$q_{R;ave} = \frac{1}{L_R} \int_{(x_b, y_b)}^{(x_d, y_d)} q_R \, dl$$

L_R (m) is the distance between the entrance and exit of the corridor



Hot exposure time

Between 1.7 to 20 kWm^{-2}, the exposure time which will lead to skin pain

$$t_b = \frac{250}{S} q_R^{-1.9}$$

safety factor (S) = 2

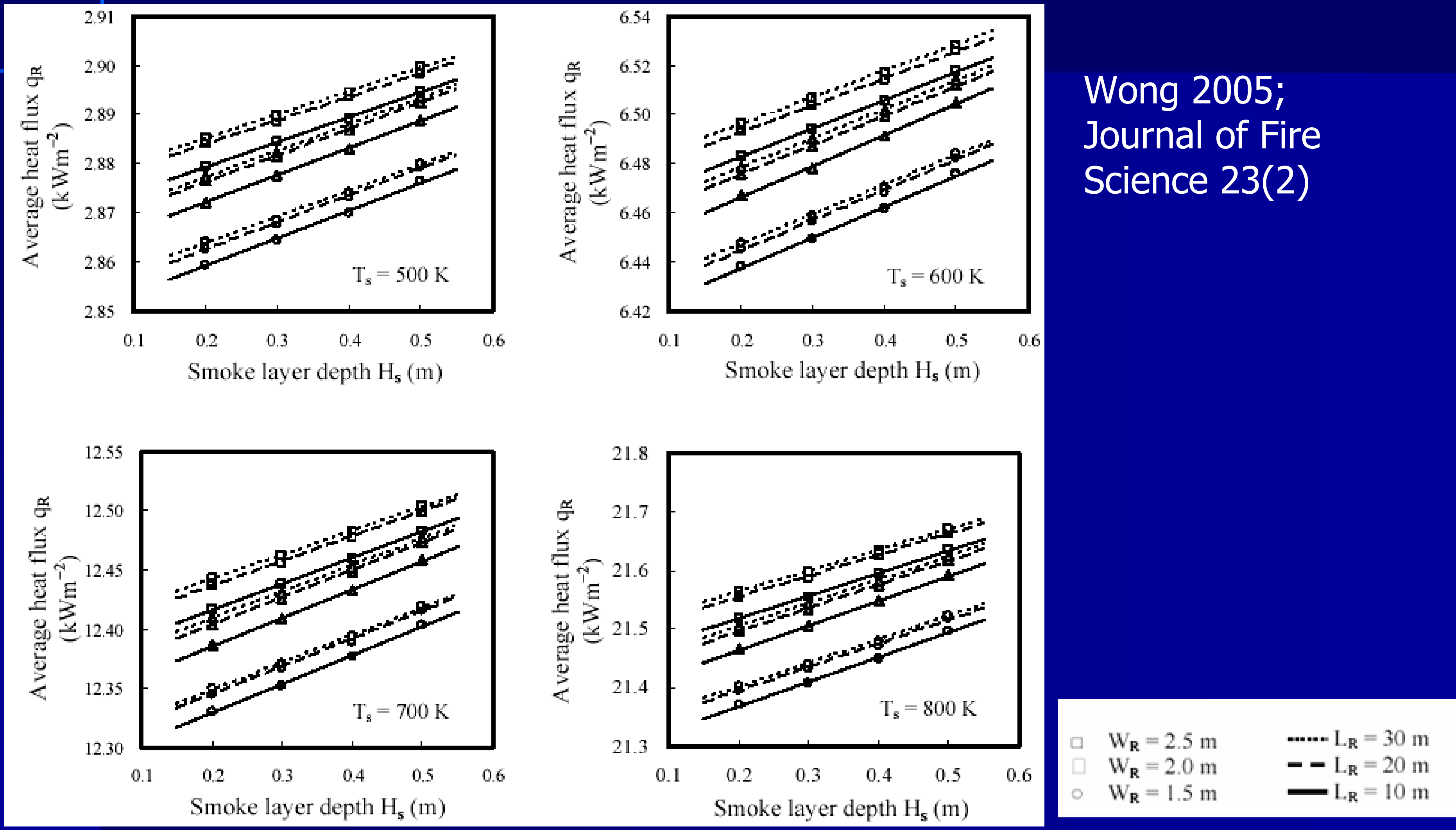
Wieczorek C. J. and Dembsey N. A. (2001). Human variability correction factors for use with simplified engineering tools for predicting pain and second degree skin burns. *Journal of Fire Production Engineering* **2:2**, 88-111.

