HKIE THE HONG KONG INSTITUTION OF ENGINEERS 香港工程師學會

Fire Division

ArchFire

Theories of Fire Dynamics & Field Test

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Part 1 – Introduction to Fire Dynamic

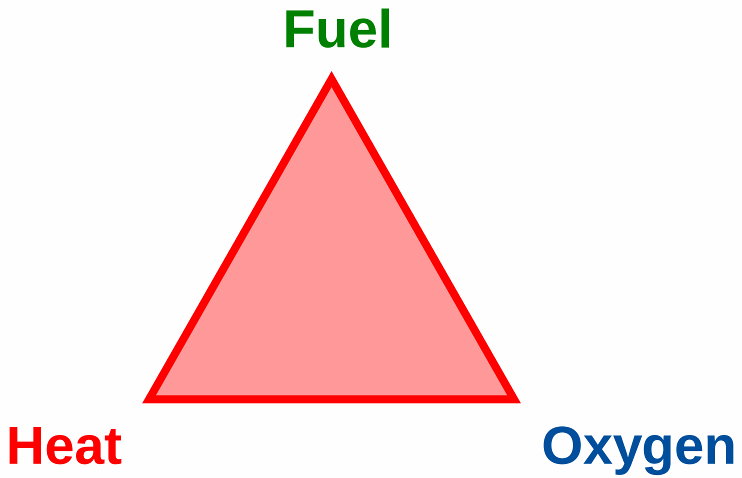
What is Fire?

- Fire is a rapid oxidation process accompanied by the evolution of heat, light, flames (a glowing mass of gas) and the emission of sound, i.e. unwanted combustion

$$\text{Fuel} + \text{Oxygen} \xrightarrow[\triangle]{} \text{Products} + \text{Heat}$$

Concept of Fire Triangle

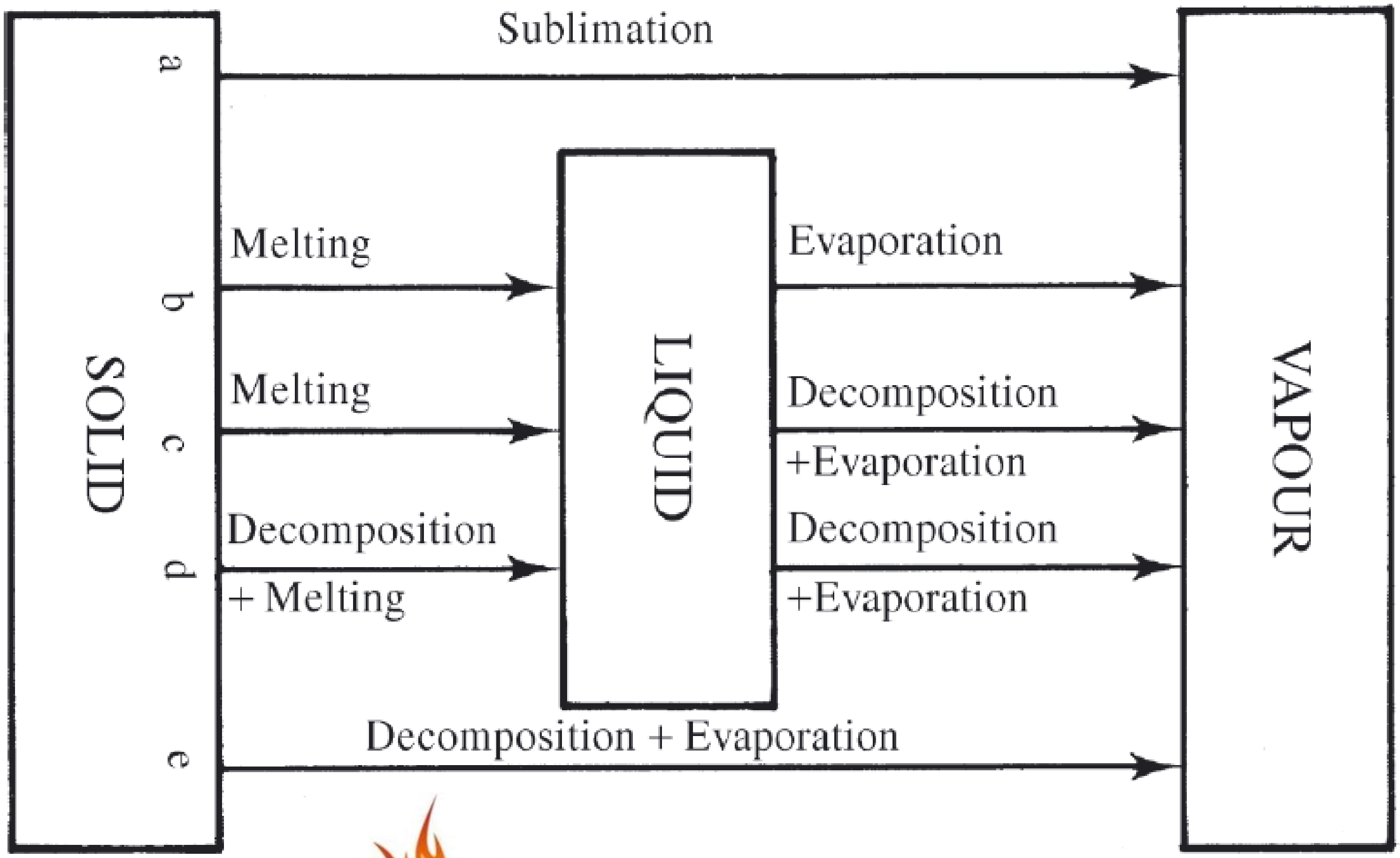
- Combustion – a series of very rapid chemical reactions



Ignition Temperatures

Materials	Pilot Ignition Temperature (°C)	Spontaneous Ignition Temperature (°C)
Cotton	230 – 266	254
Paper	230	230
White pine	228-264	260
Polyethylene	341	349
PVC	391	454
Perspex	280 – 300	450 – 462
Polystryrene foam	346	491
Polyurethane	310	416

Ignition Models



SOLID

LIQUID

VAPOUR

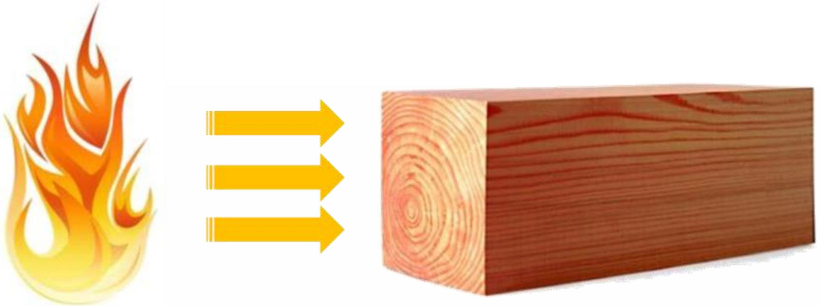
a Sublimation

b Melting → Evaporation

c Melting → Decomposition +Evaporation

d Decomposition + Melting → Decomposition +Evaporation

e Decomposition + Evaporation



Combustion

- Smouldering Combustion
  - Burning process without flame due to limited supply of oxygen
- Flaming Combustion
  - Visible manifestation of combustion between gaseous fuel and oxygen

Heat of Combustion (Δ*Hc*)

- Heat of combustion is the energy released as heat when a material undergoes complete combustion with oxygen under standard conditions.

- Different fuels have different heat of combustion. Usually, fuels with carbon-rich molecules have higher heat of combustion but also require higher ignition energy.

Heat of Combustion (ΔHc)

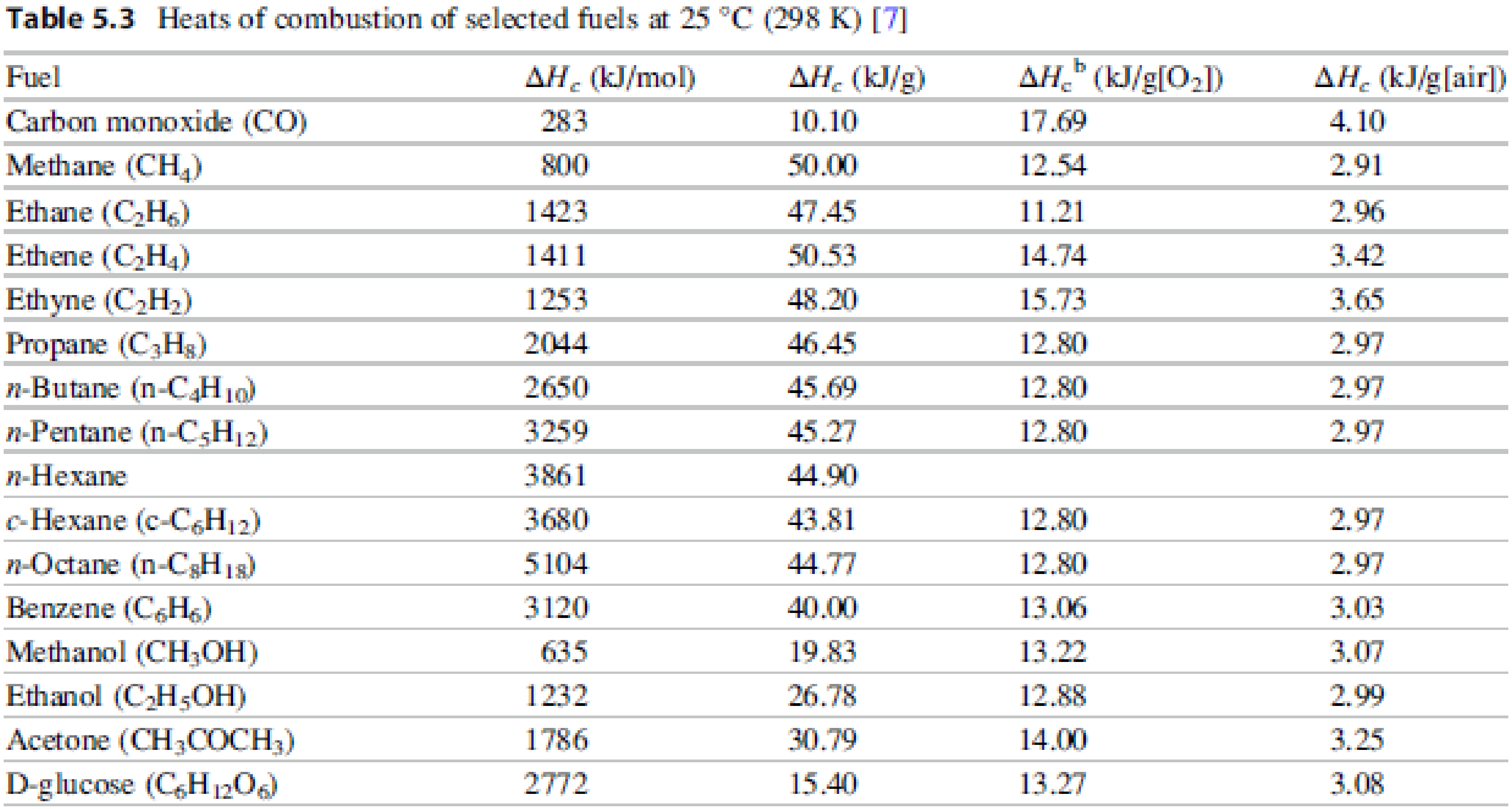
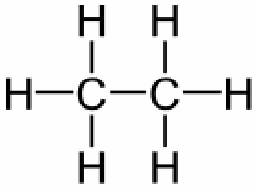
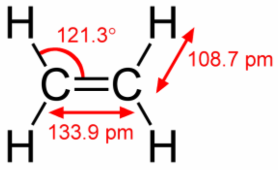
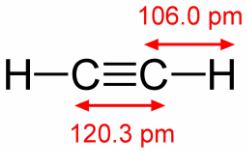


Table 5.3 Heats of combustion of selected fuels at 25 °C (298 K) [7]

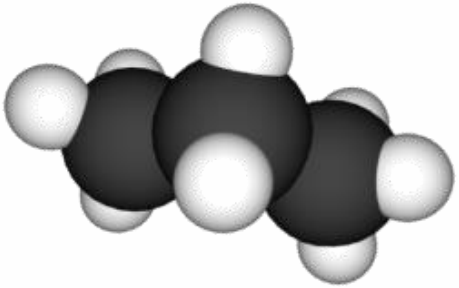
Fuel	ΔH_c (kJ/mol)	ΔH_c (kJ/g)	ΔH_c^{b} (kJ/g[O_2])	ΔH_c (kJ/g[air])
Carbon monoxide (CO)	283	10.10	17.69	4.10
Methane (CH_4)	800	50.00	12.54	2.91
Ethane (C_2H_6)	1423	47.45	11.21	2.96
Ethene (C_2H_4)	1411	50.53	14.74	3.42
Ethyne (C_2H_2)	1253	48.20	15.73	3.65
Propane (C_3H_8)	2044	46.45	12.80	2.97
n-Butane (n-C_4H_{10})	2650	45.69	12.80	2.97
n-Pentane (n-C_5H_{12})	3259	45.27	12.80	2.97
n-Hexane	3861	44.90		
c-Hexane (c-C_6H_{12})	3680	43.81	12.80	2.97
n-Octane (n-C_8H_{18})	5104	44.77	12.80	2.97
Benzene (C_6H_6)	3120	40.00	13.06	3.03
Methanol (CH_3OH)	635	19.83	13.22	3.07
Ethanol (C_2H_5OH)	1232	26.78	12.88	2.99
Acetone (CH_3COCH_3)	1786	30.79	14.00	3.25
D-glucose ($C_6H_{12}O_6$)	2772	15.40	13.27	3.08





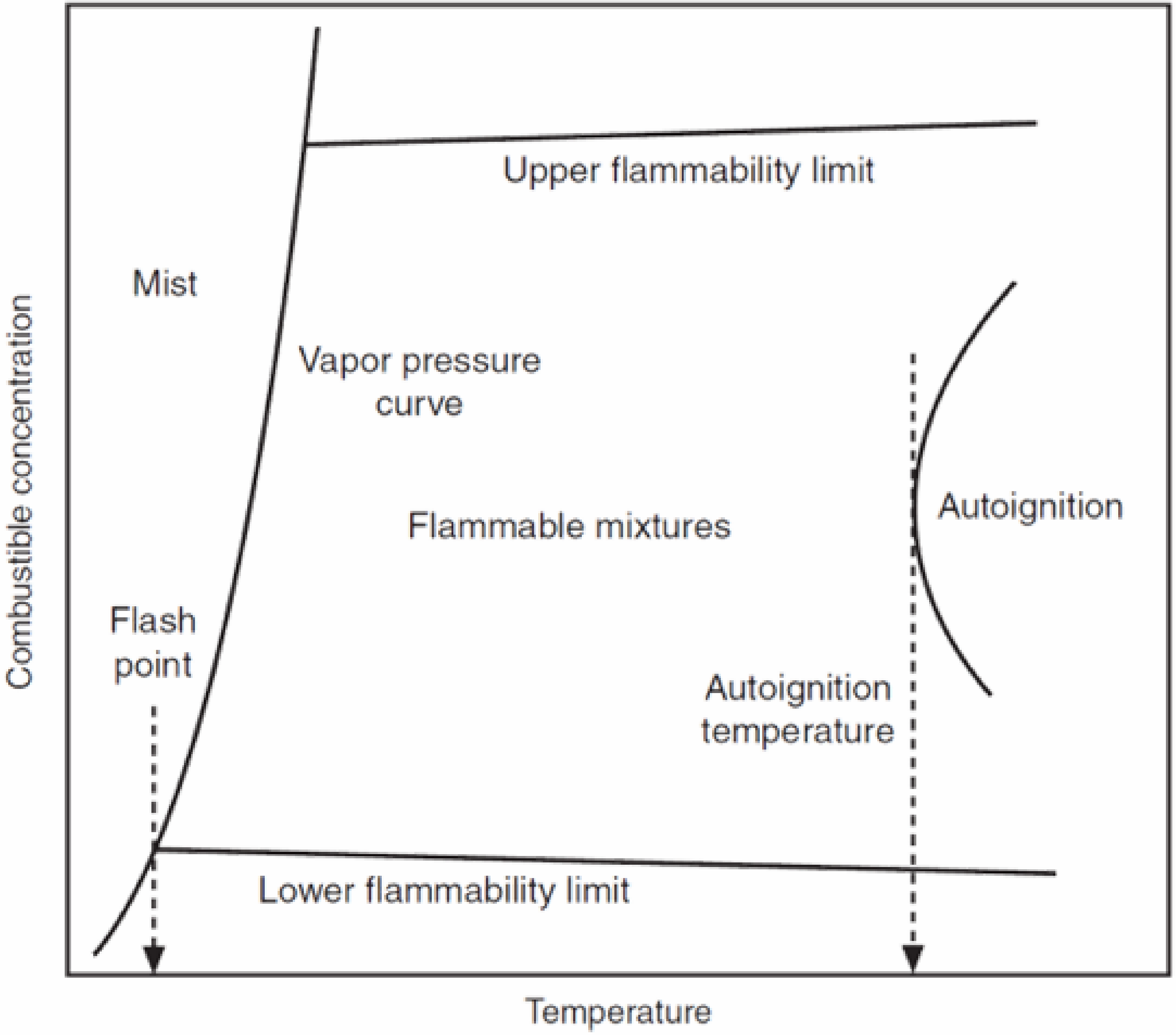


Combustion Reaction

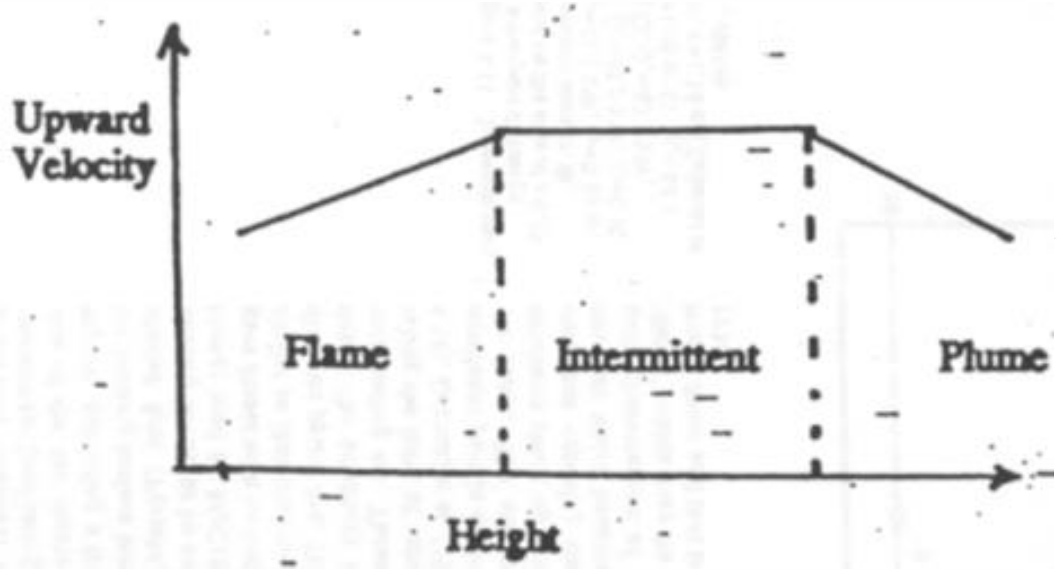


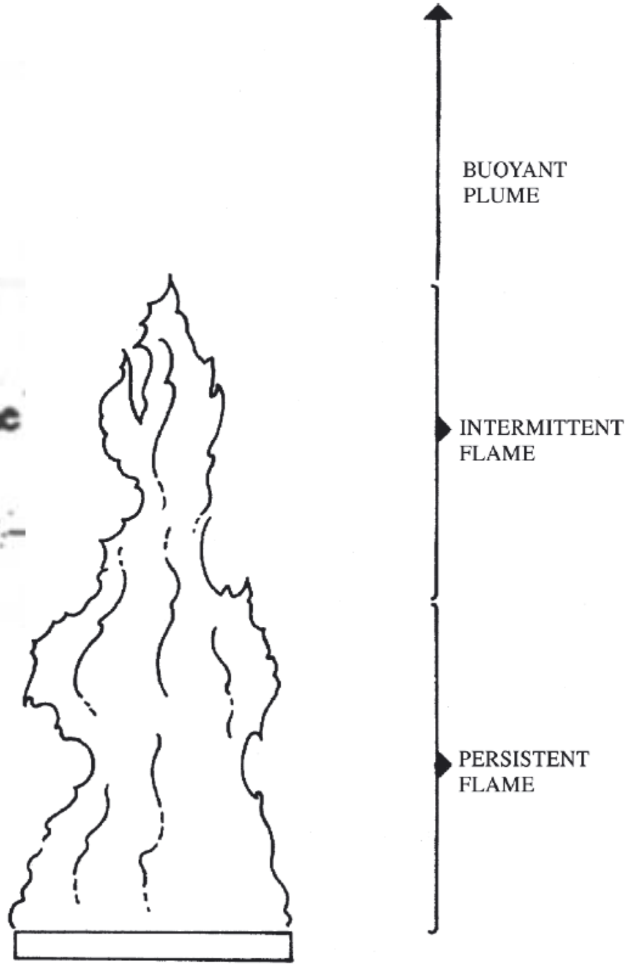
- Propane (C3H8) as an example
- $C_3H_8 + O_2 \rightarrow 3CO_2 + 4H_2O$
- The reaction produces 2044kJ/mole of C_3H_8 or 46.45kJ/g of C_3H_8.
- The energy produced by the combustion reaction will be presented in form of light and heat. (e.g. a flame)

Flammability



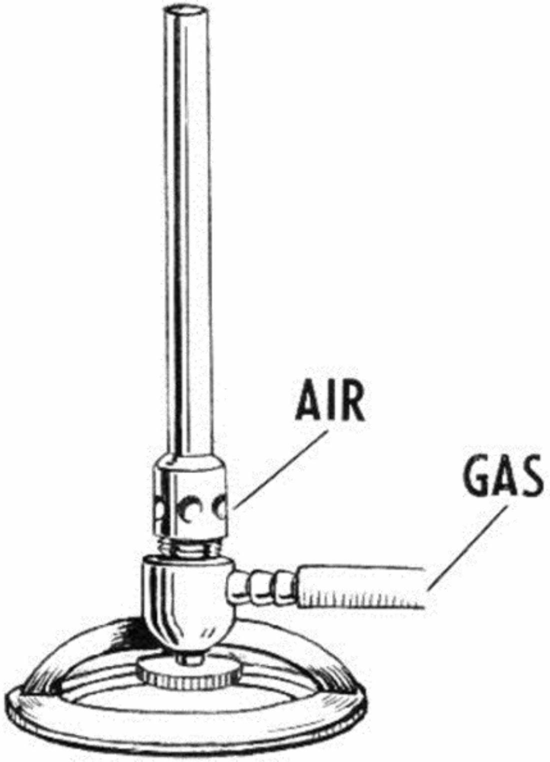
Flame Structure





Flame

- Premixed Flame
  - Fuel gas and oxygen are mixed before combustion
- Diffusion Flame
  - Fuel gas and oxygen are separated before combustion
- E.g. Bunsen burner



Buoyant Plume

- The heat produced by the combustion reaction will heat up the surrounding air.
- When the air temperature increases, the density is reduced.
- The density difference between the hot gas and the surrounding ambient air increases.
- The buoyancy force of the hot air increases and pushes the hot air to higher level.