Minimum escape velocity (MEV) V_b (ms^{-1}) of the evacuee to avoid skin pain

$$V_b = \frac{L}{t_b}$$

← available safe egress time

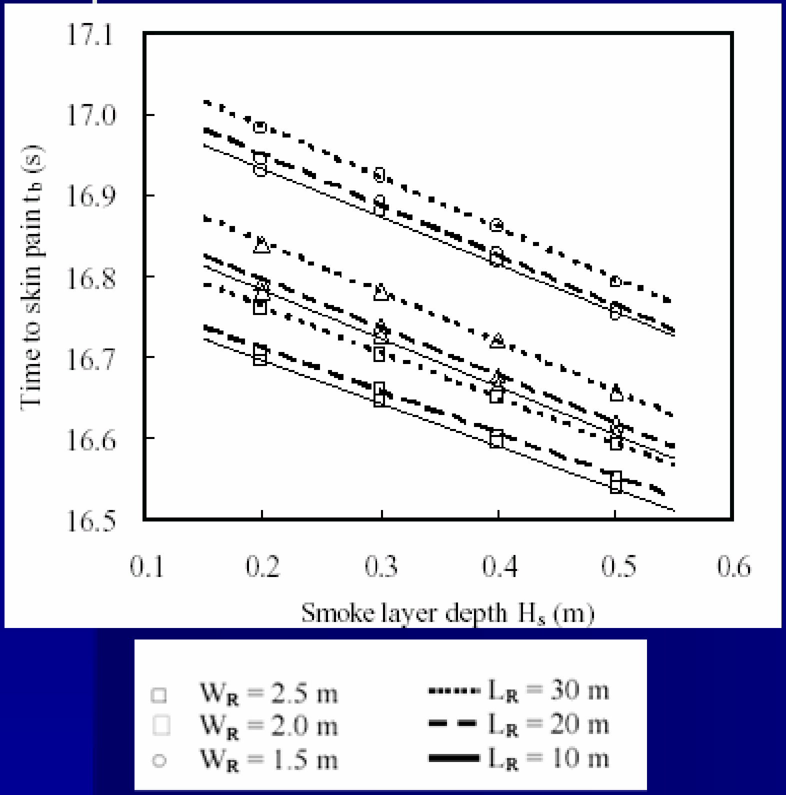
Average thermal radiant heat flux atop a head facing forward

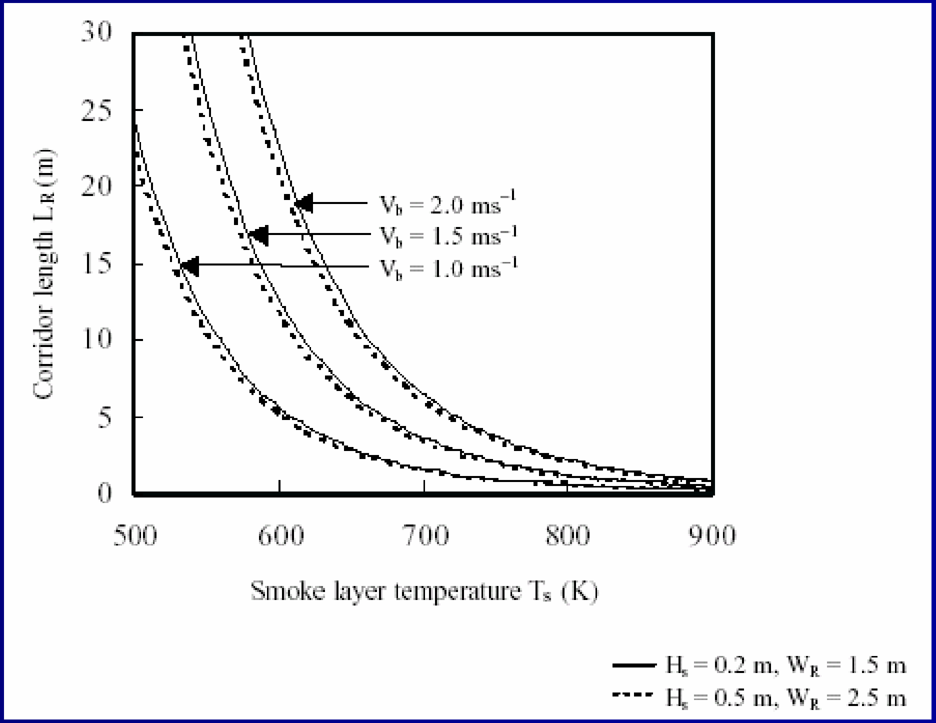


Wong 2005; Journal of Fire Science 23(2)

Example application

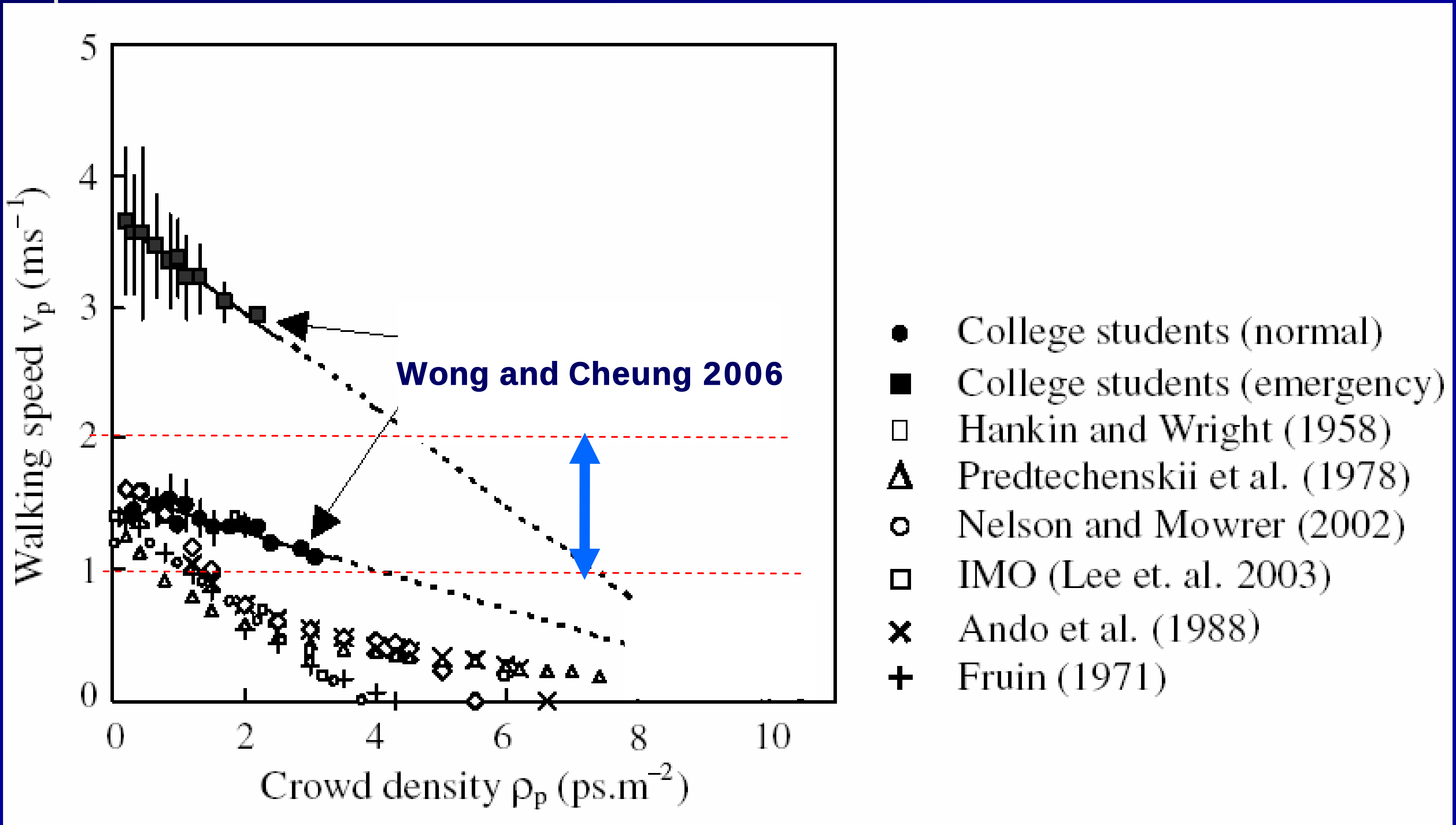
Wong 2005; Journal of Fire Science 23(2)





Example walking speeds

Wong and Cheung 2006; Safety Science



Conclusion

- A calculation method for skin layer temperature by assuming a heat balance on a homogeneous skin surface due to incident thermal heat flux and conductive heat transfer through the skin layer were reviewed; and the validity of the assumptions made in the calculations was examined.
- The calculations would reasonably estimate the skin layer temperature and would be suitable for certain building designs of fire safety.

Acknowledgement

Thank you very much

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