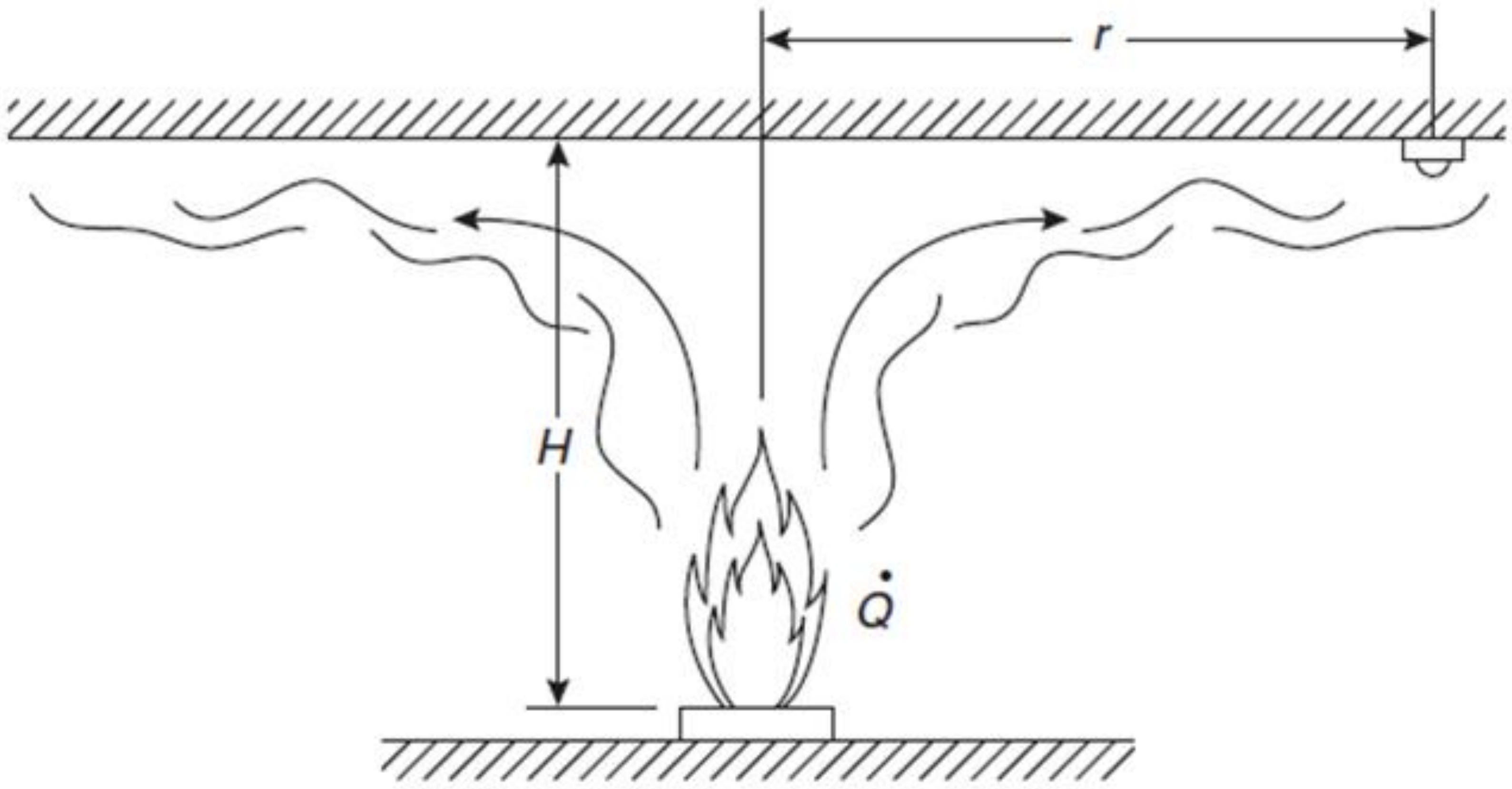
Buoyant Plume

- The hot gases created from the fire forms a hot gas column extending to the ceiling of the compartment.
- The upward movement of the hot gas column induces the entrainment of the surrounding ambient air by turbulent mixing and molecular diffusion.
- Due to the air entrainment, the temperature and velocity of the plume decreases along the upward direction. Therefore, a plume shape can be approximated by an inverted cone.

Ceiling Jet

- When the hot gas reaches the ceiling, it cannot penetrate through the slab. It spreads radially under the slab soffit.
- The air entrainment along the horizontal spread of the hot gas is not efficient.
- The speed of the ceiling jet is fast due to the thick layer of the hot smoke under the ceiling.
- The ceiling jet in contact with sprinklers and detectors.

Modelling of Ceiling Jet Temperature and Velocity



Modelling of Ceiling Jet Temperature

- Alpert's equation (for temperature)

$$T - T_{\infty} = 16.9\,\frac{\dot{Q}^{2/3}}{H^{5/3}} \qquad \text{for} \quad r/H \le 0.18$$

$$T - T_{\infty} = 5.38\,\frac{\dot{Q}^{2/3}/H^{5/3}}{(r/H)^{2/3}} \qquad \text{for} \quad r/H > 0.18$$

Modelling of Ceiling Jet Velocity

- Alpert's equation (for velocity)

$$U = 0.96\left(\frac{\dot{Q}}{H}\right)^{1/3} \qquad \text{for} \quad r/H \le 0.15$$

$$U = 0.195\frac{(\dot{Q}/H)^{2/3}}{(r/H)^{5/6}} \qquad \text{for} \quad r/H > 0.15$$

Hot and Cold Layers

- When the ceiling jet reaches the wall boundaries, it reflects back and accumulates at the upper part of the compartment.
- A thermal interface exists in the compartment to demarcate the upper hot gas layer and the lower air layer. The interface is quite stable.
- It is defined as the level which the largest change in temperature. When the thermal interface reaches the door soffit, the hot gas emerges out of the compartment.

Neutral Plane

- At the upper part of the door opening, the hot gas is emerging out of the compartment.
- At the lower part of the door opening, the ambient air is entering into the compartment.
- There exist a level at the door opening in which the air velocity is zero. It is defined as Neutral Plane.

Modelling of Hot Gas Temperature

◈ McCaffrey *et al.* equation

$$\Delta T_g = 480\left(\frac{\dot{Q}}{\sqrt{g}c_p\rho_\infty T_\infty A_o\sqrt{H_o}}\right)^{2/3}\left(\frac{h_k A_T}{\sqrt{g}c_p\rho_\infty A_o\sqrt{H_o}}\right)^{-1/3}$$

- h_k is the heat transfer coefficient which is time dependent.
- If $t \leq t_p$, $h_k = (k\rho c/t)^{1/2}$, otherwise $h_k = k/\delta$
- $t_p = (\rho c/k)(\delta/2)^2$ is the penetration time.

Modelling of Hot Gas Temperature

- Foote *et al.* equation

$$\frac{\Delta T_g}{T_\infty} = 0.63\left(\frac{\dot{Q}}{\dot{m}_g c_p T_\infty}\right)^{0.72}\left(\frac{h_k A_T}{\dot{m}_g c_p}\right)^{-0.36}$$

- $\dot{m}_g$ is the mass ventilation rate in (kg/s)

Flashover

- The fire plume and the hot gas layer emit radiation to all unburnt combustible materials inside the compartment
- When the radiation is sufficiently high, it will ignite all combustible materials
- All fuels inside the compartment are involved in the fire
- The heat release rate/temperature rapidly increase

Determination of Flashover

- Hot gas temperature at 10mm below ceiling soffit $\geq 600^{\circ}$C.
- Radiation at the floor of the compartment $\geq$ 20kW/m^2.
- Minimum heat release rate can be estimated by use of the McCaffrey equation by setting the ΔT_g = 600 - ambient temperature in $^{\circ}$C.

Determination of Flashover

- Method of Babrauskas

$$\dot{Q} = 750 A_o \sqrt{H_o}$$

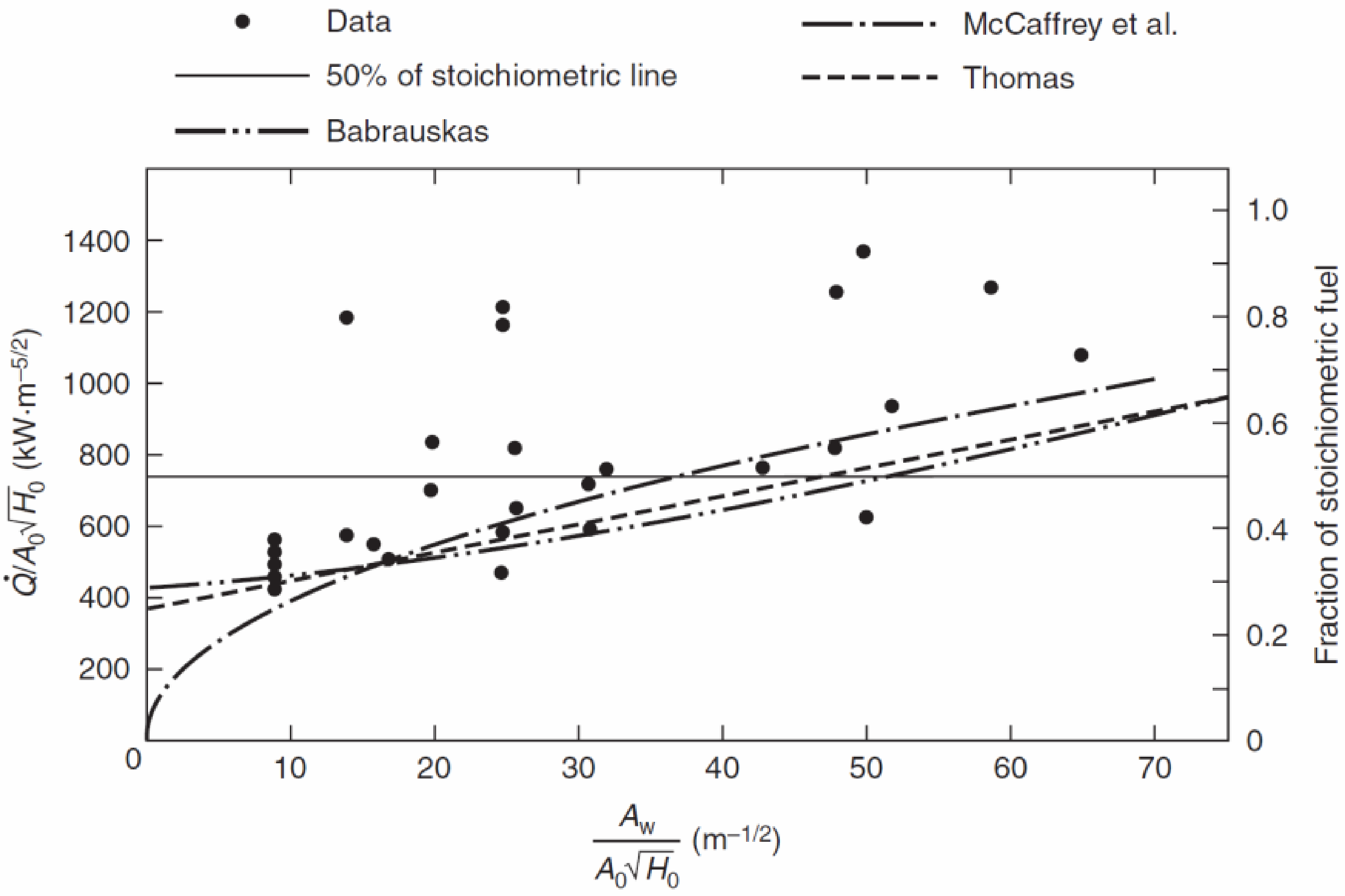
- Method of McCaffrey et al.

$$\dot{Q} = 610 \left(h_k A_T A_o \sqrt{H_o} \right)^{1/2}$$

- Method of Thomas

$$\dot{Q} = 7.8 A_T + 378 A_o \sqrt{H_o}$$

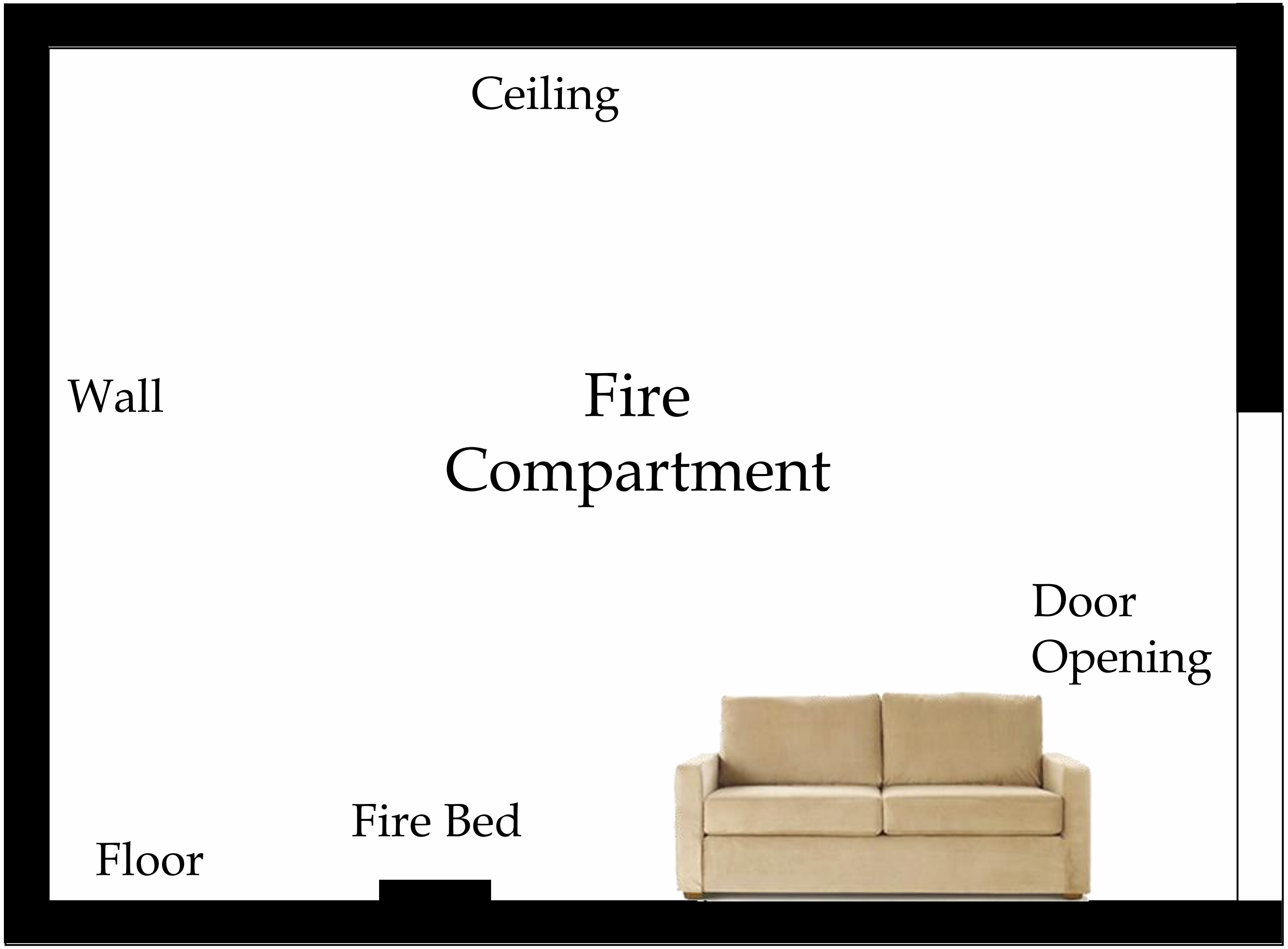
Determination of Flashover



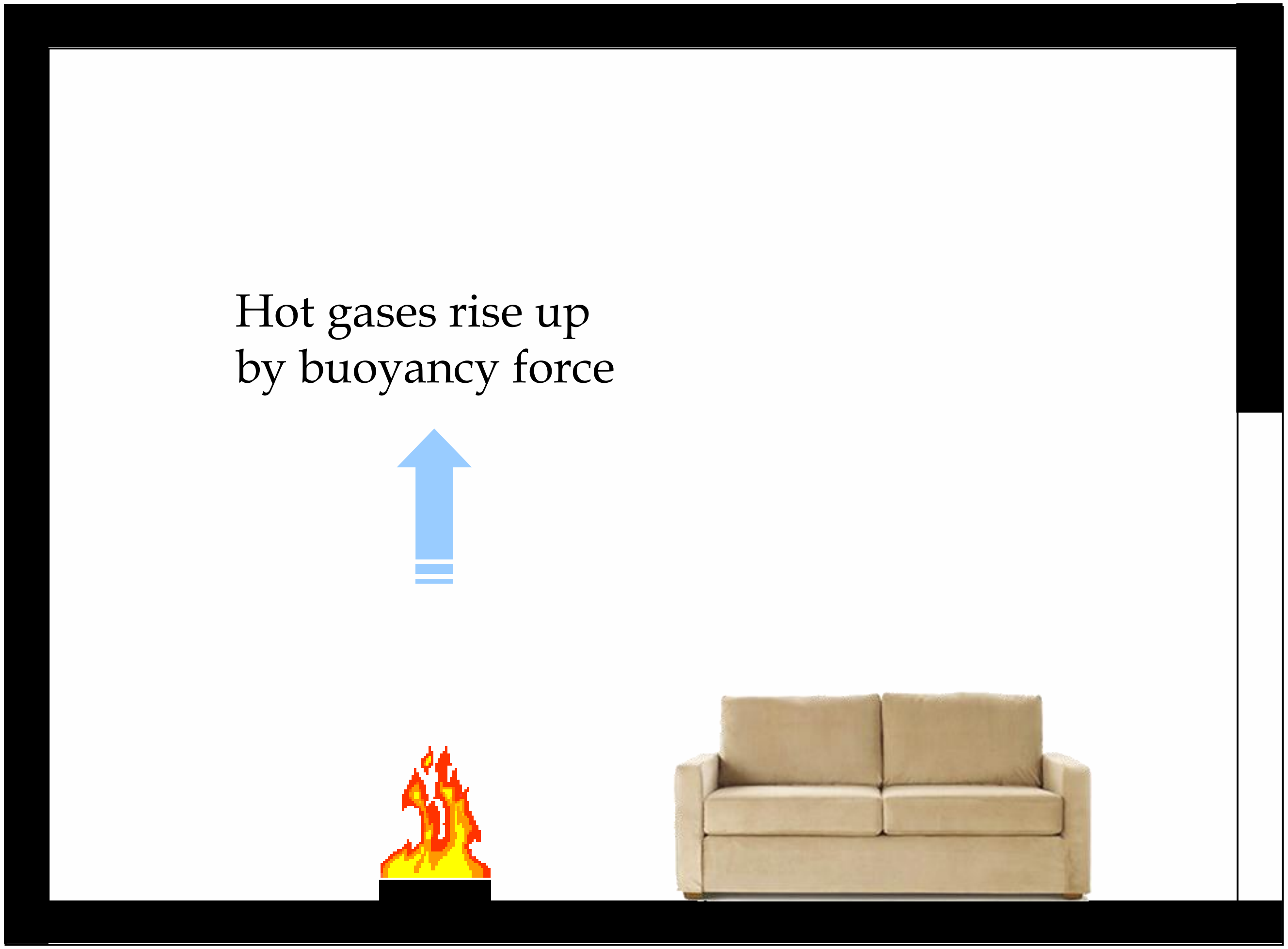
Growth Stages of Enclosure Fire

- Ignition
- Growth stage (pre-flashover stage)
- Flashover
- Fully developed stage (post-flashover stage)
- Decay stage

Enclosure Fire Dynamics

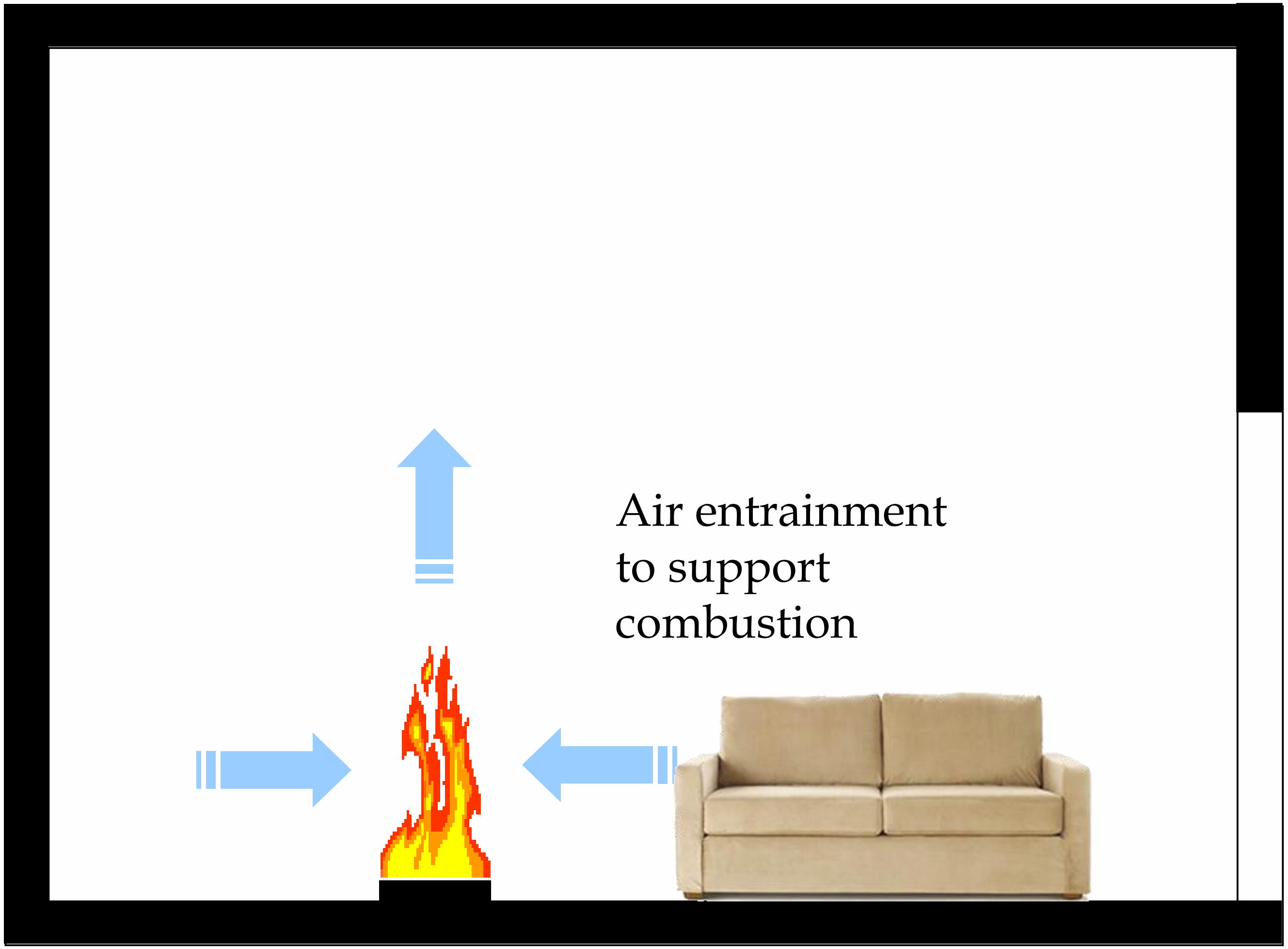


Enclosure Fire Dynamics



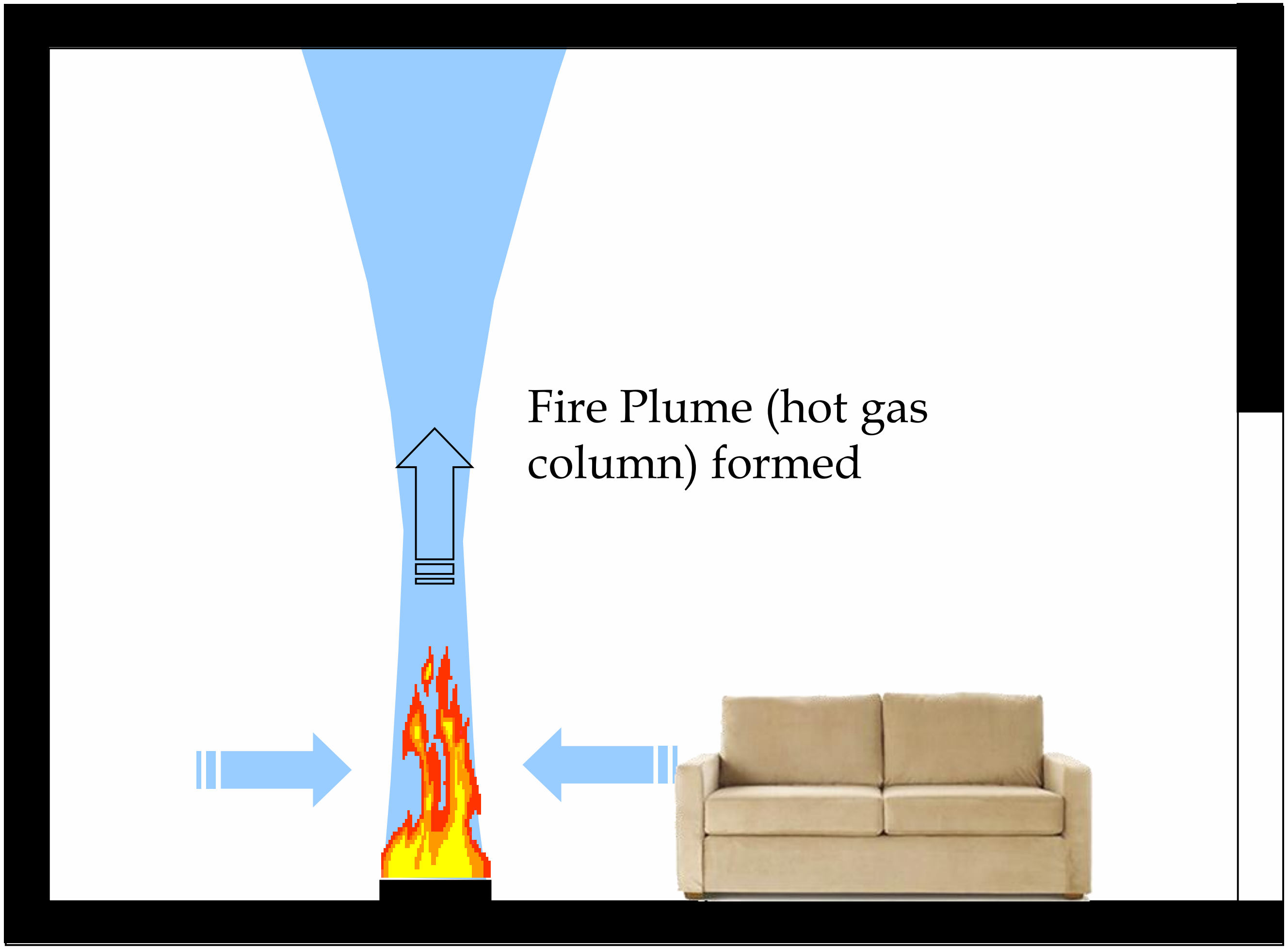
Hot gases rise up
by buoyancy force

Enclosure Fire Dynamics



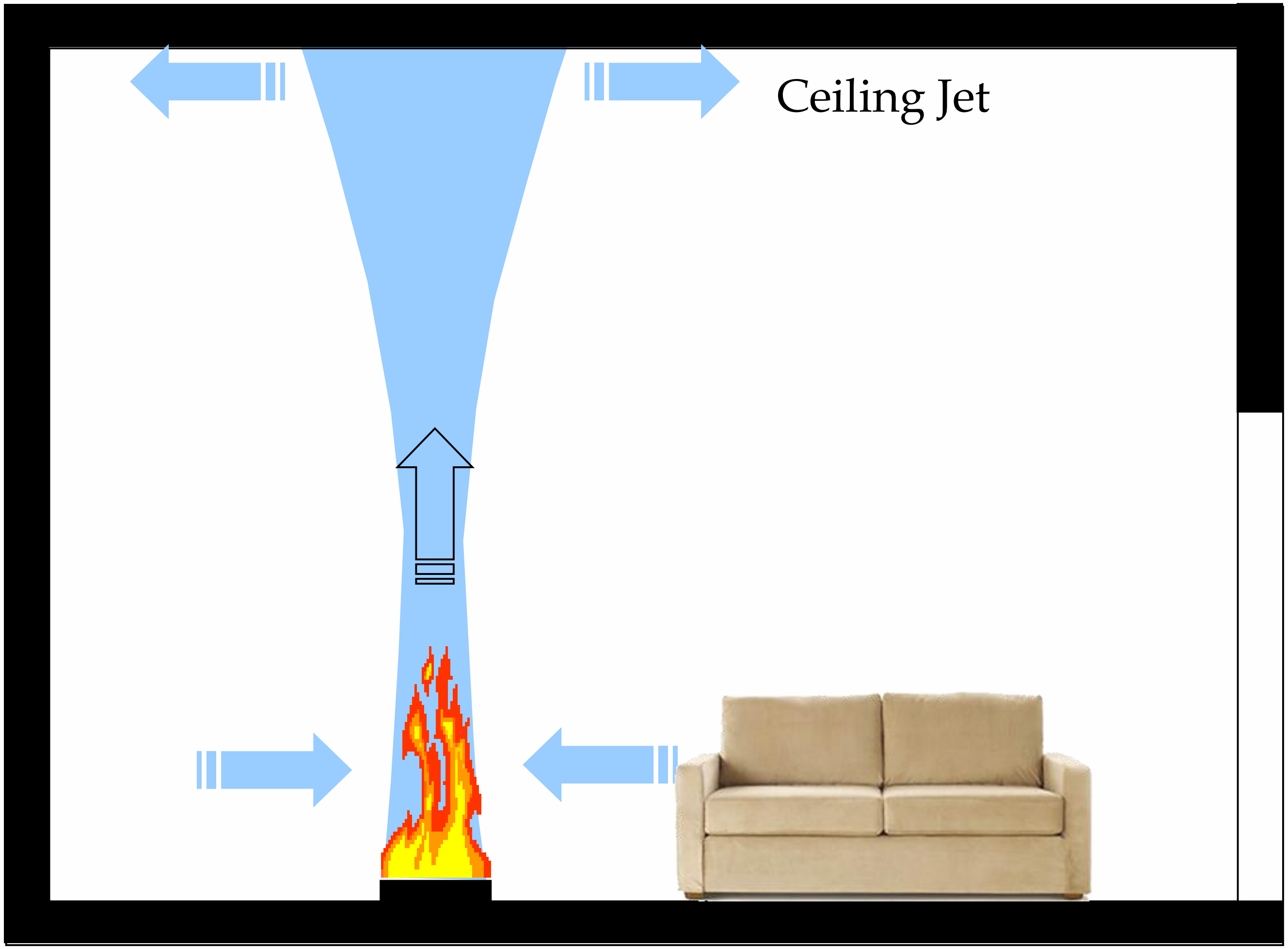
Air entrainment
to support
combustion

Enclosure Fire Dynamics

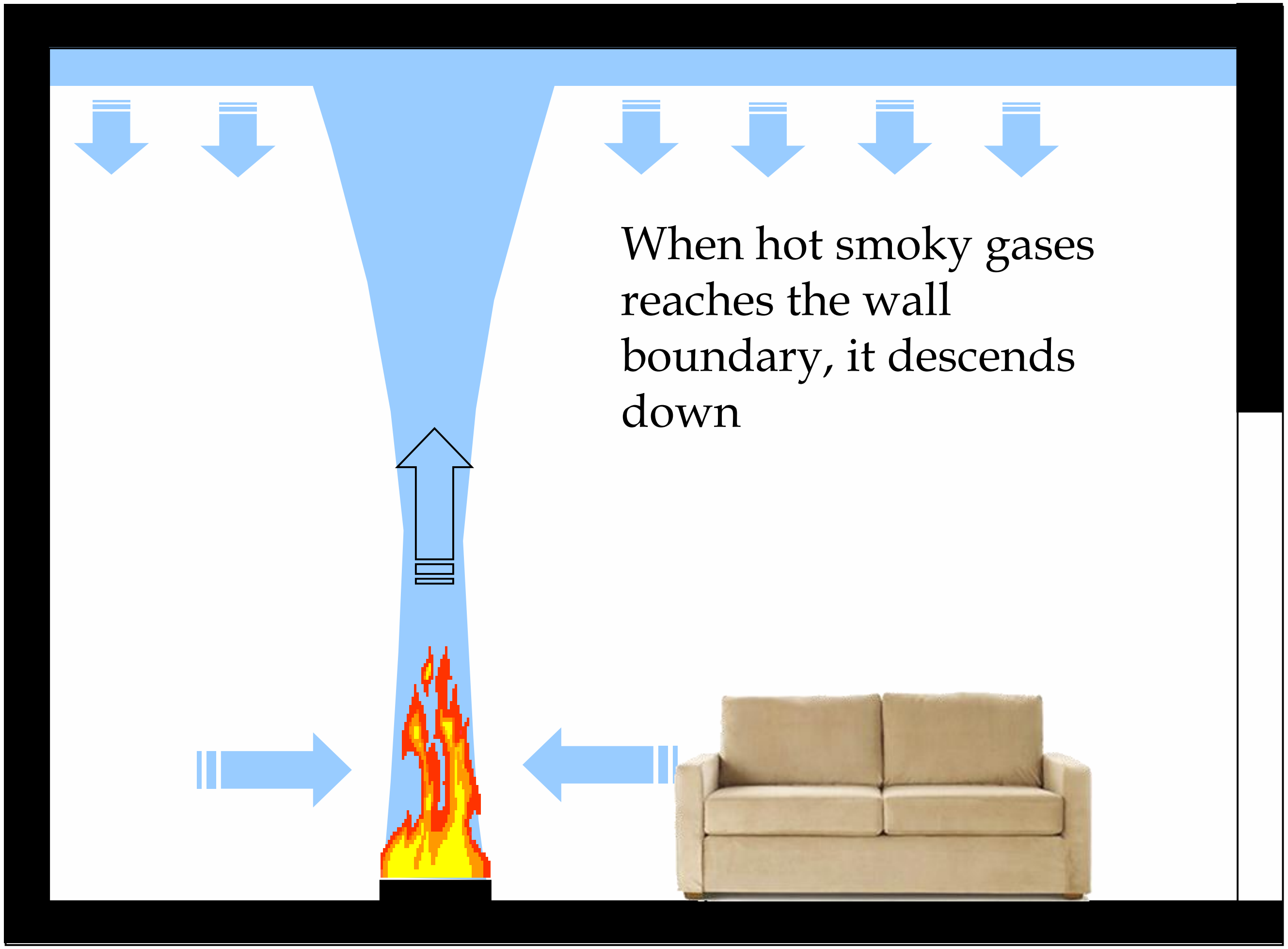


Fire Plume (hot gas column) formed

Enclosure Fire Dynamics

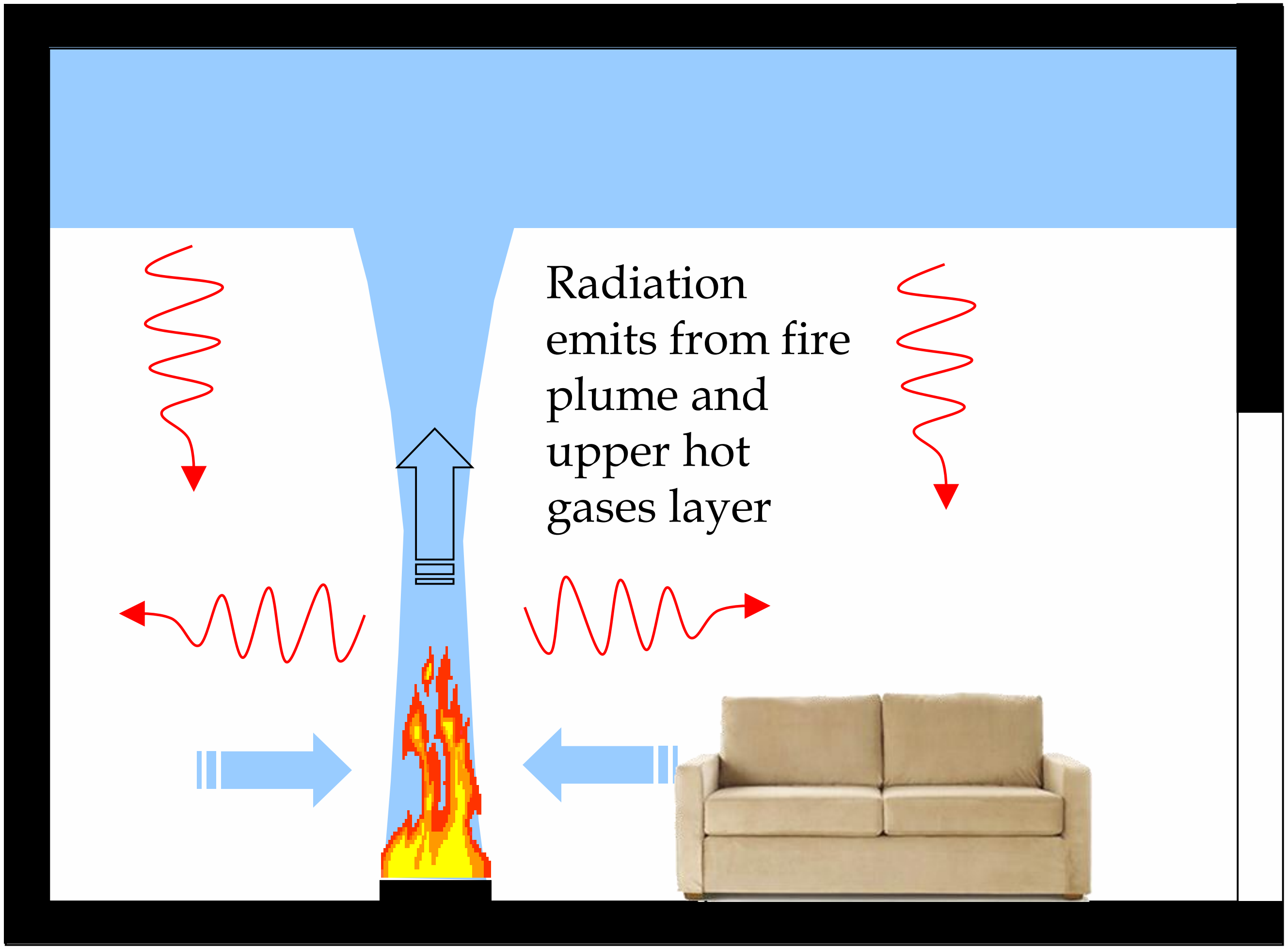


Enclosure Fire Dynamics



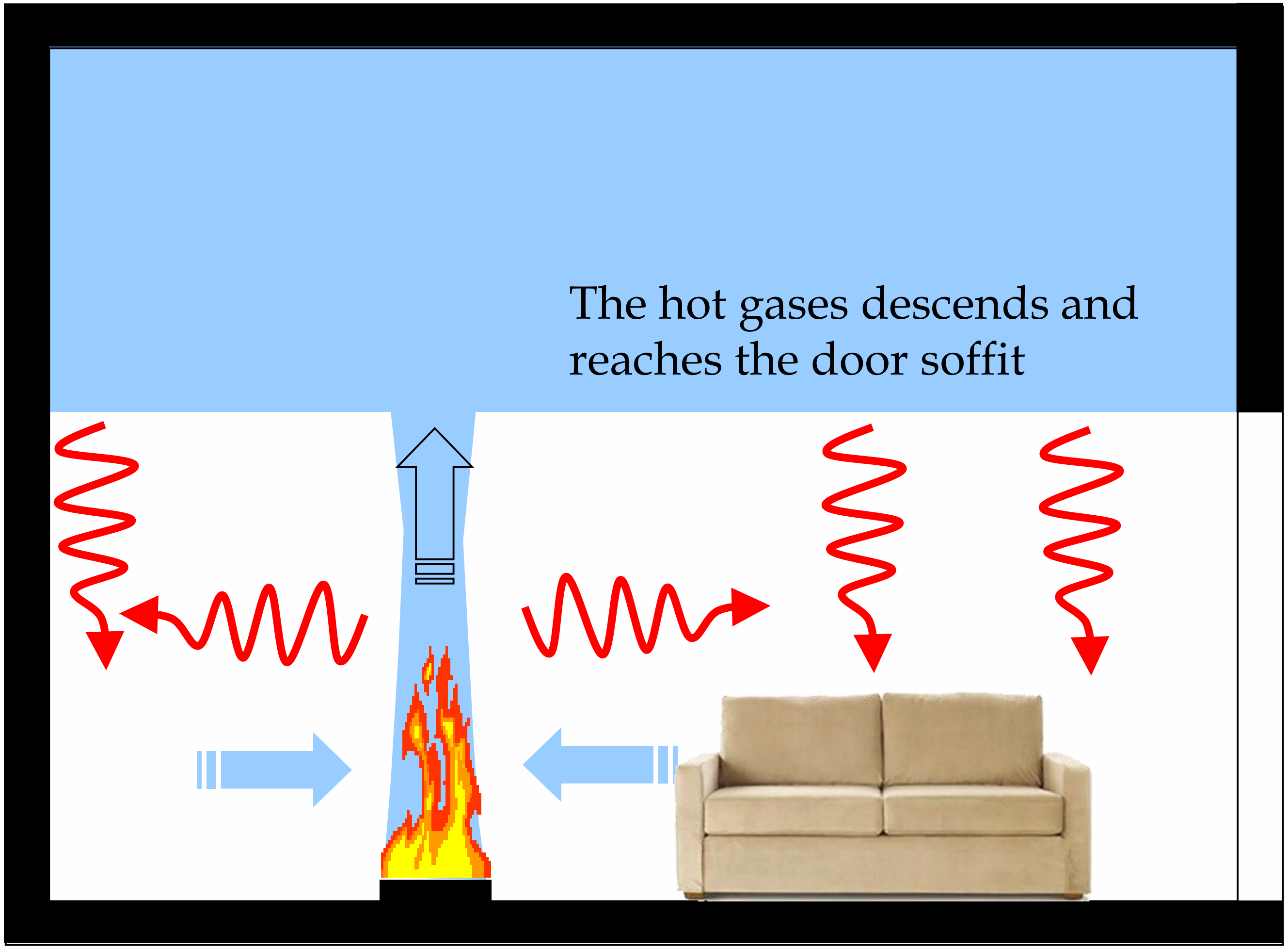
When hot smoky gases reaches the wall boundary, it descends down

Enclosure Fire Dynamics



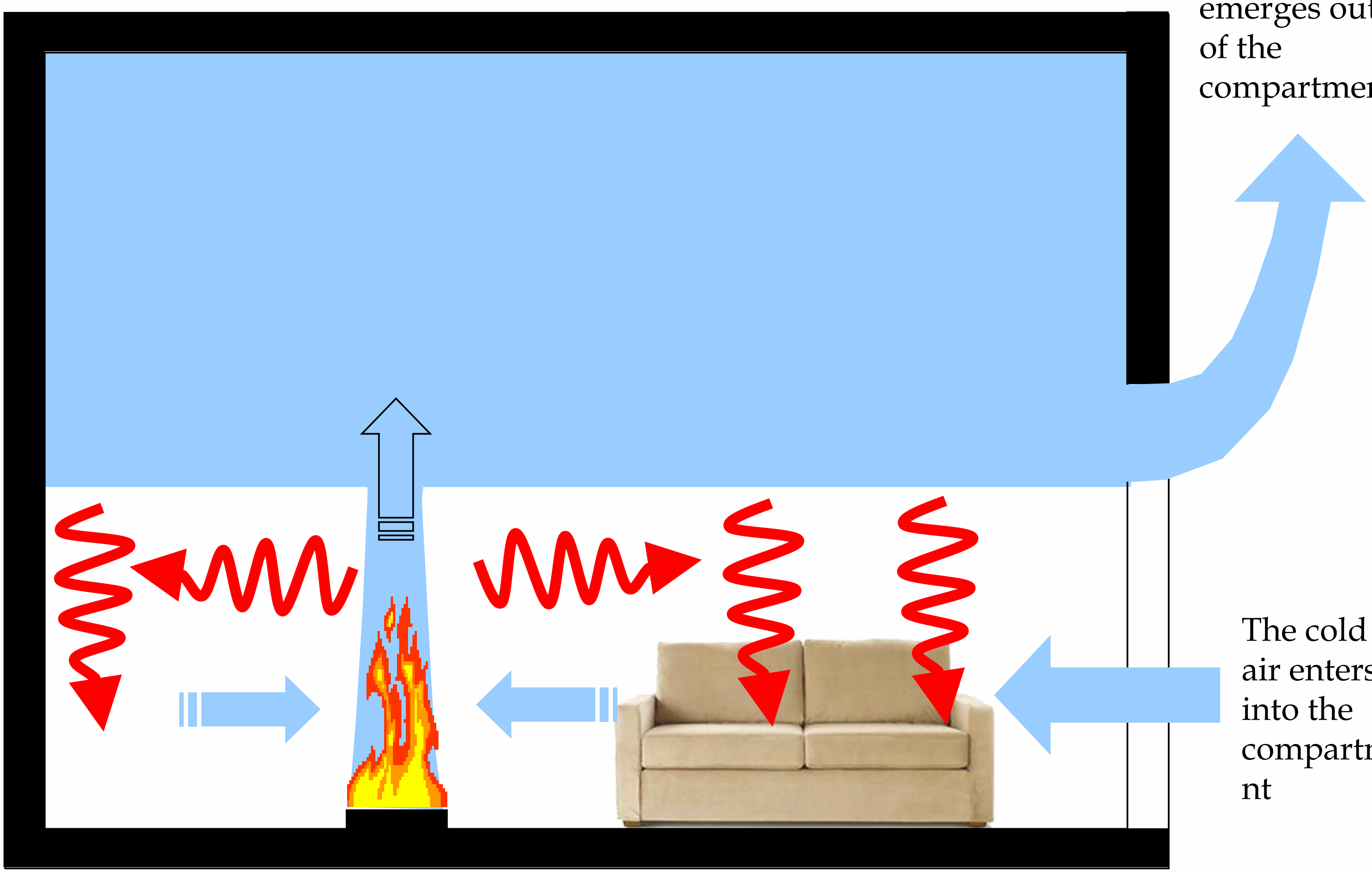
Radiation emits from fire plume and upper hot gases layer

Enclosure Fire Dynamics



The hot gases descends and
reaches the door soffit

Enclosure Fire Dynamics



The hot gases emerges out of the compartment

The cold air enters into the compartment

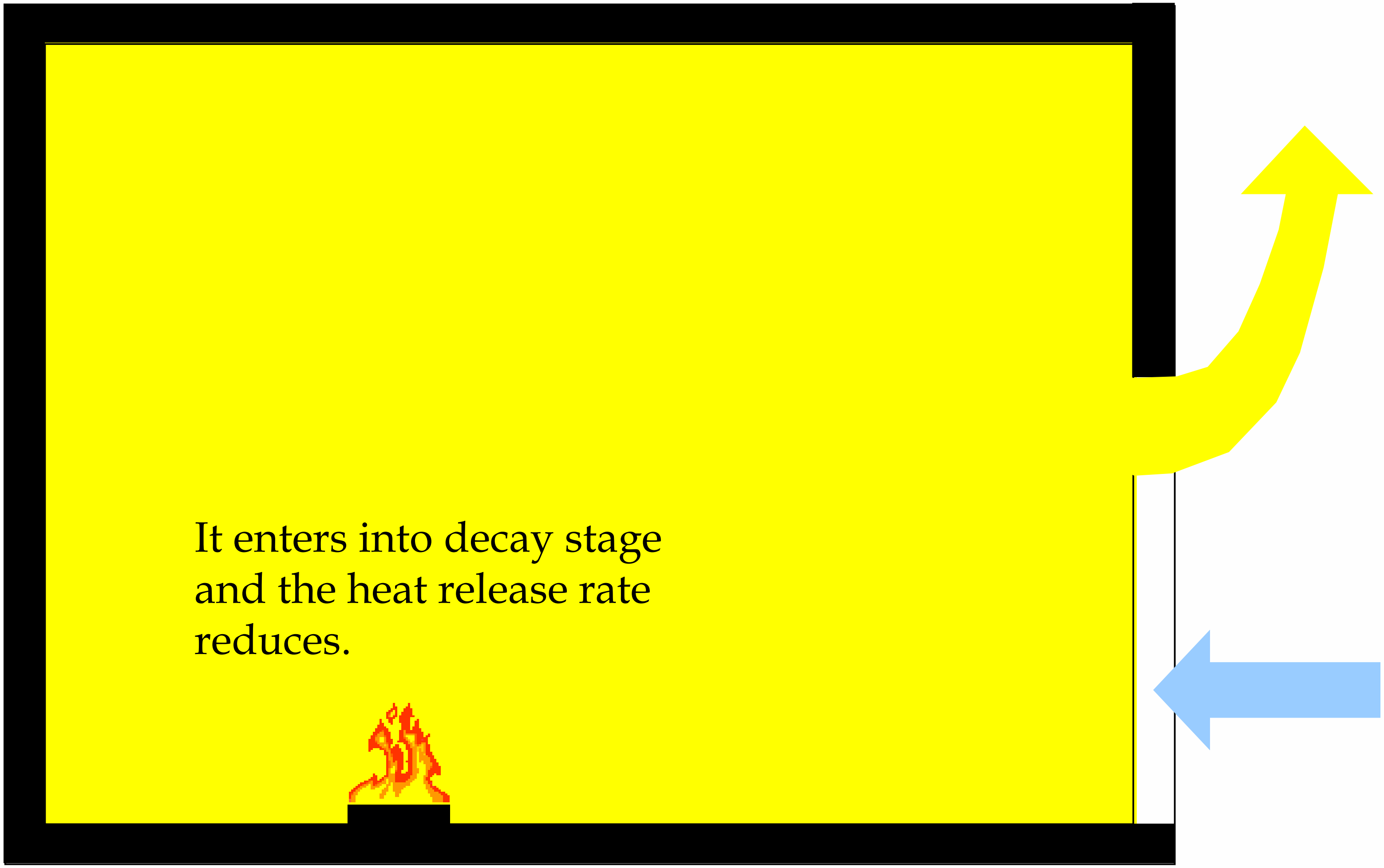
Enclosure Fire Dynamics

When radiation is sufficiently high, flashover occurs and the compartment fire enters into fully-develop stage

Enclosure Fire Dynamics

All combustible material
has been consumed

Enclosure Fire Dynamics



It enters into decay stage and the heat release rate reduces.

Energy generated by a fire

- The rate of energy release is equal to the mass loss rate of the fuel times the heat of combustion of the fuel:

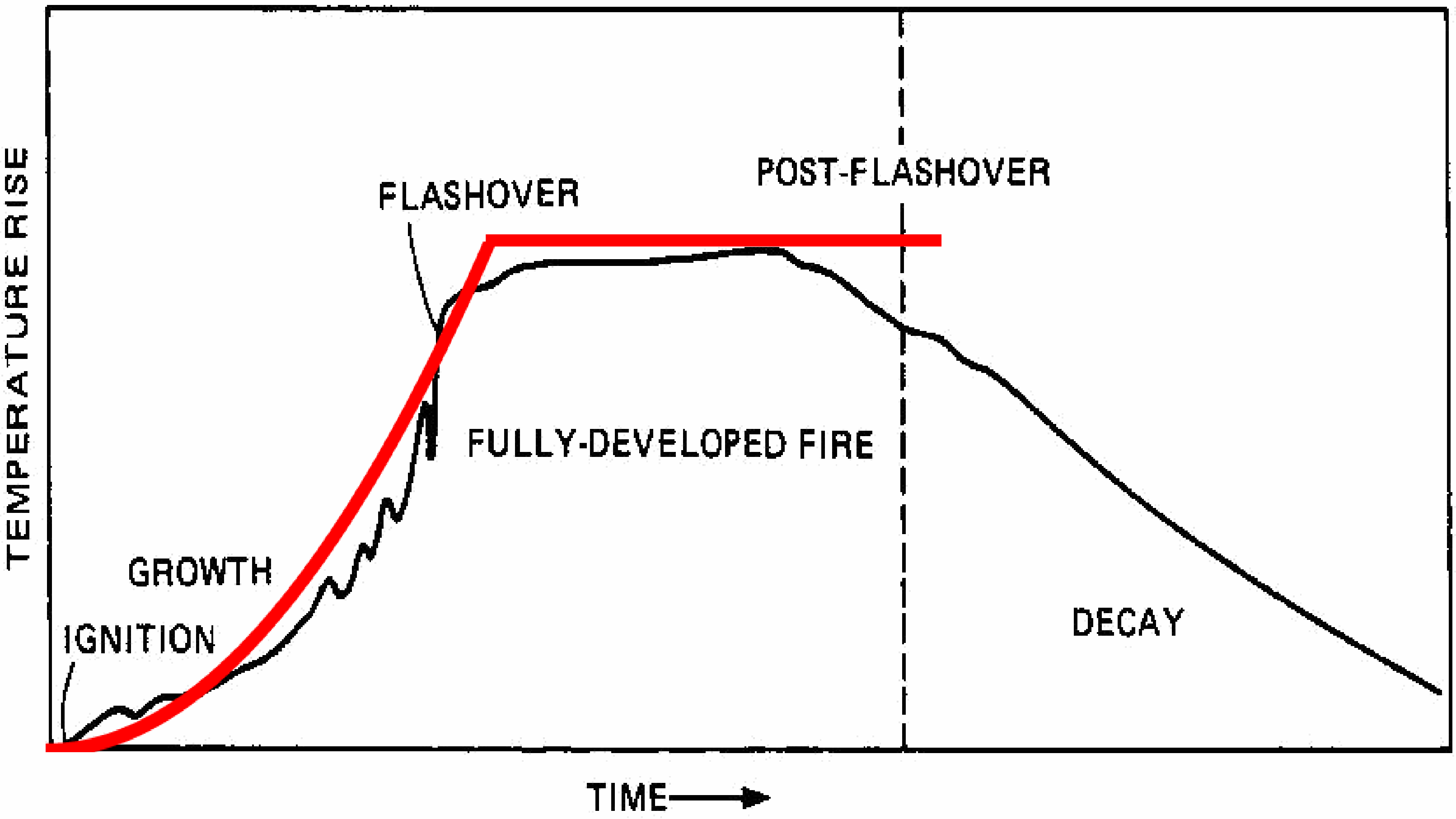
$$\dot{Q} = \dot{m}_f \Delta h_c$$

where $\dot{Q}$ = energy release rate of the fire (kW)

$\dot{m}_f$ = mass burning rate of the fuel (kg/s)

Δh_c = effective heat of combustion of the fuel (kJ/kg)

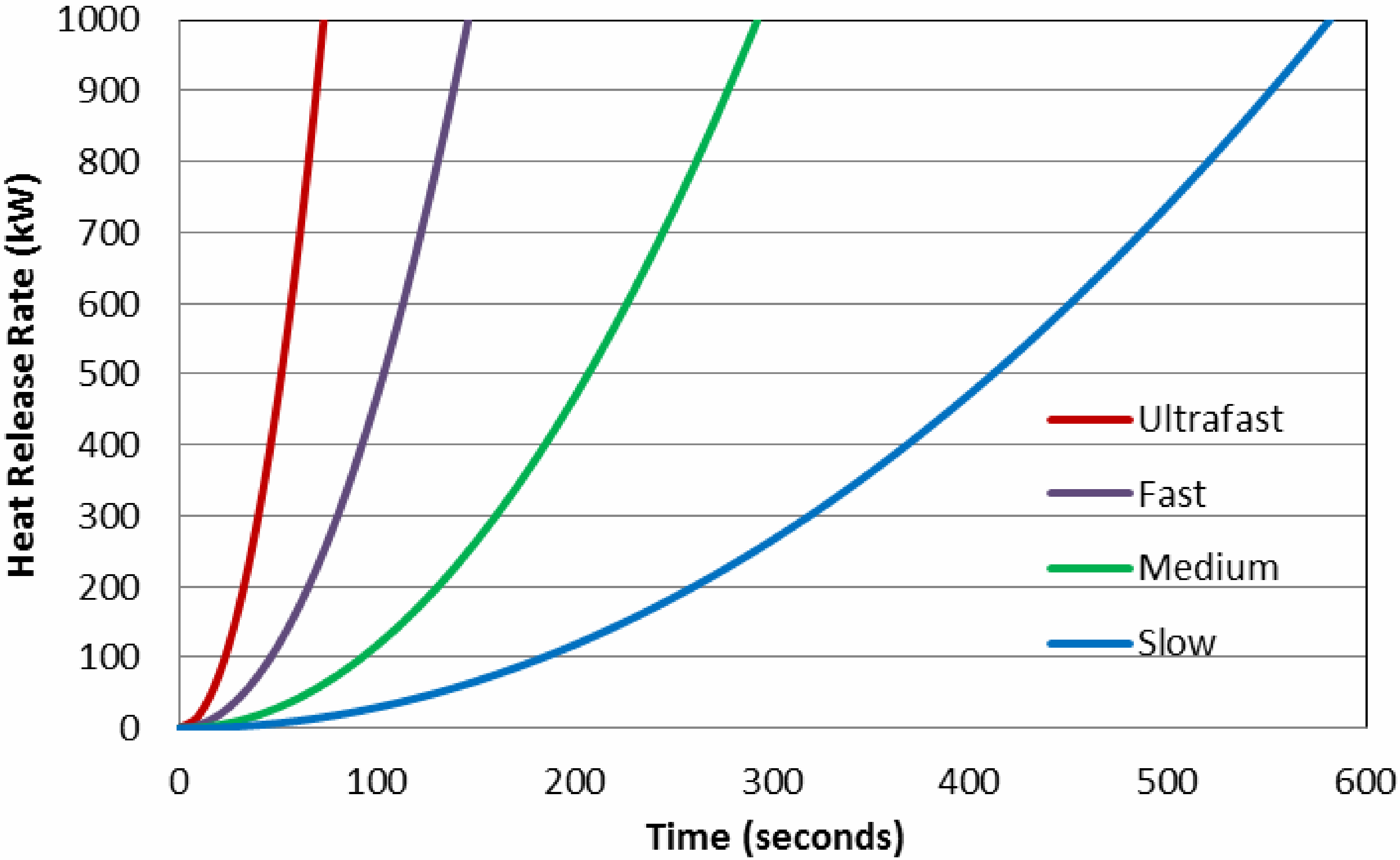
Typical Fire Growth Curve



Design Fire Growth Rate

- t^2 fire is commonly adopted in fire engineering.
- It owns a parabolic increasing profile
  - Extra fast growth (75 seconds to reach 1MW)
  - Fast growth (150 seconds to reach 1MW)
  - Medium growth (300 seconds to reach 1MW)
  - Slow growth (600 seconds to reach 1MW)
- The fire size parabolically increases until it reaches the maximum heat release rate.

Design Fire Growth Rate



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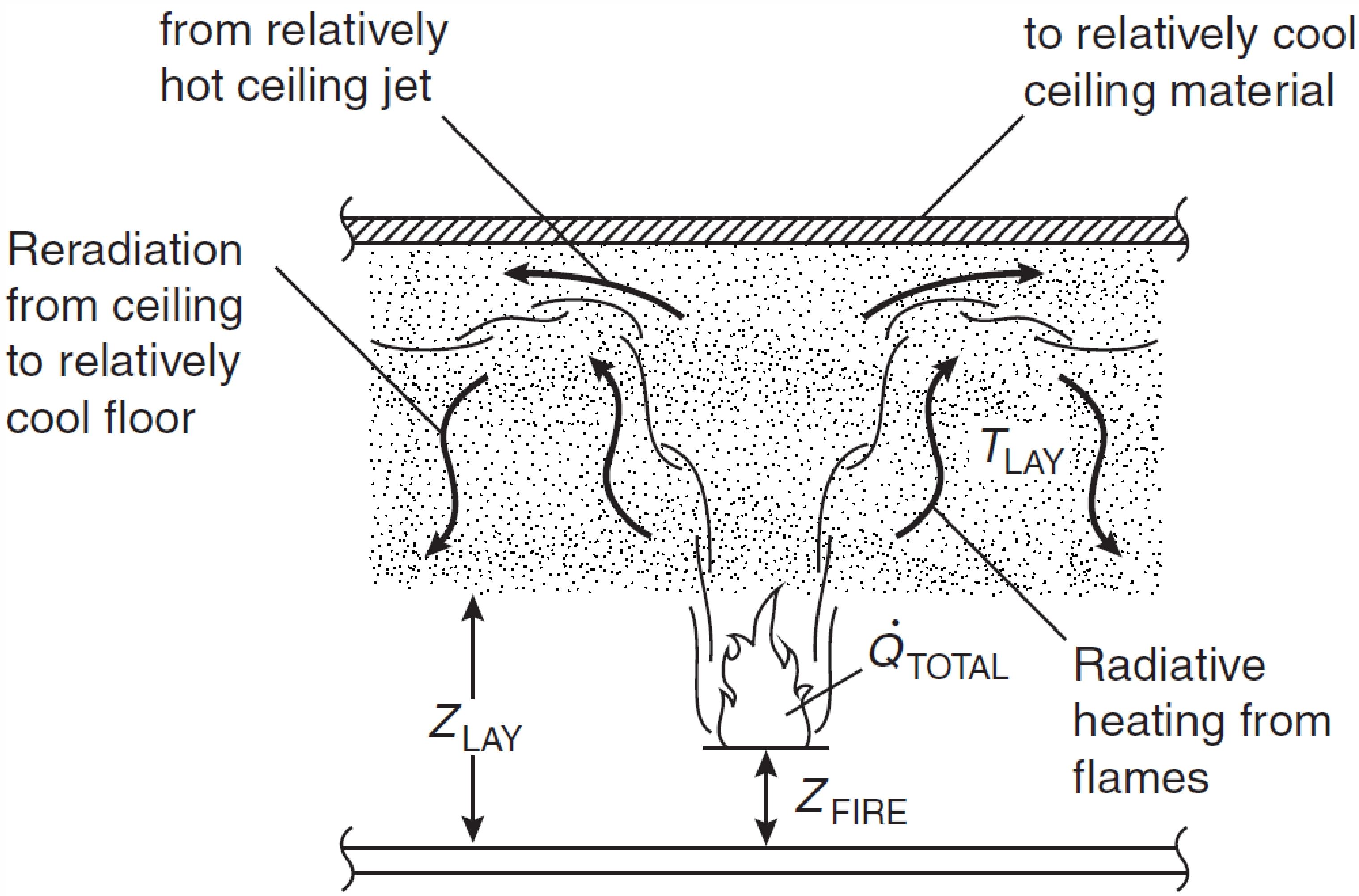
Smoke / Hot Gas Production Rate

- Smoke Production Rate can be approximated by the air entrainment rate

$$\dot{m}_{smoke} = \dot{m}_{fuel} + \dot{m}_{air}$$

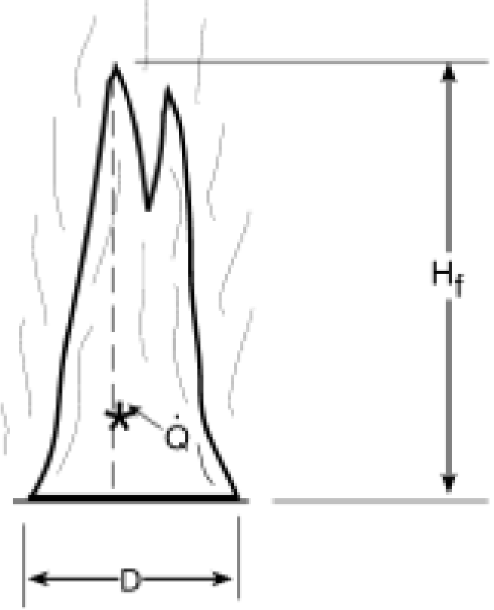
$$\dot{m}_{fuel} \ll \dot{m}_{air}$$

Smoke / Hot Gas Production Rate



Smoke / Hot Gas Production Rate

- Heskestad (1995)



$$z_f = 0.235\, Q^{2/5} - 1.02\, d_s$$

where z_f is the flame height (m)
Q is the heat output of fire (kW)
d_s is the fire diameter (m)

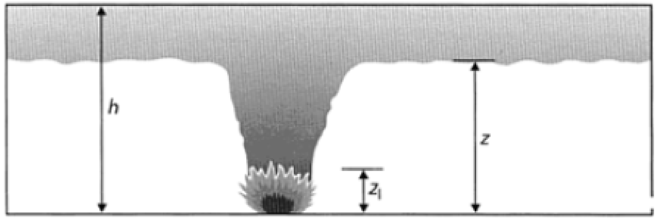
$$D = \sqrt{\frac{4A_f}{\pi}}$$

A_f is the surface area of the non-circular pool

Given: Rate of heat release per unit area (q) = 500 kW/m^2
We have: Area of burning = Q/q = 20 m^2

d_s = 5.046265044 m
z_f = 4.208328163 m

Smoke / Hot Gas Production Rate



i) If the smoke layer interface is well above the flaming region, then the plume mass entrainment rate in *kg/s* can be estimated as follows:

$$M = 0.071 Q_c^{1/3} (z - z_0)^{5/3} \left(1 + 0.026 \frac{Q_c^{2/3}}{(z - z_0)^{5/3}} \right)$$

For $z_f < z$

where z_0 is the virtual height (m)

ii) If the height of smoke layer interface is less than the flame height, then the plume mass entrainment rate in *kg/s* can be estimated as follows:

$$M = 0.033 z Q_c^{3/5}$$

For $z_f > z$

Smoke / Hot Gas Production Rate

Given: Smoke free layer height (z) = 10 m

We have: z_f = 4.208328163 m < z

Location of virtual origin of an assumed point source can be determined as:

$$z_0 = 0.083Q^{\frac{2}{5}} - 1.02d_s$$

We have: Q=10MW d_s = 5.046265044 m

z_0= -1.842900829 m

$$M = 0.071Q_c^{1/3}(z - z_0)^{5/3}\left(1 + 0.026\frac{Q_c^{2/3}}{(z - z_0)^{5/3}}\right)$$

= 96.49279168 kg/s

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Smoke / Hot Gas Production Rate

Given: Smoke free layer height (z) = 2.5 m

We have: $z_f = 4.208328163 \text{ m} > z$

$$M = 0.032 z Q_c^{3/5}$$

$$= 16.22365906 \text{ kg/s}$$

Volume of Smoke Produced (V)

The volume flow rate (V) is given by:

$$V = \frac{M}{\rho_0} + \frac{Q_c}{\rho_0 T_0 C_p}$$

Where V is volume flow rate (m^3/s);

ρ_0 is density of air at T_0 (kg/m^3);

Q_p is the convective heat output of fire (kW)

M is the mass flow entering the layer (kg/s)

c_p is the specific heat of air (kJ/kg.K)

Given: Specific heat capacity of air or smoke (c_p)= 1.02 kJ/kg.K

Ambient temperature (T_0) = 24℃

Density of air at 24℃ is 1.2 kg/m^3

Mass flow rate (M) = 96.49279168 kg/s

Then V=99.66639795 m^3/s

Mechanical Smoke Extraction

- Smoke is removed by extraction fan.
- The mass extraction rate should be higher than the mass of smoke generation rate.
- Volumetric flow rate = mass flow rate / density
- By ideal gas law with constant pressure, we have ρT=constant. That is,

$$\rho T = \rho_{273} T_{273} = 1.2922 \times 273 = 352.77$$

Static Smoke Vent

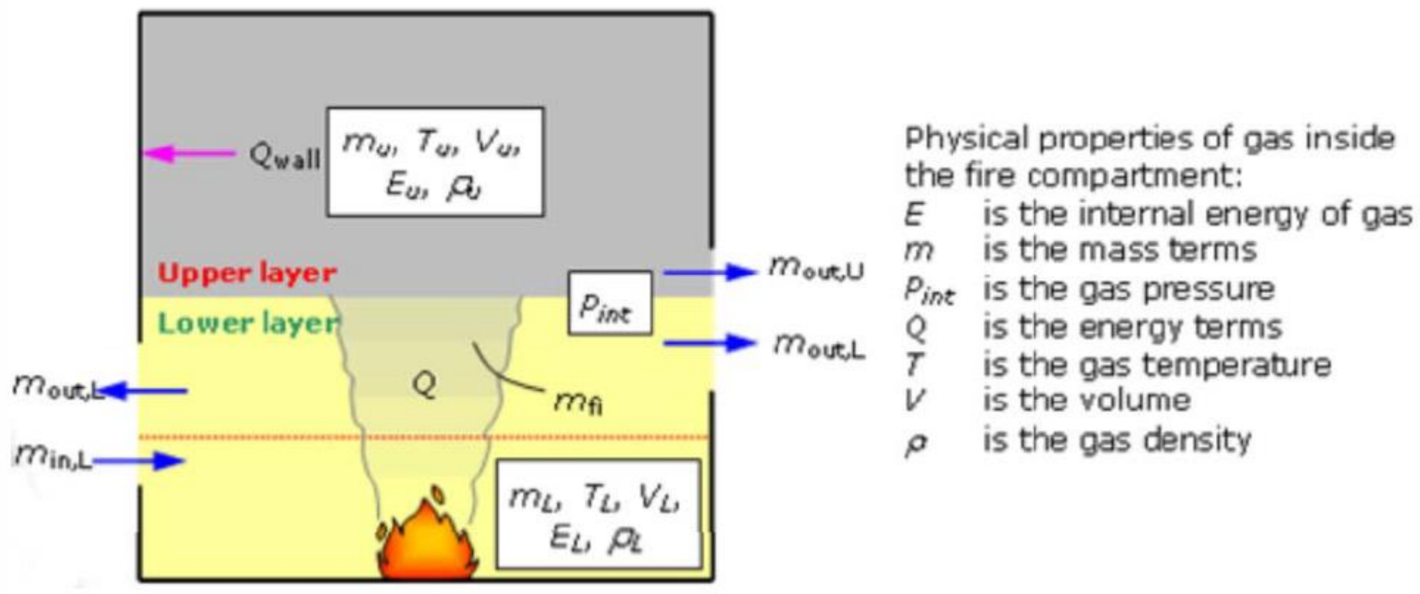
- Smoke is driven by its buoyancy to the atmosphere naturally (natural vent)

$$\dot{m}_g = \frac{C_{d,v} A_v \rho_o \sqrt{2 g z_{lay} (T - T_o)}}{\left[\frac{T}{T_o} + \left(\frac{C_{d,v} A_v}{C_{d,i} A_i} \right)^2 \left(\frac{T_o}{T} \right) \right]^{1/2}}$$

where $C_{d,v}$ and $C_{d,i}$ are the discharge coefficients of vent outlet and inlet respectively.

Zone Modelling

- Zone model approximate the smoke layer can be defined as one zone; the clear air underneath is another.
- Heat and mass are transferred from lower zone to upper zone is treated as the third zone
- Heat release rate should be specified as a function of time (e.g. t^2 fire)
- Generally responds quick and useful in simple geometry.

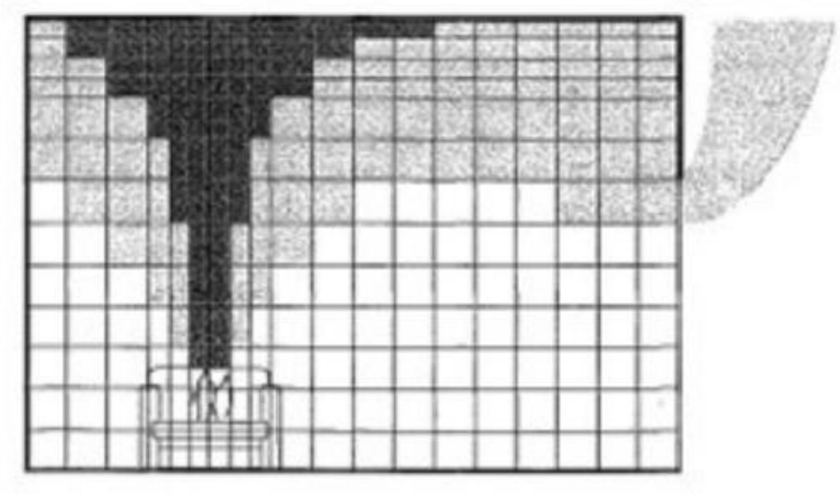


Physical properties of gas inside the fire compartment:

E	is the internal energy of gas
m	is the mass terms
P_{int}	is the gas pressure
Q	is the energy terms
T	is the gas temperature
V	is the volume
ρ	is the gas density

Field Modelling

- Computational fluid dynamics (CFD) techniques
- Computational domain is divided into many small volumes.
- A large set of partial differential equations to describe the chemistry of combustion, heat transfer, fluid flow, radiation, species movement, soot production of one volume and its neighboring volumes.
- The problem is solved iteratively by numerical approach until the solution converge.



Example (Heat Conduction Problem)

- 2D heat equation without heating source (i.e. Laplace equation)

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} = 0$$

- Consider the domain is divided into volumes

	$T_{i,j+1}$	
$T_{i-1,j}$	$T_{i,j}$	$T_{i+1,j}$
	$T_{i,j-1}$	

Example (Discretization)

$$\frac{\partial^2 T}{\partial x^2} \rightarrow \frac{\left(\frac{T_{i+1,j}-T_{i,j}}{\Delta x}\right) - \left(\frac{T_{i,j}-T_{i-1,j}}{\Delta x}\right)}{\Delta x}$$

$$\frac{\partial^2 T}{\partial y^2} \rightarrow \frac{\left(\frac{T_{i,j+1}-T_{i,j}}{\Delta y}\right) - \left(\frac{T_{i,j}-T_{i,j-1}}{\Delta y}\right)}{\Delta y}$$

Example (Discretization)

$$\frac{\left(\frac{T_{i+1,j}-T_{i,j}}{\Delta x}\right)-\left(\frac{T_{i,j}-T_{i-1,j}}{\Delta x}\right)}{\Delta x}+\frac{\left(\frac{T_{i,j+1}-T_{i,j}}{\Delta y}\right)-\left(\frac{T_{i,j}-T_{i,j-1}}{\Delta y}\right)}{\Delta y}=0$$

Put $\Delta x = \Delta y$ (i.e. square mesh);

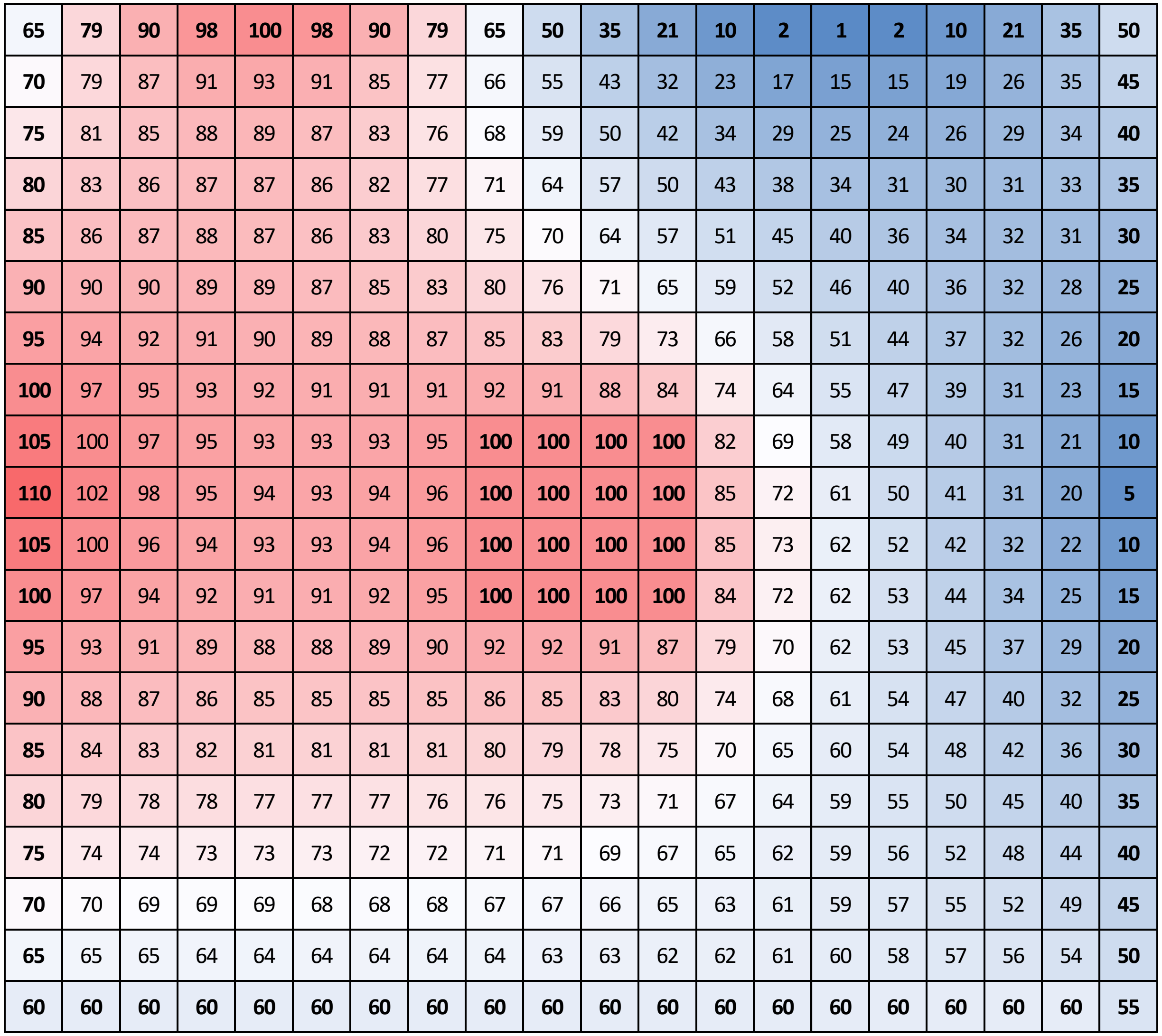
$$T_{i,j}=\frac{T_{i+1,j}+T_{i-1,j}+T_{i,j+1}+T_{i,j-1}}{4}$$

The partial differential equation is discretized into a linear algebraic equation.

Example (boundary condition)

65	79	90	98	100	98	90	79	65	50	35	21	10	2	1	2	10	21	35	50
70																			45
75																			40
80																			35
85																			30
90																			25
95																			20
100																			15
105								100	100	100	100								10
110								100	100	100	100								5
105								100	100	100	100								10
100								100	100	100	100								15
95																			20
90																			25
85																			30
80																			35
75																			40
70																			45
65																			50
60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	60	55

Example (solving)



65	**79**	**90**	**98**	**100**	**98**	**90**	**79**	**65**	**50**	**35**	**21**	**10**	**2**	**1**	**2**	**10**	**21**	**35**	**50**
70	79	87	91	93	91	85	77	66	55	43	32	23	17	15	15	19	26	35	**45**
75	81	85	88	89	87	83	76	68	59	50	42	34	29	25	24	26	29	34	**40**
80	83	86	87	87	86	82	77	71	64	57	50	43	38	34	31	30	31	33	**35**
85	86	87	88	87	86	83	80	75	70	64	57	51	45	40	36	34	32	31	**30**
90	90	90	89	89	87	85	83	80	76	71	65	59	52	46	40	36	32	28	**25**
95	94	92	91	90	89	88	87	85	83	79	73	66	58	51	44	37	32	26	**20**
100	97	95	93	92	91	91	91	92	91	88	84	74	64	55	47	39	31	23	**15**
105	100	97	95	93	93	93	95	**100**	**100**	**100**	**100**	82	69	58	49	40	31	21	**10**
110	102	98	95	94	93	94	96	**100**	**100**	**100**	**100**	85	72	61	50	41	31	20	**5**
105	100	96	94	93	93	94	96	**100**	**100**	**100**	**100**	85	73	62	52	42	32	22	**10**
100	97	94	92	91	91	92	95	**100**	**100**	**100**	**100**	84	72	62	53	44	34	25	**15**
95	93	91	89	88	88	89	90	92	92	91	87	79	70	62	53	45	37	29	**20**
90	88	87	86	85	85	85	85	86	85	83	80	74	68	61	54	47	40	32	**25**
85	84	83	82	81	81	81	81	80	79	78	75	70	65	60	54	48	42	36	**30**
80	79	78	78	77	77	77	76	76	75	73	71	67	64	59	55	50	45	40	**35**
75	74	74	73	73	73	72	72	71	71	69	67	65	62	59	56	52	48	44	**40**
70	70	69	69	69	68	68	68	67	67	66	65	63	61	59	57	55	52	49	**45**
65	65	65	64	64	64	64	64	64	63	63	62	62	61	60	58	57	56	54	**50**
60	**60**	**60**	**60**	**60**	**60**	**60**	**60**	**60**	**60**	**60**	**60**	**60**	**60**	**60**	**60**	**60**	**60**	**60**	**55**

Meshing

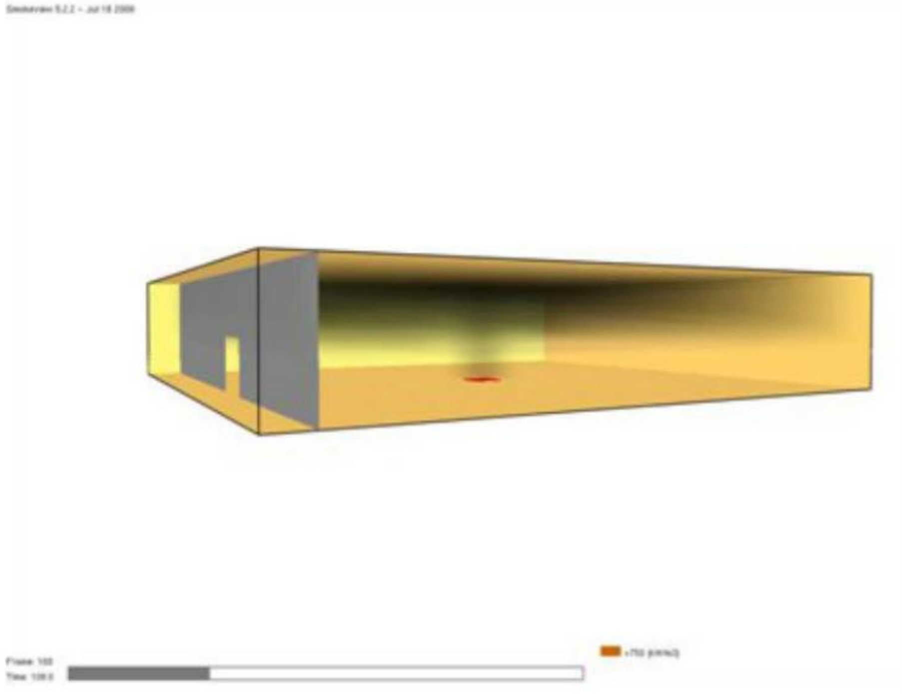
- Mesh size is critical to the simulation.
- Small grid size can capture the behavior but takes too long time
- Large grid size cannot accurately resolve the fire dynamics
- Some CFD models provide equation to determine the grid size. Others may require grid sensitivity study

Fire Size and Growth

- Some of the CFD model can solve the fire chemistry and determine the fire size by its own.
- However, pre-determining a maximum fire size can cope with the worst scenario but it should be determined reasonably with supports from literature
- T-square fire is usually adopted

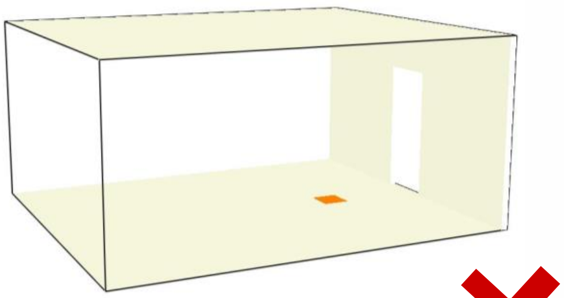
Smoke Generation

- With only heat release rate specified, the fire source is only a heating element. The soot yield rate should also be pre-determined since it will affect the visibility.



Boundary Conditions Setting

- Boundary materials
- Extended regions should be provided at the openings
- Patching of fire location
- The fire bed area



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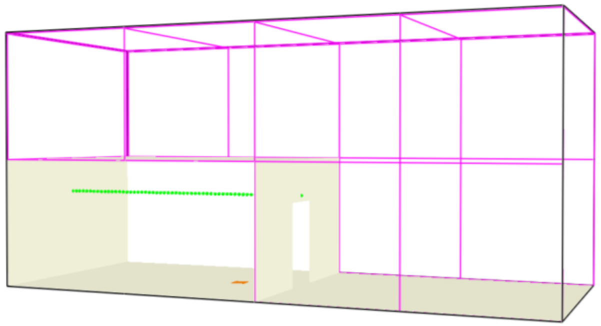


○

Convergence

- Some of the CFD packages can terminate the simulation of the preset convergence criterion.
- Some of the CFD packages (e.g. LES model) require user to determine the simulation time. To confirm the convergence, the time averages of two consecutive time frames should be compared.

Conclusions

- Fundamentals of fire science were introduced
- Useful equations in fire engineering were demonstrated
- Basic fire modelling techniques were introduced

Part 2 - Hot Smoke Test

CoP of FSI (2012)

- Smoke Extraction System (Static or Dynamic)
  - e.g. Commercial building with
    - a) atrium exceeds 28,000m^3 or basement exceeds 7,000m^3 .
    - b) any compartment exceeding 7,000m^3 with
      - i) Aggregate area of openable windows < 6.25%
      - ii) Fire Load < 1,135MJ/m^2

- Compartments requiring hot smoke test
  - i) Compartments with headroom of 12m or more; or
  - ii) Compartments with irregular geometrical dimensions or extraordinary large size.

Salient Points for the Test

- Temperature of simulated hot air plume ≤ Sprinkler activation temperature – 10°C (avoid it’s actuation);
- Fire size of test fire ≥ 1 MW or agreed by the Director of Fire Services;
- Fuel: Non-contaminating industrial grade methylated spirit (Grade 95);
- Smoke generator: Non-toxic oil based smoke generator;
- Reference to Australian Standard AS 4391-1999 or other equivalent international standard

Safety Measures for the Test

- Adequate safety measures – to prevent any possible spread of fire during the test;
- Adequate fire extinguishers should be provided at scene;
- The standing-by fire appliance may be required if considered necessary.

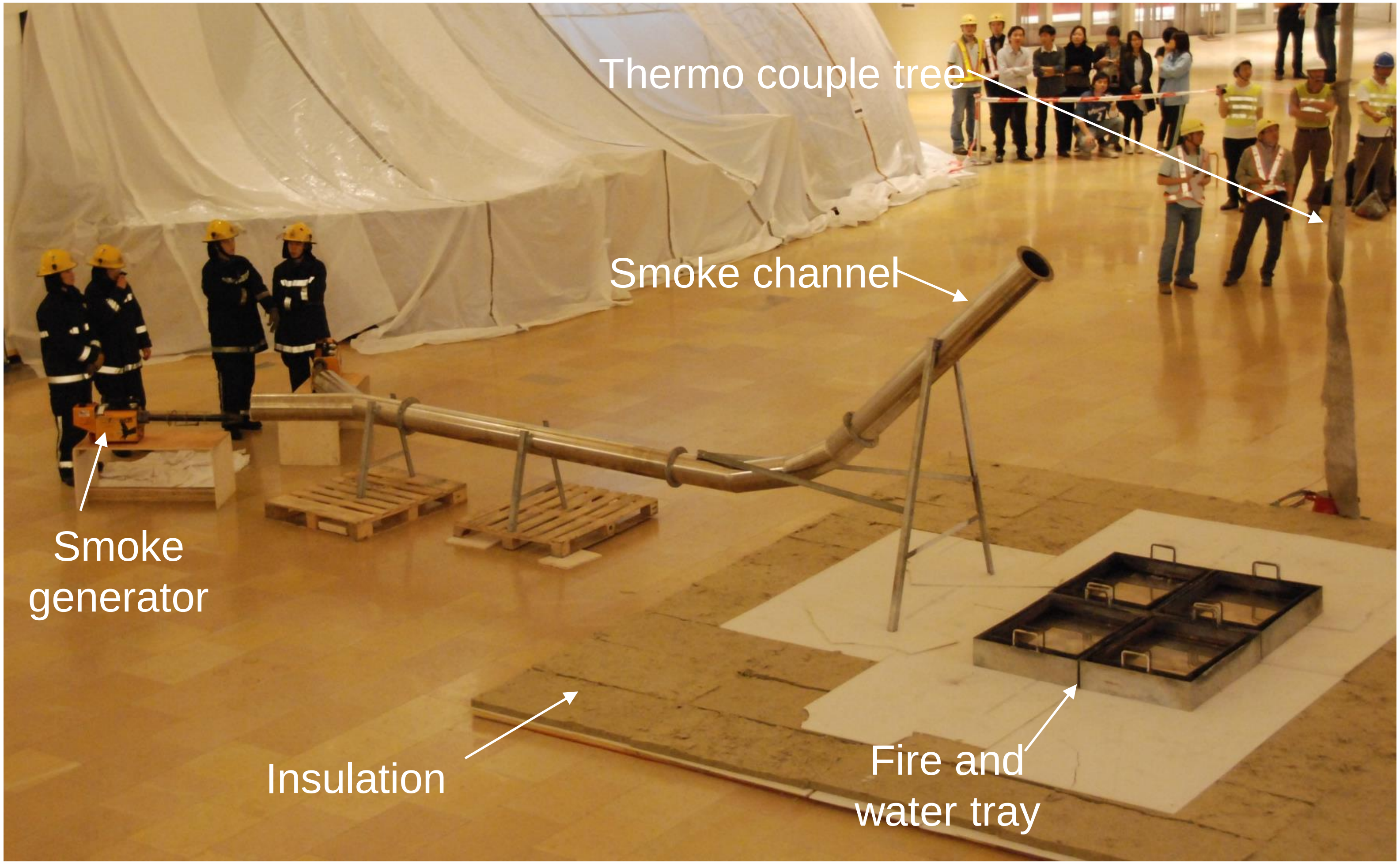
Acceptable Criteria

- Maintain the designed smoke clear height;
- "Scouring" effect should be observed and make-up fresh air should not affect the stability of the smoke layer;
- Smoke extraction system should actuate promptly in response to a fire alarm signal;
- No significant disperse of smoke at adjoining smoke compartment(s);
- No deflection at hanging smoke curtains;
- No significant smoke in "stagnant corners" beneath the smoke layers
- No smoke re-circulated into the building

Test Objectives

- To verify the satisfactory performance of the smoke control system;
- To demonstrate the proper operation of the smoke control system; and
- To resolve any uncertainties related to the smoke control system.

Example of Set-up



General Procedure

1. Submission of Method Statement to Client, Consultant and FSD

2. FSD Engagement

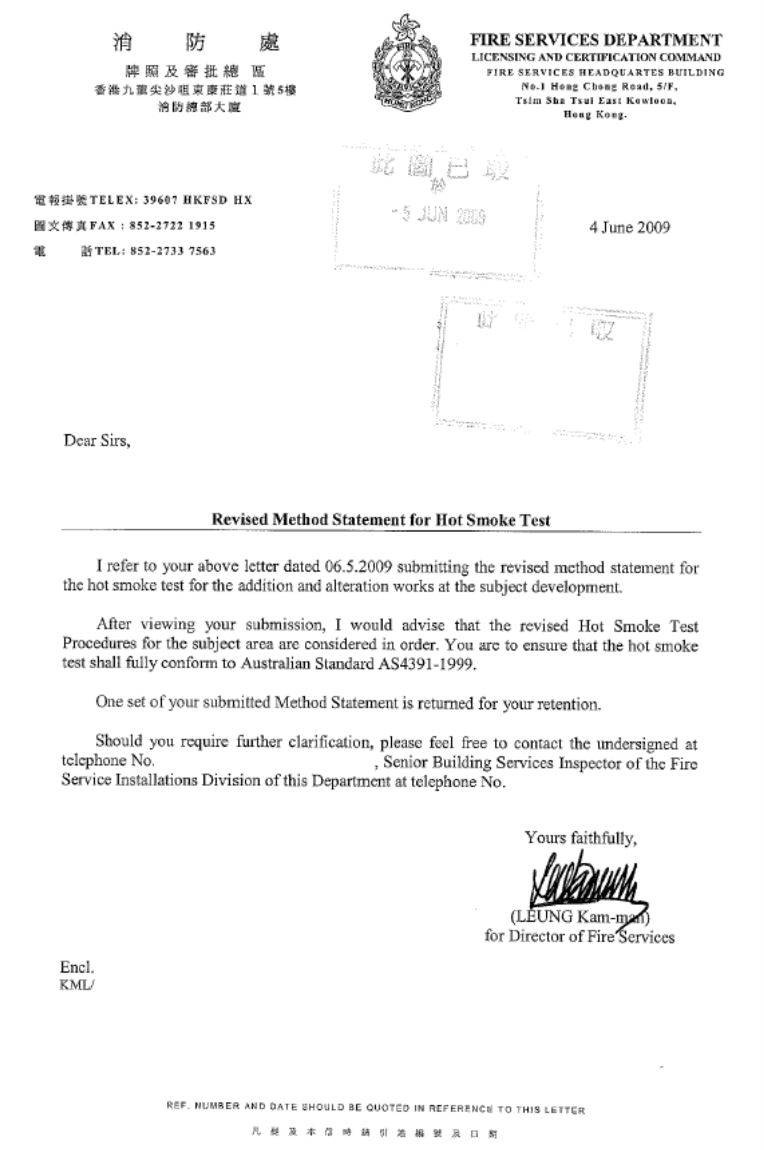
    e.g. Fire Fighters, Smoke generators and etc.

1. Mock-up test (highly recommended) &

2. Formal test

3. Submission of Test Report

General Procedure



消　防　處
牌照及審批總區
香港九龍尖沙咀東康莊道1號5樓
消防總部大廈

FIRE SERVICES DEPARTMENT
LICENSING AND CERTIFICATION COMMAND
FIRE SERVICES HEADQUARTES BUILDING
No.1 Hong Chong Road, 5/F,
Tsim Sha Tsui East Kowloon,
Hong Kong.

電報掛號TELEX: 39607 HKFSD HX
圖文傳真FAX : 852-2722 1915
電　話TEL: 852-2733 7563

此函已收
於
-5 JUN 2009

4 June 2009

Dear Sirs,

Revised Method Statement for Hot Smoke Test

I refer to your above letter dated 06.5.2009 submitting the revised method statement for the hot smoke test for the addition and alteration works at the subject development.

After viewing your submission, I would advise that the revised Hot Smoke Test Procedures for the subject area are considered in order. You are to ensure that the hot smoke test shall fully conform to Australian Standard AS4391-1999.

One set of your submitted Method Statement is returned for your retention.

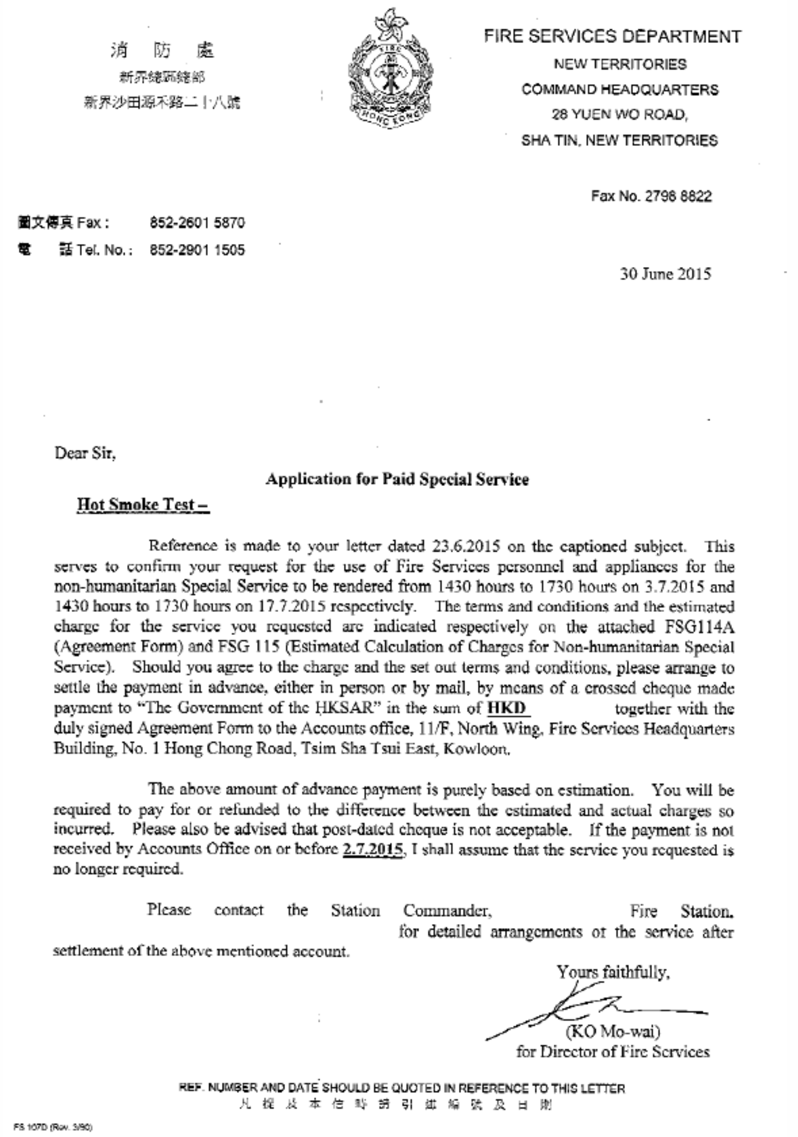
Should you require further clarification, please feel free to contact the undersigned at telephone No. , Senior Building Services Inspector of the Fire Service Installations Division of this Department at telephone No.

Yours faithfully,

(LEUNG Kam-man)
for Director of Fire Services

Encl.
KML/

REF. NUMBER AND DATE SHOULD BE QUOTED IN REFERENCE TO THIS LETTER
凡提及本信時請引述編號及日期



消　防　處
新界總區總部
新界沙田源禾路二十八號

FIRE SERVICES DEPARTMENT
NEW TERRITORIES
COMMAND HEADQUARTERS
28 YUEN WO ROAD,
SHA TIN, NEW TERRITORIES

Fax No. 2798 8822

圖文傳真 Fax : 852-2601 5870
電　話 Tel. No. : 852-2901 1505

30 June 2015

Dear Sir,

Application for Paid Special Service

Hot Smoke Test –

Reference is made to your letter dated 23.6.2015 on the captioned subject. This serves to confirm your request for the use of Fire Services personnel and appliances for the non-humanitarian Special Service to be rendered from 1430 hours to 1730 hours on 3.7.2015 and 1430 hours to 1730 hours on 17.7.2015 respectively. The terms and conditions and the estimated charge for the service you requested are indicated respectively on the attached FSG114A (Agreement Form) and FSG 115 (Estimated Calculation of Charges for Non-humanitarian Special Service). Should you agree to the charge and the set out terms and conditions, please arrange to settle the payment in advance, either in person or by mail, by means of a crossed cheque made payment to "The Government of the HKSAR" in the sum of **HKD** together with the duly signed Agreement Form to the Accounts office, 11/F, North Wing, Fire Services Headquarters Building, No. 1 Hong Chong Road, Tsim Sha Tsui East, Kowloon.

The above amount of advance payment is purely based on estimation. You will be required to pay for or refunded to the difference between the estimated and actual charges so incurred. Please also be advised that post-dated cheque is not acceptable. If the payment is not received by Accounts Office on or before 2.7.2015, I shall assume that the service you requested is no longer required.

Please contact the Station Commander, Fire Station, for detailed arrangements of the service after settlement of the above mentioned account.

Yours faithfully,

(KO Mo-wai)
for Director of Fire Services

REF. NUMBER AND DATE SHOULD BE QUOTED IN REFERENCE TO THIS LETTER
凡提及本信時請引述編號及日期

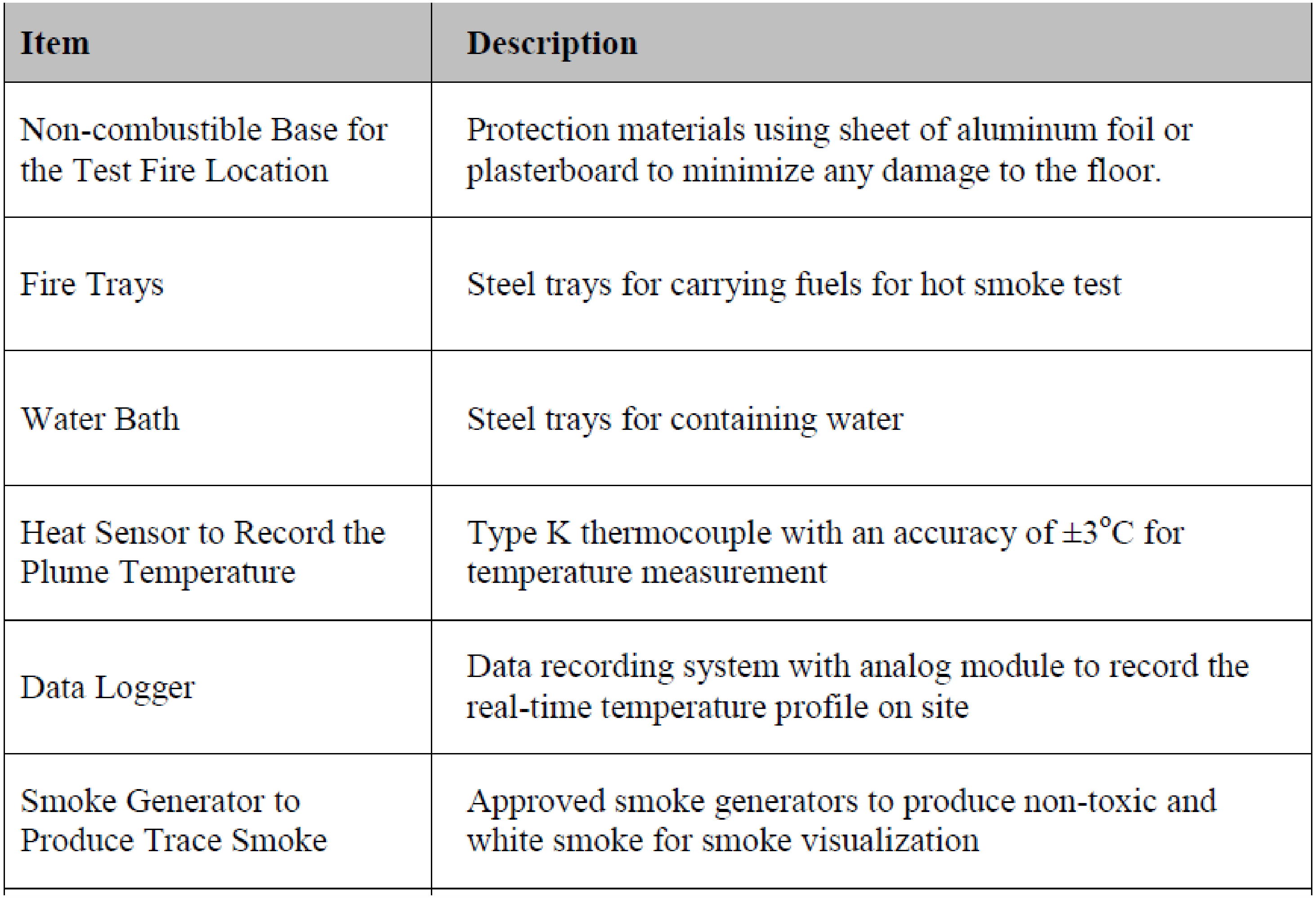
FS 107D (Rev. 3/90)

Method Statement

- Introduction
- Test Requirements
- Test Apparatus
- Test Approach – Fire Location & Size!
- Test Procedure
- Preparation inventory
- Life and Asset Safety Requirement

Test Standard

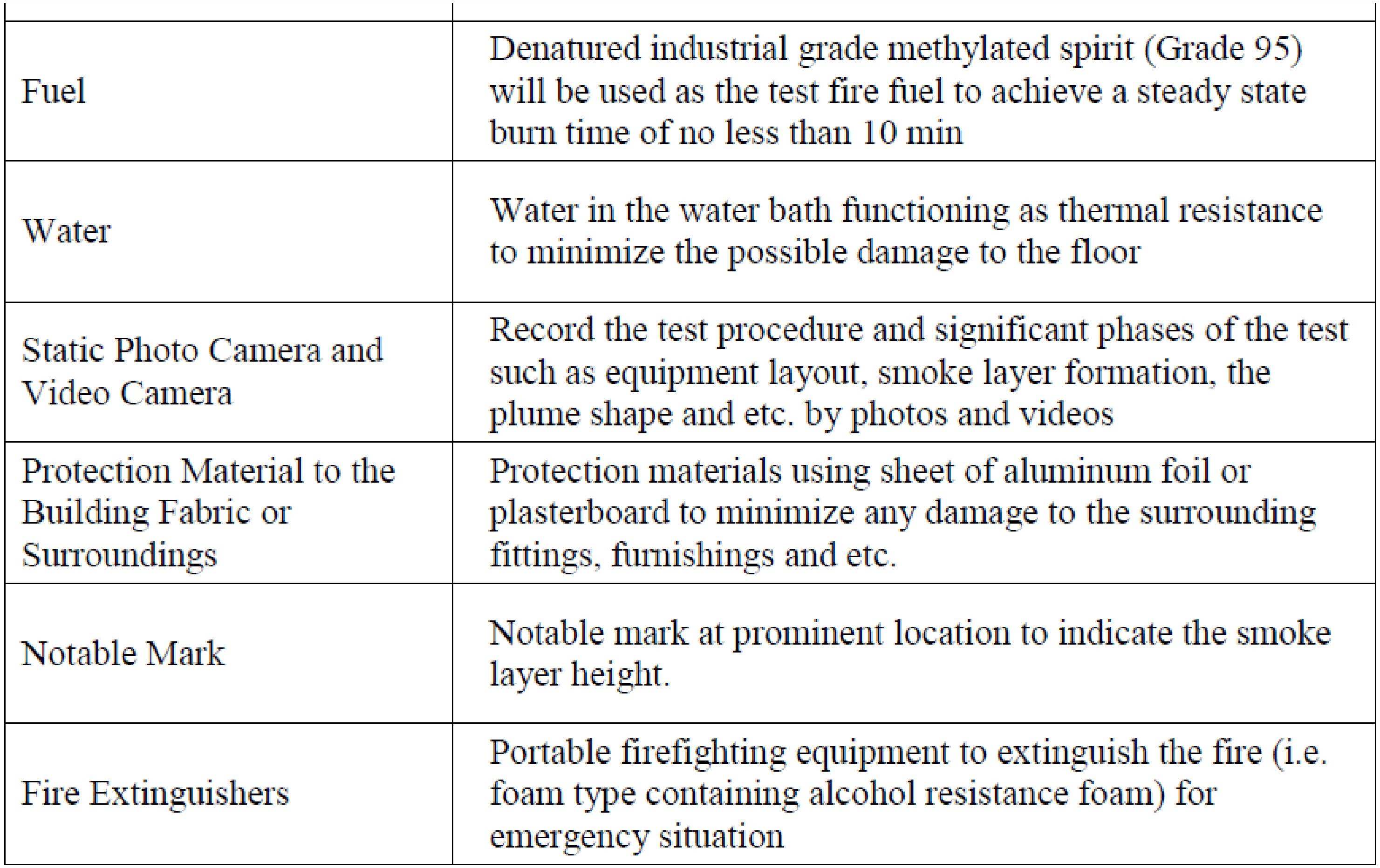
Test apparatus specified in Australian Standard AS 4391-1999, the main test apparatus are listed in table



Item	Description
Non-combustible Base for the Test Fire Location	Protection materials using sheet of aluminum foil or plasterboard to minimize any damage to the floor.
Fire Trays	Steel trays for carrying fuels for hot smoke test
Water Bath	Steel trays for containing water
Heat Sensor to Record the Plume Temperature	Type K thermocouple with an accuracy of ±3°C for temperature measurement
Data Logger	Data recording system with analog module to record the real-time temperature profile on site
Smoke Generator to Produce Trace Smoke	Approved smoke generators to produce non-toxic and white smoke for smoke visualization

Test Standard

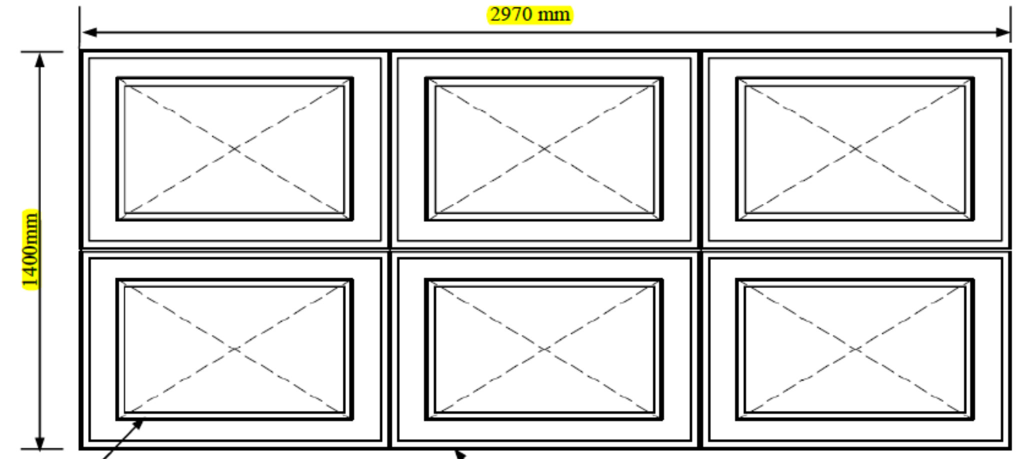
Test apparatus specified in Australian Standard AS 4391-1999, the main test apparatus are listed in table



Fuel	Denatured industrial grade methylated spirit (Grade 95) will be used as the test fire fuel to achieve a steady state burn time of no less than 10 min
Water	Water in the water bath functioning as thermal resistance to minimize the possible damage to the floor
Static Photo Camera and Video Camera	Record the test procedure and significant phases of the test such as equipment layout, smoke layer formation, the plume shape and etc. by photos and videos
Protection Material to the Building Fabric or Surroundings	Protection materials using sheet of aluminum foil or plasterboard to minimize any damage to the surrounding fittings, furnishings and etc.
Notable Mark	Notable mark at prominent location to indicate the smoke layer height.
Fire Extinguishers	Portable firefighting equipment to extinguish the fire (i.e. foam type containing alcohol resistance foam) for emergency situation

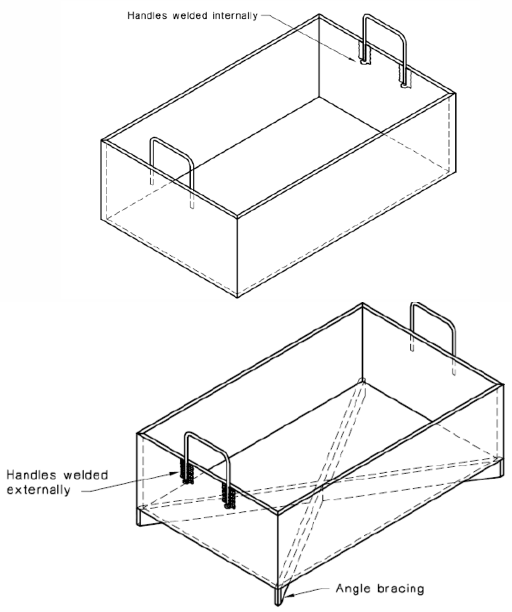
Fire Trays Set-up

Based on the Australian Standard AS 4391-1999 [2], the proposed fire size will be set up by burning the denatured industrial grade methylated spirit (Grade 95) on 6 numbers of A1 size fire trays as illustrated in Figure 5- 4. Each fire tray shall sit on a B1 size water tray. The fire trays shall be all welded-constructed from 1.6mm steel with 10mm diameter steel handles at the outside of the tray wall (See details in Table 5- 1 and Figure 5- 5). The specification of the water tray may refer to Section 5.5.

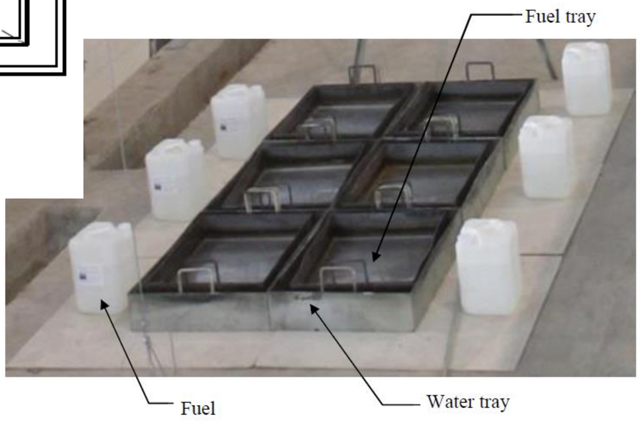


Fire Tray (A1 size)
841mm*595mm*130mm
(Details referred to Section 5.4)

Water Tray (B1 size)
990mm*700mm*180mm
(Details referred to Section 5.5)

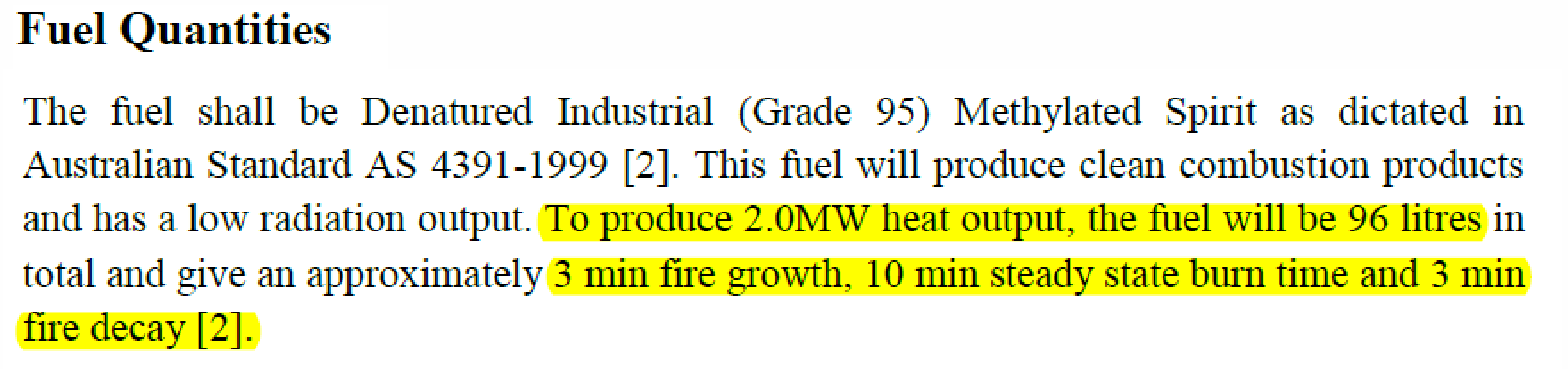


Fill each fire tray with 16 litres methylated spirit



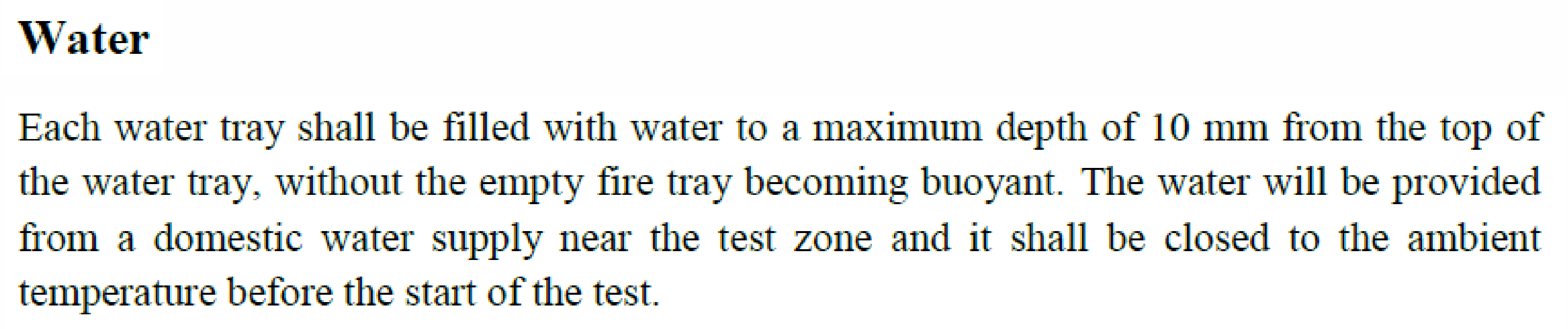
Typical Indicative Set-up of Fuel and Water Trays

Fire Trays Set-up



Fuel Quantities

The fuel shall be Denatured Industrial (Grade 95) Methylated Spirit as dictated in Australian Standard AS 4391-1999 [2]. This fuel will produce clean combustion products and has a low radiation output. To produce 2.0MW heat output, the fuel will be 96 litres in total and give an approximately 3 min fire growth, 10 min steady state burn time and 3 min fire decay [2].



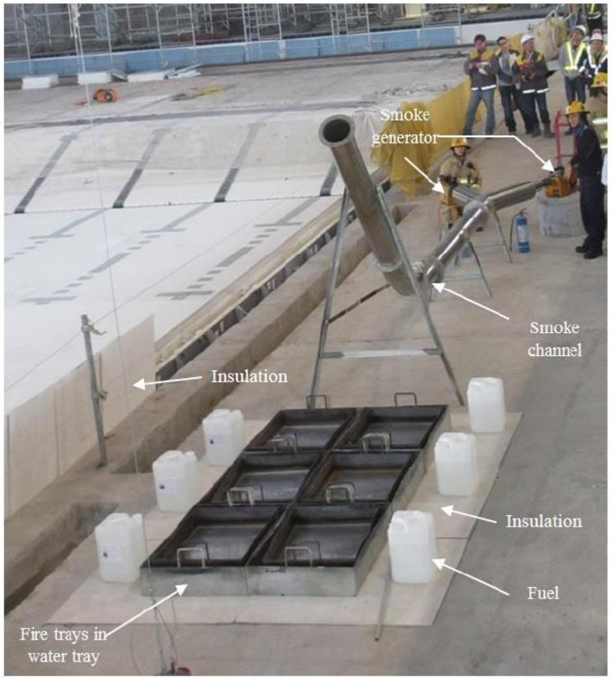
Water

Each water tray shall be filled with water to a maximum depth of 10 mm from the top of the water tray, without the empty fire tray becoming buoyant. The water will be provided from a domestic water supply near the test zone and it shall be closed to the ambient temperature before the start of the test.

Fire Trays Set-up

Metal rod wrapped with cloth at the remote

Typical Indicative of 2m metal rod



Typical Indicative Set-up for Hot Smoke Test

Following gives the tray set-up sequence:

(1) Place the waterproof cover at the centre of the test fire location;

(2) Place the plasterboard above the waterproof cover (i.e. at the centre of the test fire location);

(3) Lay the empty water trays on top of plasterboard;

(4) Place the empty fire trays centrally in the water trays;

(5) Fill the water tray with water until the empty fire tray is about to float;

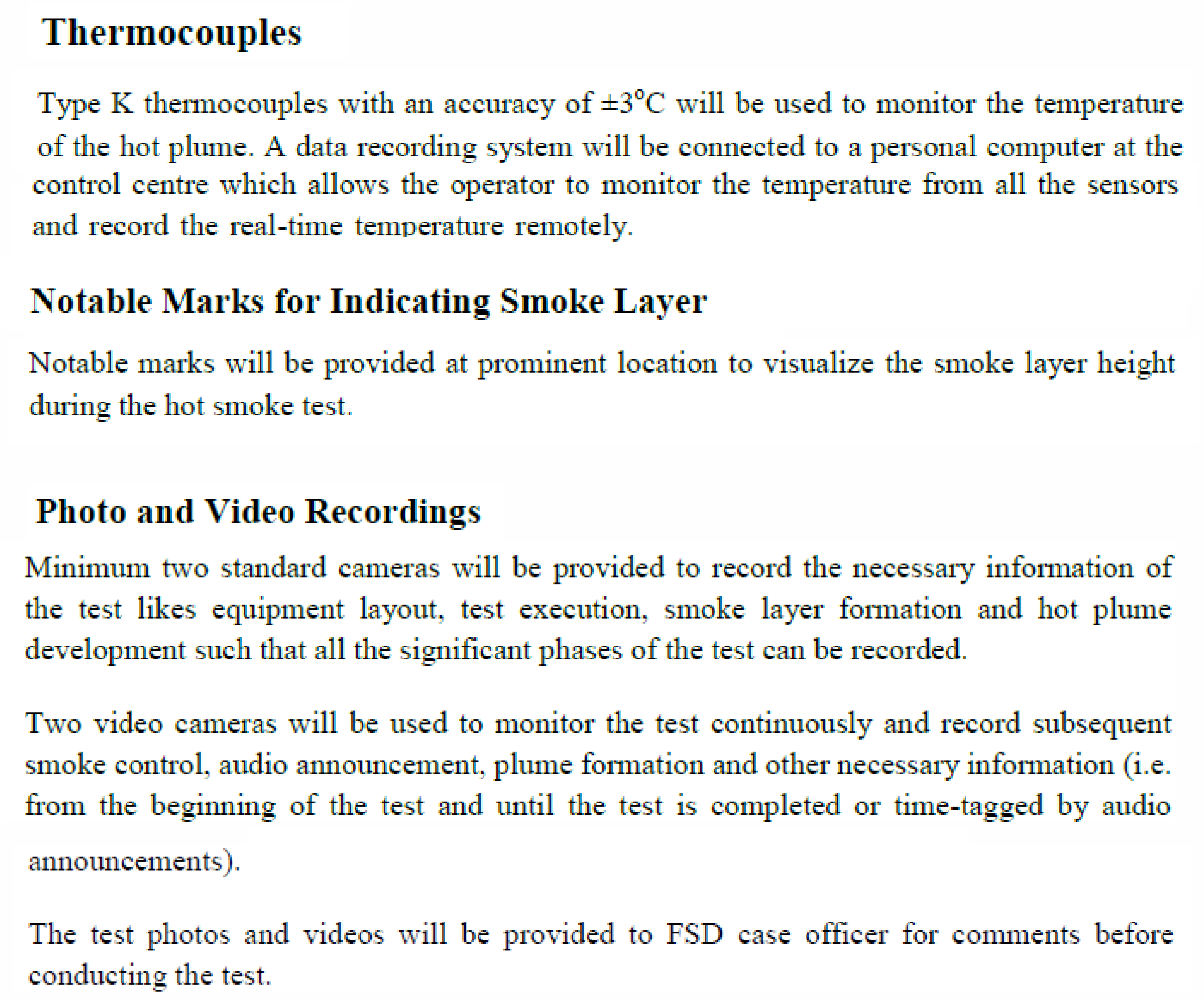
(6) Fill the fire tray with specified fuels;

(7) Insert the engine discharge tube of the smoke generator into the end of the smoke channel.

Tracer Smoke

To visualize the hot plume, the tracer smoke shall be white in colour and leave minimal residue. It is required to be continuously generated at a rate great enough to maintain the total colouring of the plume. Therefore, non-toxic oil based smoke generators will be used to generate the tracer smoke. The smoke will be introduced into the centre of the fire flumes and directed toward the ceiling using a mental duct elbow. The Golden Eagle Pepper Fog Generator (Model No. 3032) will be used to generate the tracer smoke during the test. As illustrated in Figure 5- 8, the engine discharge tube of the smoke generators will be inserted into the two ends of the smoke channel to minimize the emitted radiation to the fire fighters nearby and distribute the smoke to the center of the fire trays. The specification of proposed smoke generator is

Thermocouples



Thermocouples

Type K thermocouples with an accuracy of ±3°C will be used to monitor the temperature of the hot plume. A data recording system will be connected to a personal computer at the control centre which allows the operator to monitor the temperature from all the sensors and record the real-time temperature remotely.

Notable Marks for Indicating Smoke Layer

Notable marks will be provided at prominent location to visualize the smoke layer height during the hot smoke test.

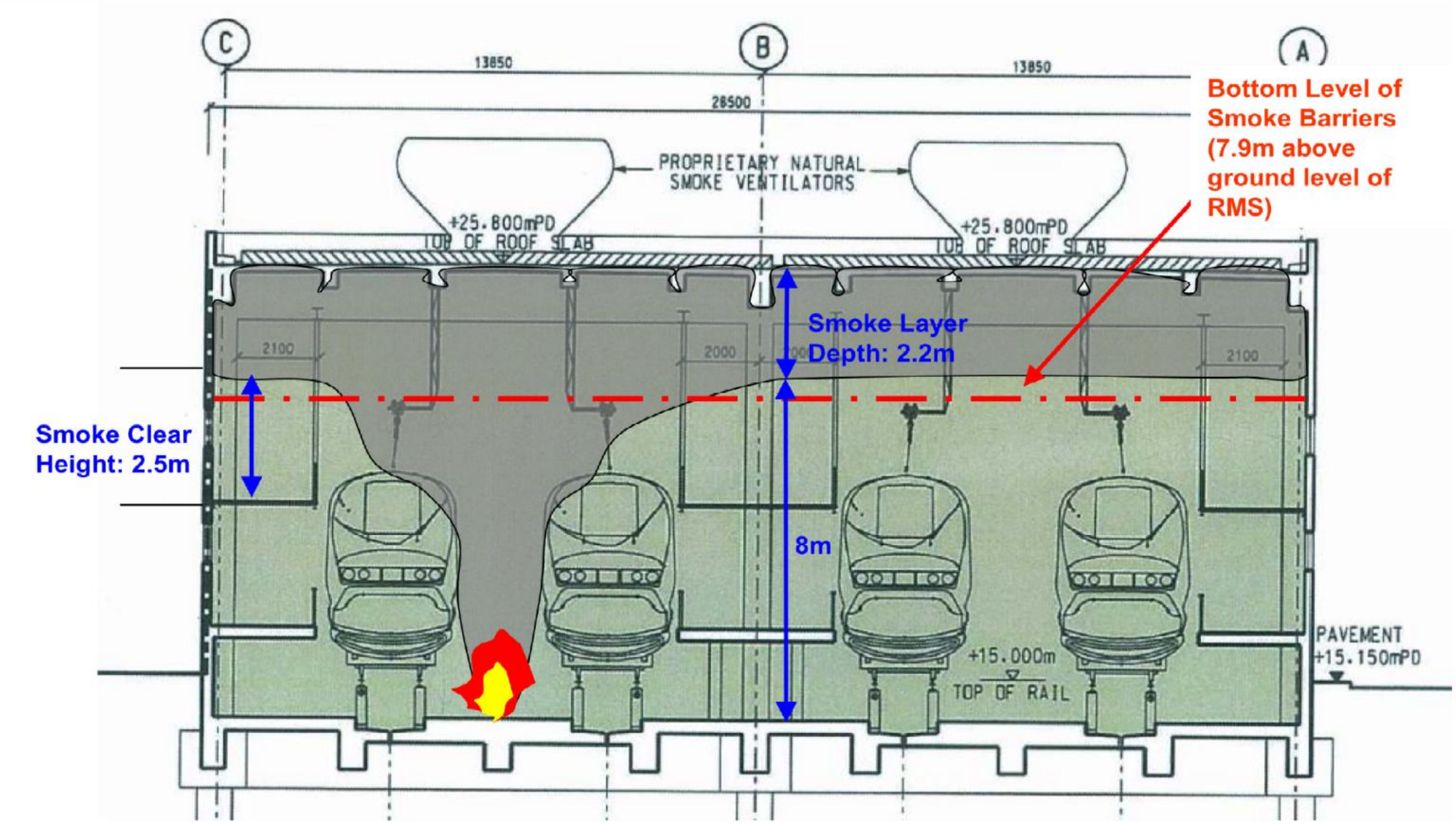
Photo and Video Recordings

Minimum two standard cameras will be provided to record the necessary information of the test likes equipment layout, test execution, smoke layer formation and hot plume development such that all the significant phases of the test can be recorded.

Two video cameras will be used to monitor the test continuously and record subsequent smoke control, audio announcement, plume formation and other necessary information (i.e. from the beginning of the test and until the test is completed or time-tagged by audio announcements).

The test photos and videos will be provided to FSD case officer for comments before conducting the test.

Test Fire Location



Bottom Level of Smoke Barriers (7.9m above ground level of RMS)

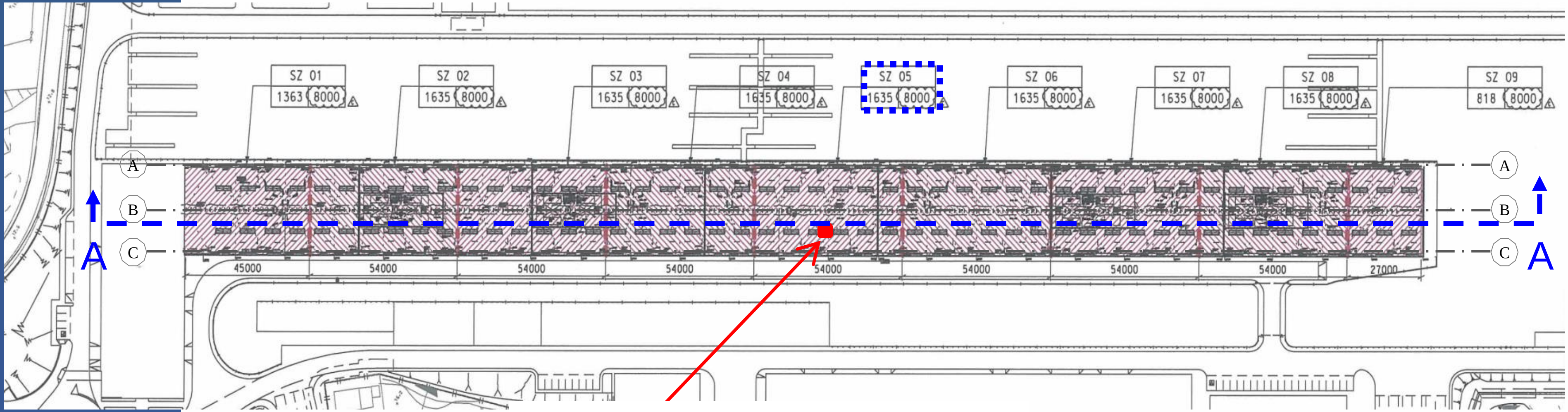
Smoke Layer Depth: 2.2m

Smoke Clear Height: 2.5m

8m

* Refers to the smoke control calculation extracted from Fire Safety Strategy report

Test Fire Location

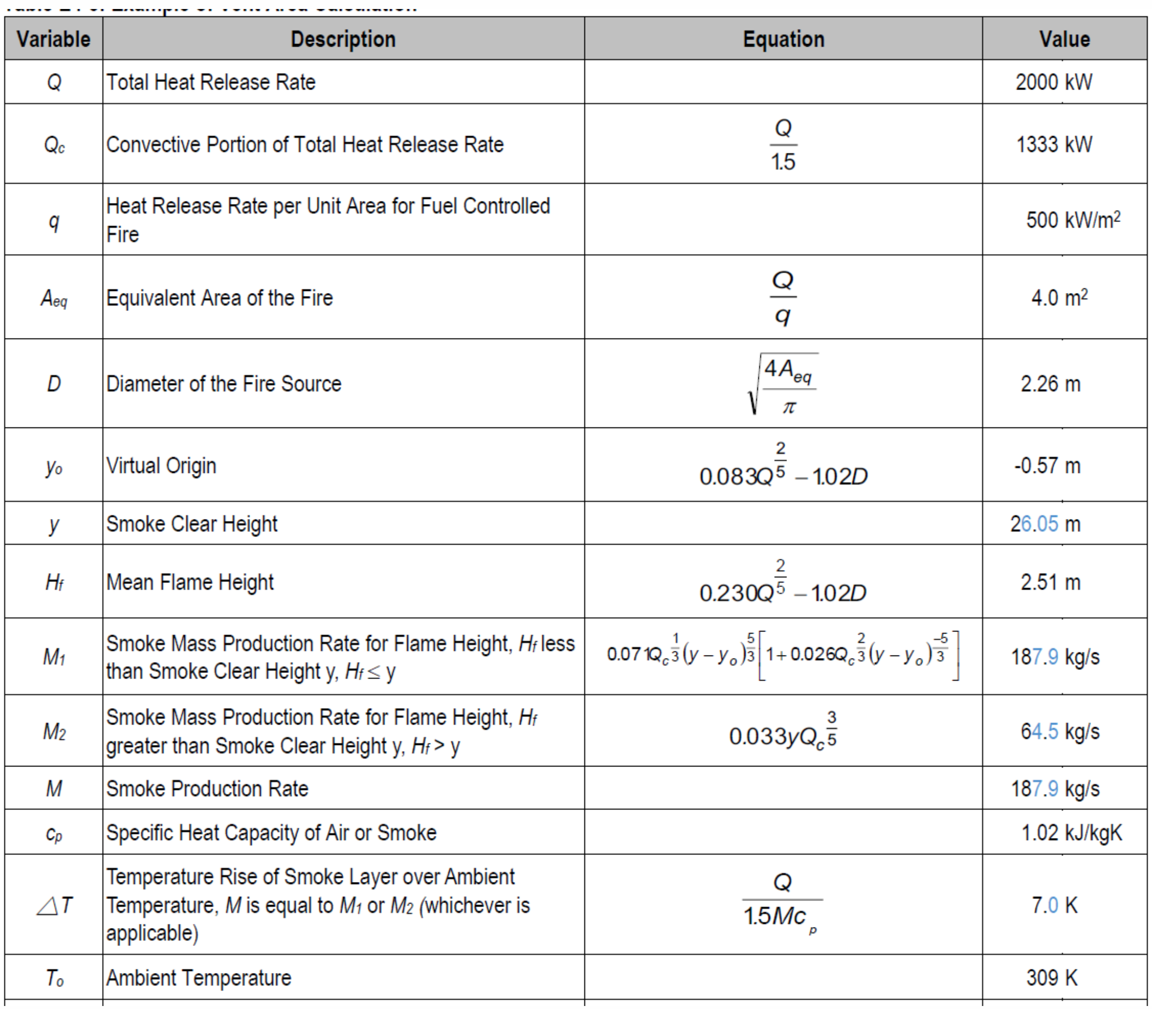


Proposed Test Fire Location

Test Fire Size

- Peak heat release rate of 4MW was adopted in the Fire Safety Strategy Report
- At least 1 MW or such size agreed by FSD is required for the test fire size
- Considering the averaged clear headroom of approximately 11.1m, the test fire size is proposed to be 1.5 MW.
- CFD modelling by FDS ver 6.0 will be employed for the evaluation

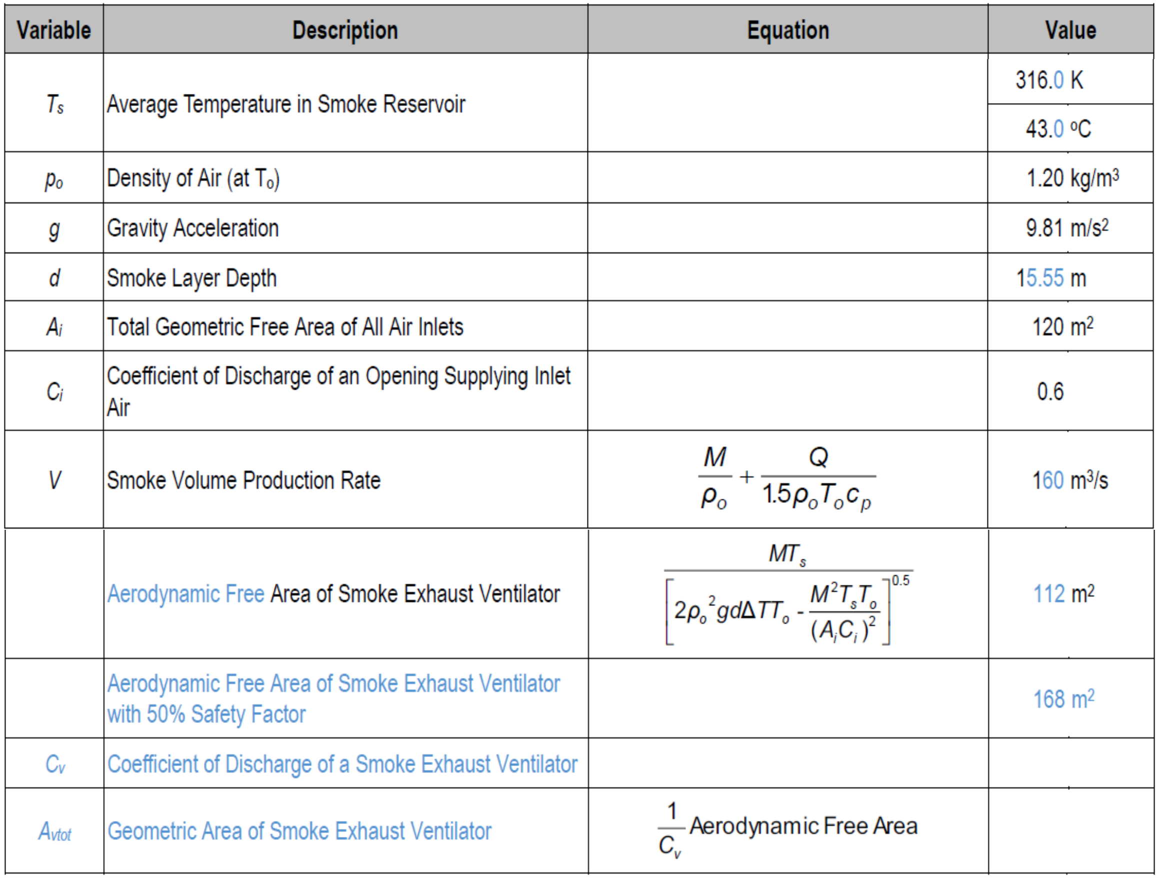
Background – Smoke Vents Calculation



Variable	Description	Equation	Value
Q	Total Heat Release Rate		2000 kW
Q_c	Convective Portion of Total Heat Release Rate	$\frac{Q}{1.5}$	1333 kW
q	Heat Release Rate per Unit Area for Fuel Controlled Fire		500 kW/m^2
A_{eq}	Equivalent Area of the Fire	$\frac{Q}{q}$	4.0 m^2
D	Diameter of the Fire Source	$\sqrt{\frac{4A_{eq}}{\pi}}$	2.26 m
y_o	Virtual Origin	$0.083Q^{\frac{2}{5}}-1.02D$	-0.57 m
y	Smoke Clear Height		26.05 m
H_f	Mean Flame Height	$0.230Q^{\frac{2}{5}}-1.02D$	2.51 m
M_1	Smoke Mass Production Rate for Flame Height, H_f less than Smoke Clear Height y, $H_f \leq y$	$0.071Q_c^{\frac{1}{3}}(y-y_o)^{\frac{5}{3}}\left[1+0.026Q_c^{\frac{2}{3}}(y-y_o)^{\frac{-5}{3}}\right]$	187.9 kg/s
M_2	Smoke Mass Production Rate for Flame Height, H_f greater than Smoke Clear Height y, $H_f > y$	$0.033yQ_c^{\frac{3}{5}}$	64.5 kg/s
M	Smoke Production Rate		187.9 kg/s
c_p	Specific Heat Capacity of Air or Smoke		1.02 kJ/kgK
$\triangle T$	Temperature Rise of Smoke Layer over Ambient Temperature, M is equal to M_1 or M_2 (whichever is applicable)	$\frac{Q}{1.5Mc_p}$	7.0 K
T_o	Ambient Temperature		309 K

The provided total free vent area was about 300 m^2 with the consideration of 50% safety factor

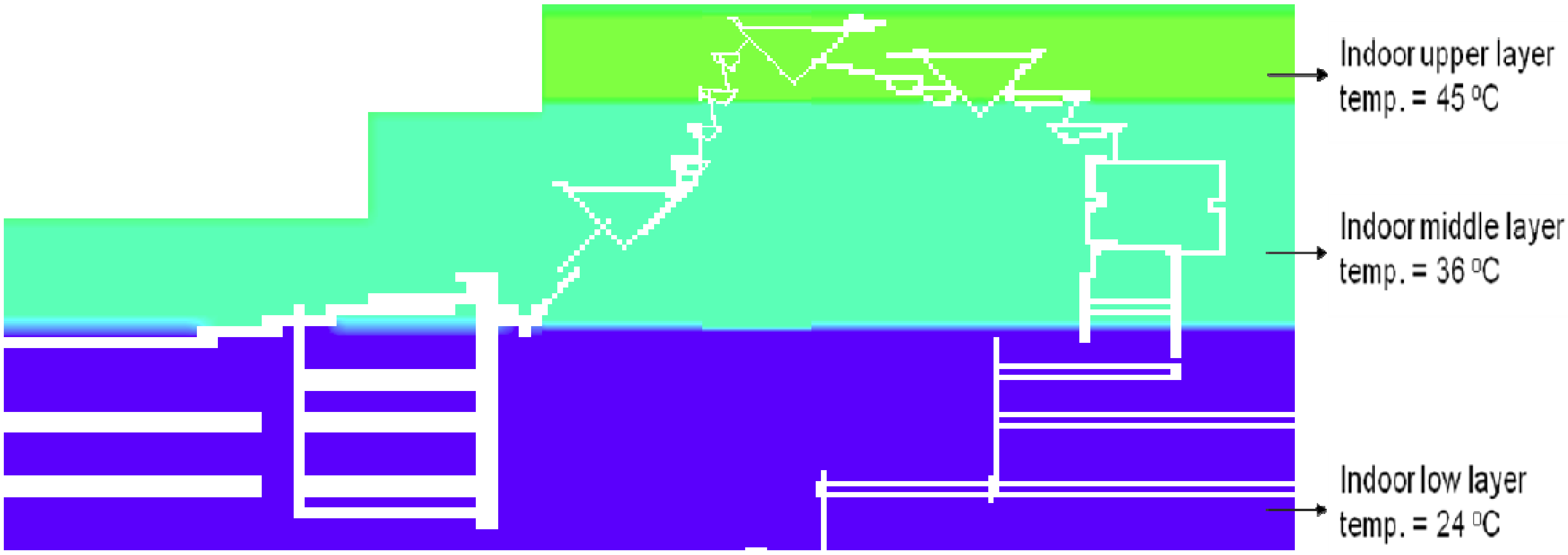
Background – Smoke Vents Calculation



Variable	Description	Equation	Value
T_s	Average Temperature in Smoke Reservoir		316.0 K 43.0 °C
ρ_o	Density of Air (at T_o)		1.20 kg/m^3
g	Gravity Acceleration		9.81 m/s^2
d	Smoke Layer Depth		15.55 m
A_i	Total Geometric Free Area of All Air Inlets		120 m^2
C_i	Coefficient of Discharge of an Opening Supplying Inlet Air		0.6
V	Smoke Volume Production Rate	$\frac{M}{\rho_o} + \frac{Q}{1.5\rho_o T_o c_p}$	160 m^3/s
	Aerodynamic Free Area of Smoke Exhaust Ventilator	$\frac{MT_s}{\left[2\rho_o{}^2 gd\Delta TT_o - \frac{M^2 T_s T_o}{(A_i C_i)^2}\right]^{0.5}}$	112 m^2
	Aerodynamic Free Area of Smoke Exhaust Ventilator with 50% Safety Factor		168 m^2
C_v	Coefficient of Discharge of a Smoke Exhaust Ventilator		
A_{vtot}	Geometric Area of Smoke Exhaust Ventilator	$\frac{1}{C_v}$ Aerodynamic Free Area	

The provided total free vent area was about 300 m^2 with the consideration of 50% safety factor

Hot Summer Day Assumption

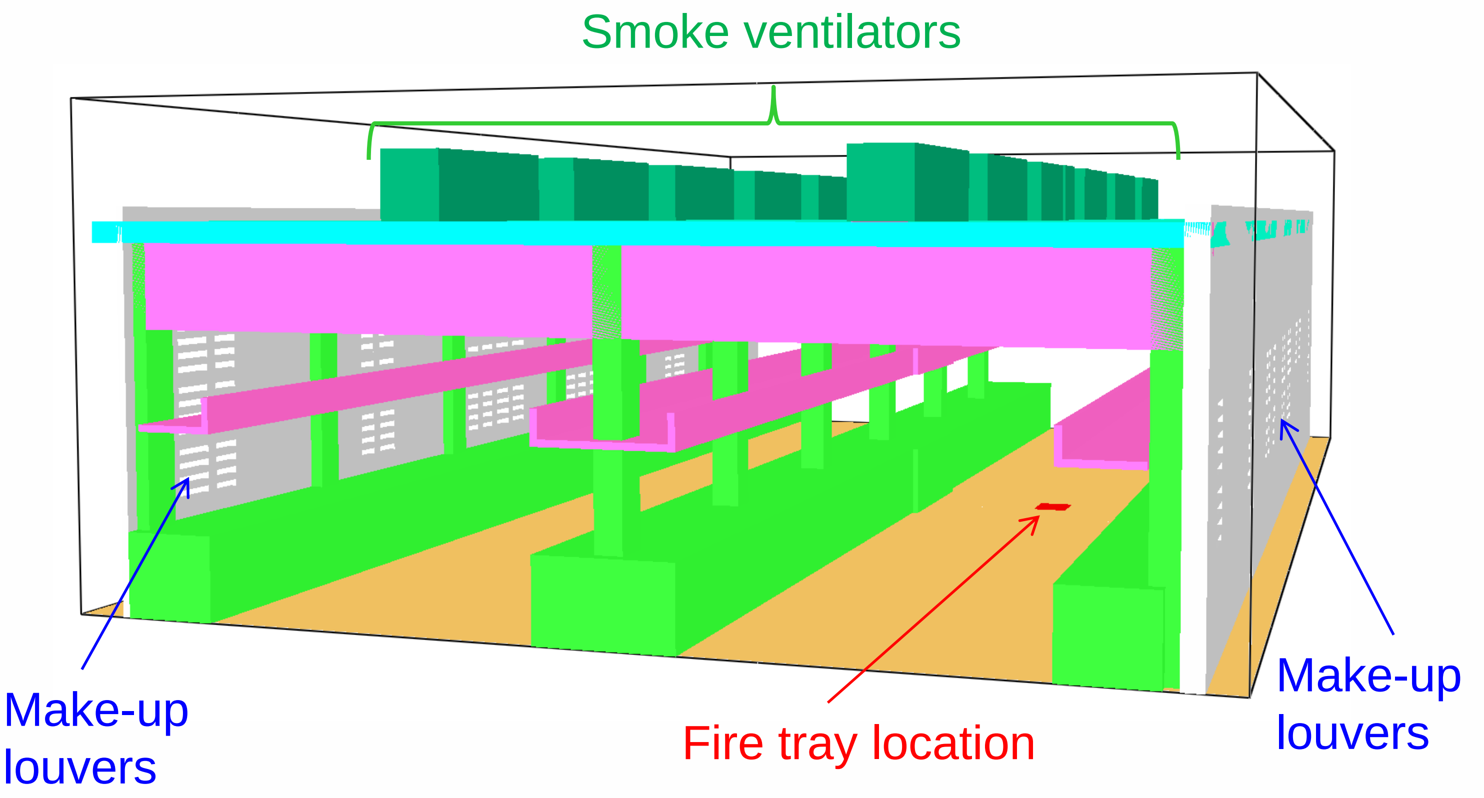


Predicted Plume Temperature based on Table A1 in AS4391

Smoke layer height	**Entrained air**	**6A1**	**4A1**	**2A1**	**A1**	**A2**	**A3**	**A4**	**A5**
m	(°C)	(2MW)	(1.5MW)	(700kW)	(340kW)	(140kW)	(60 kW)	(26kW)	(11kW)
2	10		436	309	221	135	83	56	37
2	20		454	325	234	147	95	67	48
2	30		471	340	248	159	110	77	58
25	10		20	17	15	13	12	11	11
25	20		30	27	25	23	22	21	21
25	30		40	37	35	33	32	31	31
26	**10**	**21.1211**	**19.4**	**16.6**	**14.8**	**12.8**	**11.8**	**11**	**10.8**
26	**20**	**31.1211**	**29.4**	**26.6**	**24.8**	**22.8**	**21.8**	**21**	**20.8**
26	**30**	**41.4735**	**39.6**	**36.6**	**34.8**	**32.8**	**31.8**	**31**	**30.8**
26	**36.1**	**47.7222**	**45.7844**	**42.7**	**40.9**	**38.9**	**37.9**	**37.1**	**36.9**
30	10		17	15	14	12	11	11	10
30	20		27	25	24	22	21	21	20
30	30		38	35	34	32	31	31	30

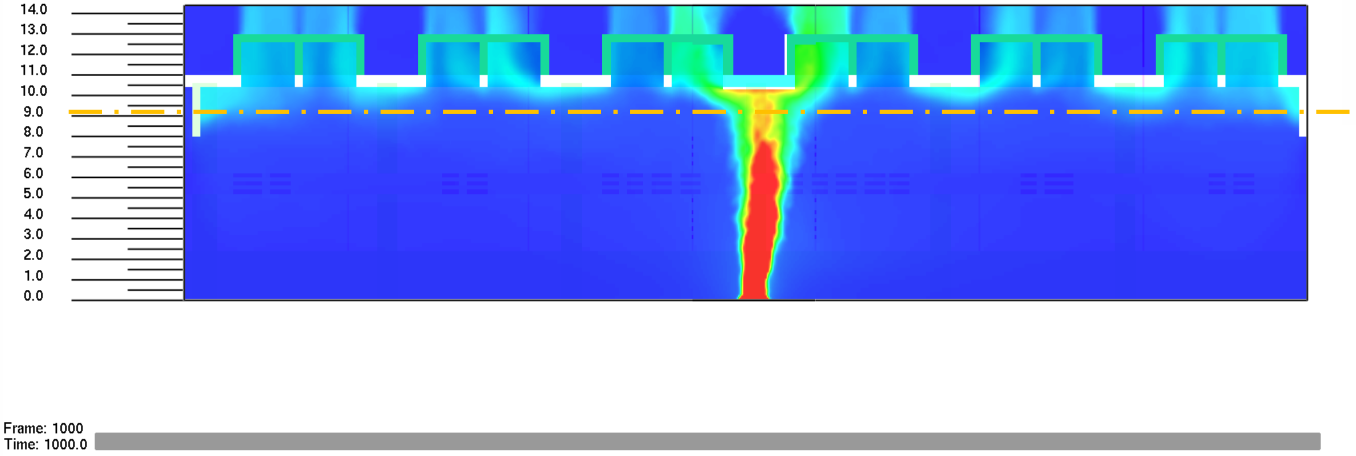
- Extrapolation of the predicted plume temperature given smoke layer height as 26m and ambient temperature at 36.1°C (hot summer day assumed)
- Extrapolation using smoothing spline algorithm

CFD Modelling by FDS v6.0

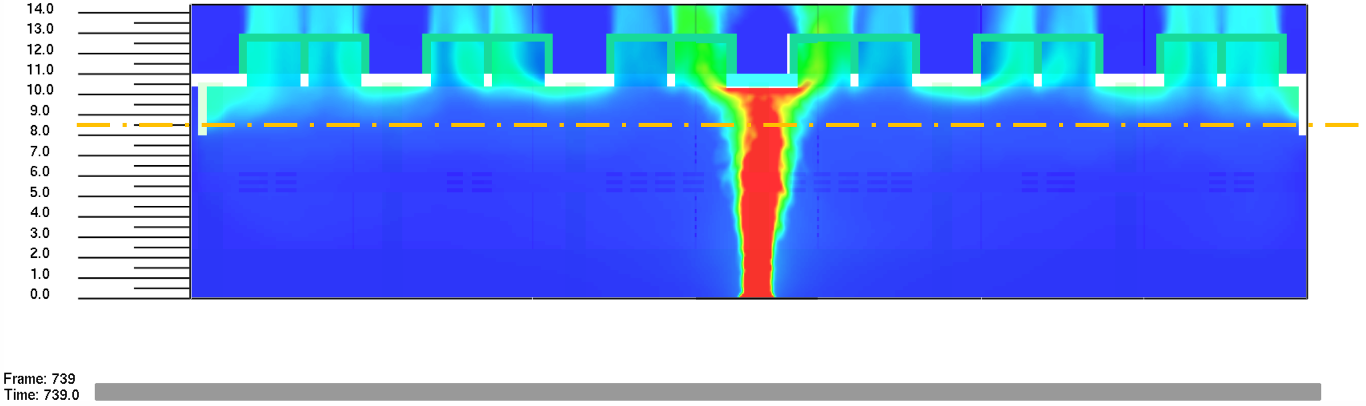


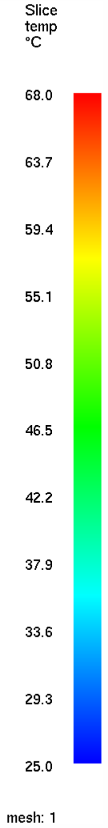
Averaged Temperature Profile (60s averaged)

1.0 MW



1.5 MW

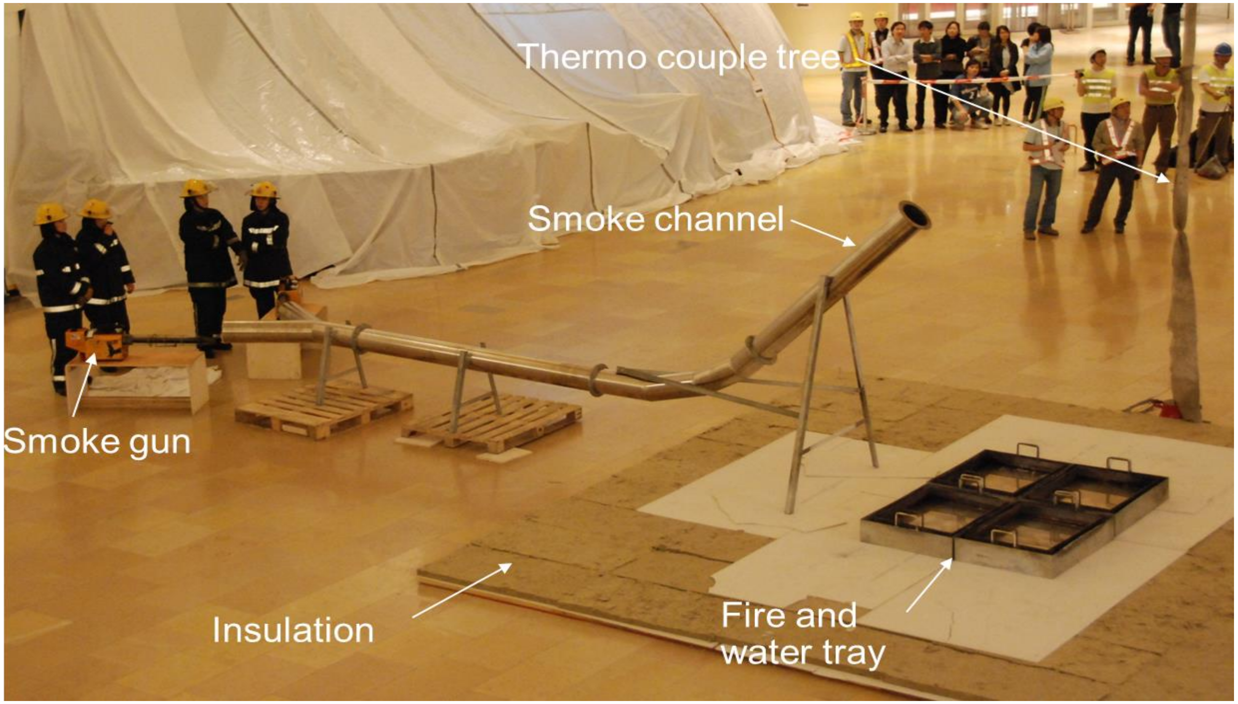




Typical Program for Hot Smoke Test

Task	Tentative Schedule
1. Equipment Set-up and Protection Works	1 day prior to the test date
2. Final Preparation Works	2-3 hours prior to the test date
3. Hot Smoke Test Execution	14:30 – 17:30 (3 hours reserved)
3.1 Briefing to FSD	14:30 – 16:00
3.2 Test Execution	16:00 – 16:30
4. Equipment Removal	After the test

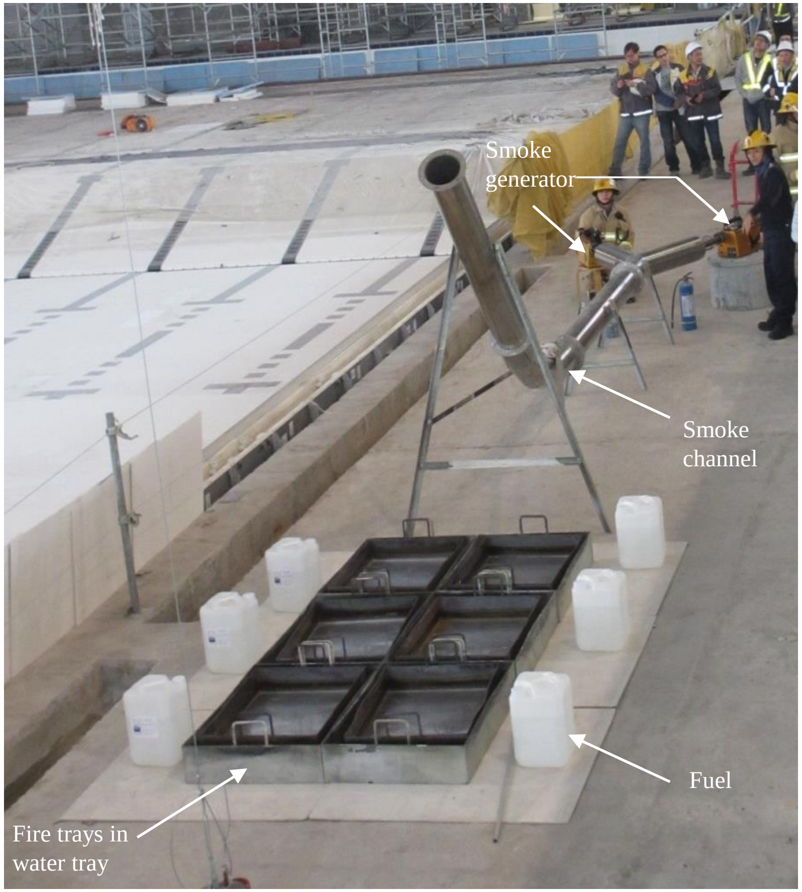
Equipment Set-up by Field Team



Major Equipment Provided by AFP:

- Thermocouples
- Fire/water trays
- Data logger with laptop
- Fire channel
- Marking labels
- Fuels (4×16=64 liters)

Equipment Set-up by Field Team



Ground level

Roof level

ArchFire

Equipment Set-up Supported by Main Contractor

- Provide high reach appliance with operator for thermocouple set-up and labels mounting on walls;
- Provide handcart to move the heavy equipment;
- Provide temporary electric power supply (220V, 13A), working desk and chairs at the control center for data logging test;
- Reserve storage area with appropriate security level for temporary storage of test equipment;
- Reserve DG room (CAT 5) for temporally storage of fuel (4 x 16litre)

Equipment Set-up Supported by Main Contractor

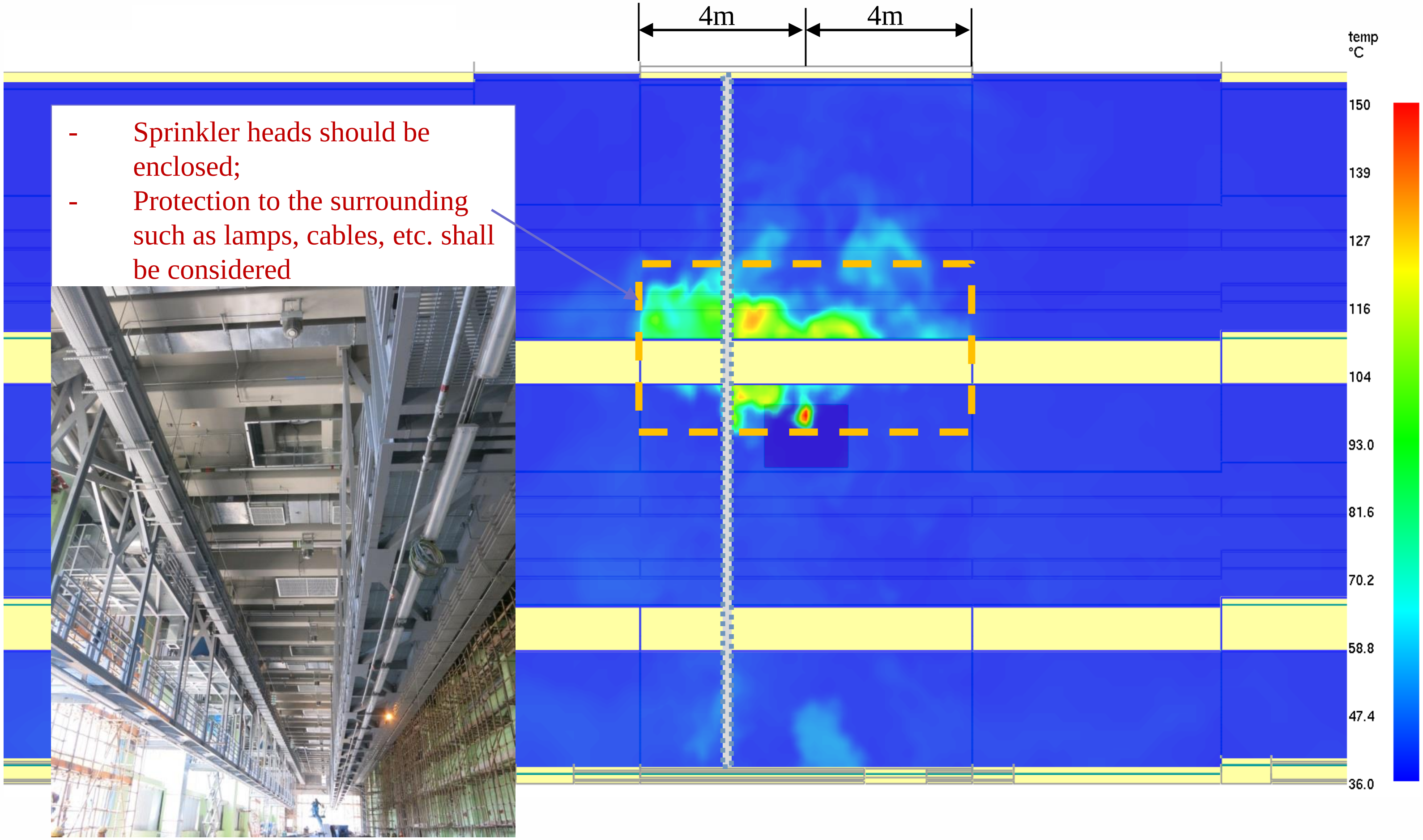
- Ensure all the relevant FSI installations (e.g. detection, alarm, smoke exhaust fans, make-up louver, etc.) have been finished as design;
- Provide insulation protection by 20mm Promat Supalux board or aluminum foil, etc. to protect the floor and/or surroundings where is necessary;
- Protect overhead all lightings, sprinkler heads and exposed cables nearby;
- Remove the combustible construction materials and rubbishes;
- Isolate the area for hot smoke test

Protection Works to Surroundings

Promat board to protect the building fabric close to the fire tray (Insulation protection)

High temperature fiberglass to protect the lamps/cables which might be affected by the smoke plume.

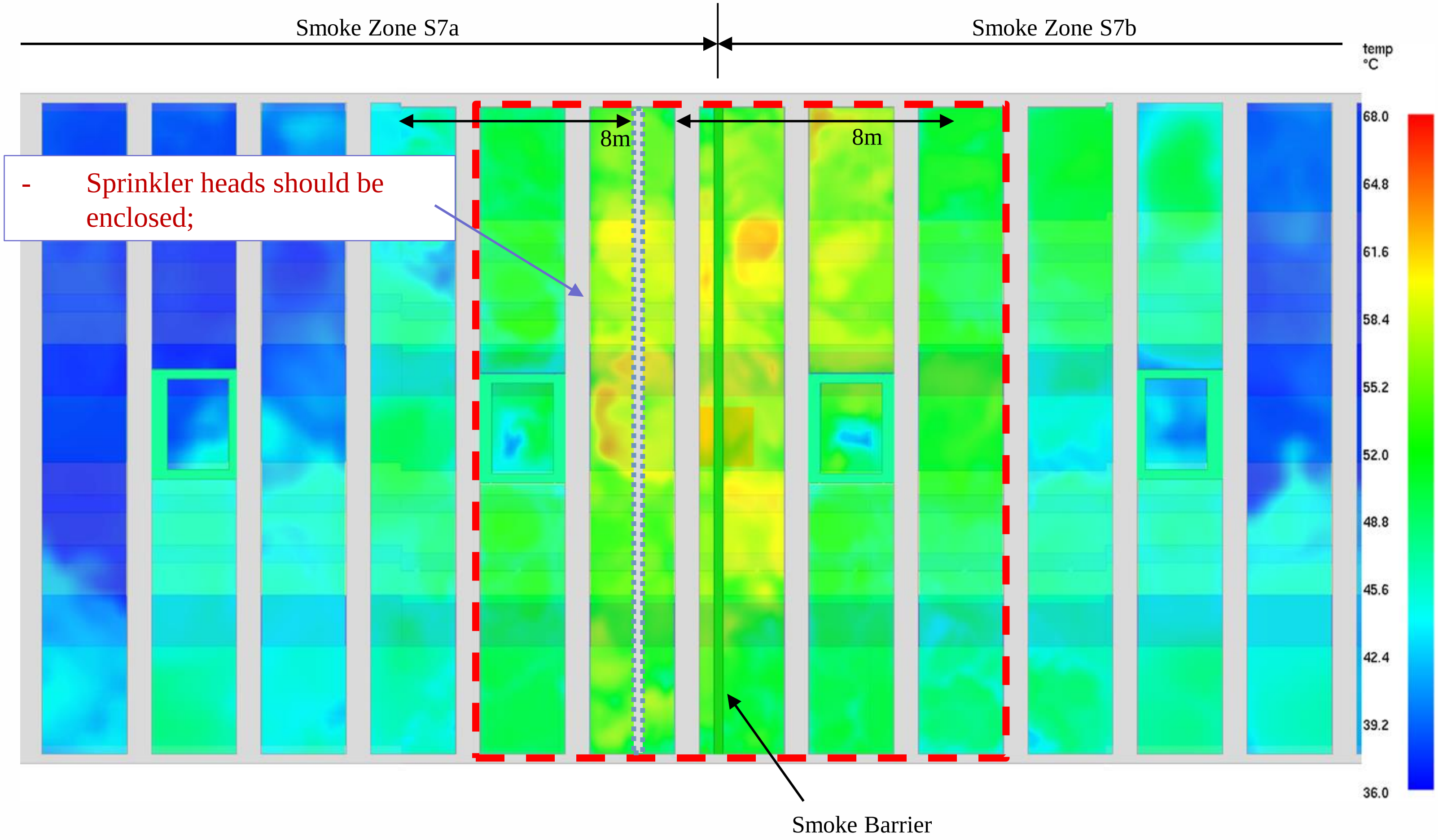
Protection Works to Surroundings



- Sprinkler heads should be enclosed;
- Protection to the surrounding such as lamps, cables, etc. shall be considered

M/F

Protection Works to Surroundings



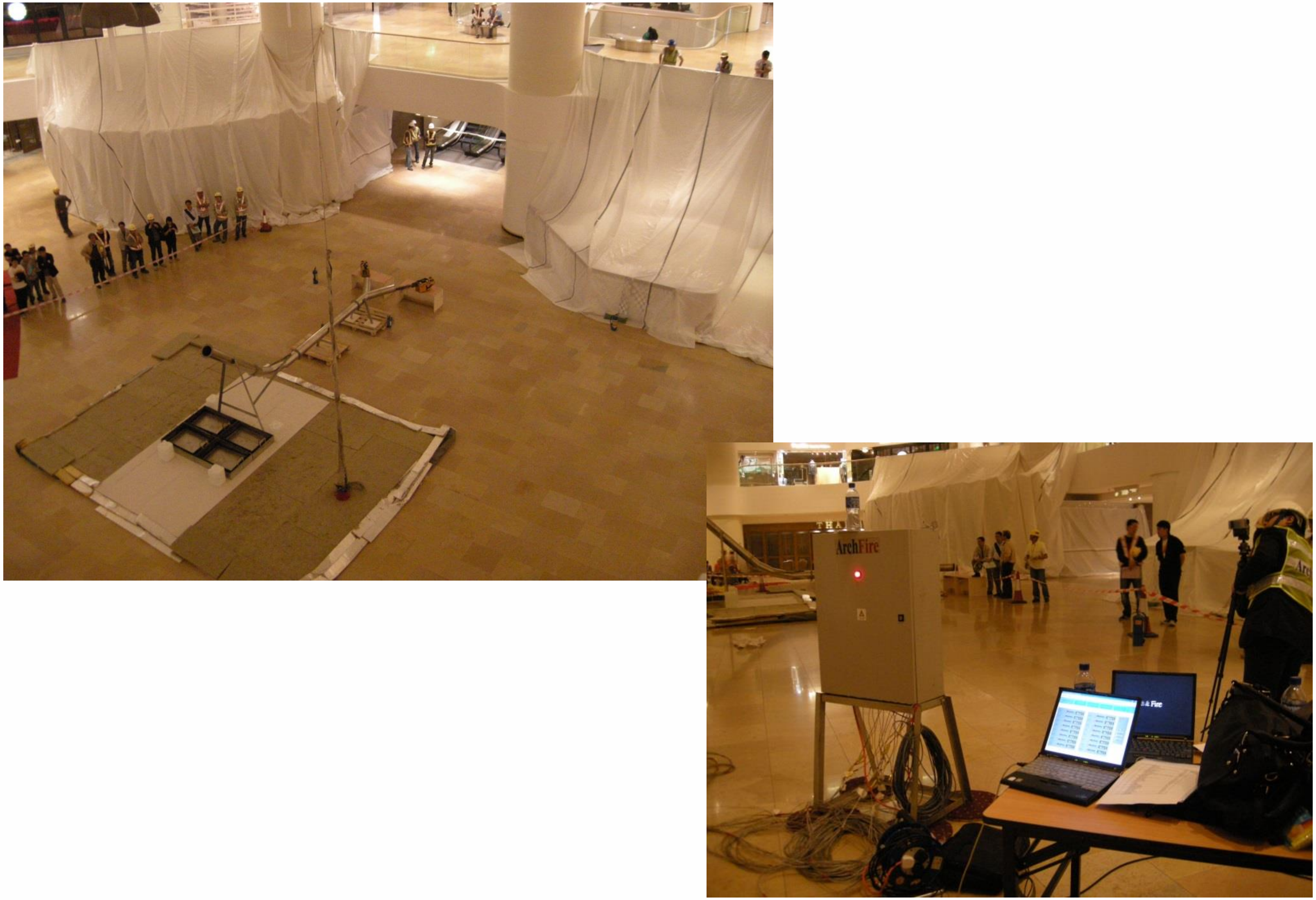
- Sprinkler heads should be enclosed;

R/F

Final Set-up of Equipment

- Set-up the water trays, fire trays and smoke channel;
- Set-up the control center for data-logging;
- Set-up the video/photo camera;
- Synchronize the time of all the equipment and the fire control panel

Final Set-up of Equipment



Final Set-up of Equipment

- Temporarily suspend the sprinkler heads near the test location;
- Provide adequate walkie to communicate between the test site and the fire control center;
- Provide 4 no. of foam fire extinguishers containing alcohol-resistant foam at the corner of the fire tray;
- Provide temporary electric power supply(220V, 13A), working desk and chairs at the control center for data logging on site;
- Provide portable water for filling up water trays;
- Provide 2 no. of stands/seats to support the smoke generators for the convenience of fire fighters.
- Stop the ventilation system;
- Ensure water supply from building fire hydrant is ready;
- Keep clear of the Emergency Vehicle Access (EVA) and exit routes;
- Assign staff to monitor the fire control panel. In case of signal failure, the smoke exhaust fans should be opened manually;
- Clear the obstacles/rubbish on floor;
- Isolate the area for hot smoke test by fencing/barrier

Test Briefing to FSD

- Assign personnel to lead firemen to arrive the site
- Assign responsible person to explain the smoke management system to FSD
- Assist the fire fighters to connect the building fire hydrant/nearest street fire hydrant and F.S. inlet
- Assign safety officer to standby for emergency management
- Brief the set-up of hot smoke test and operation procedure to FSD
- Assist the fire fighters to set up the smoke generators

Test Execution

- Ignite the test fuel;
- Record the real-time temperature profile by data-logging system;
- Take video/photo recording;
- Record the smoke layer height.
- Monitor the fire control panel and record any failures in the smoke control system;
- Record the activation time of smoke detectors, fire alarm and smoke exhaust fans by fire control panel;
- Safety officer to assist the evacuation in case of emergency

Test Execution

After Test Execution

Remove all the test equipment

- Provide high reach appliance for thermocouple removal;
- Reserve storage area with appropriate security level for temporary storage of test equipment if required;
- Clear the test area
- Prepare Video and Photo Record

- Q & A -

jason@afp.com.hk for further queries

- THE END -