Active and passive fire protection in tunnels

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Motivation

- Fire in tunnels can cause loss of life, damage to assets and disruption to traffic.
- Passive and active fire protection can reduce the risk levels in tunnels.
- What are the latest recent research findings and project designs for tunnel fire protection?

Contents

- Recent Tunnel Fires
- UK Road Tunnel Context
- LTA Fire Suppression Tests
- Passive Fire Protection to Tunnels

Recent Tunnel Fires

Bryglas Tunnel Fire, South Wales

- 26th July 2011
- Lorry fire in westbound tunnel tube
- Severe traffic disruption for 4 days
- Extensive clean-up and repairs required

Simplon Rail Tunnel Fire

- 9th June 2011
- Fire on goods train, 3 km from Italian portal
- Fire spread to 10 other goods carriages
- Damage to tunnel and rail infrastructure
- Severe traffic disruption

Østfold - Hurum Fjord Tunnel, Oslo

- 24th June 2011
- Truck fire
- Fire brigade needed to evacuate tunnel
- Five persons treated for smoke inhalation

Key Issues from Real Tunnel Fires

- Life safety – for tunnel users and emergency responders
- Traffic disruption – impact on local, regional and national economy
- Tunnel damage – structure and installations
- Secondary impacts – toll collection, diversion routes, reputation

UK Road Tunnel Context

Legislation

- EU Directive 2004/54/EC on Road Tunnel Safety
- Transposed into UK legislation by the Road Tunnel Safety Regulations 2007
- Deadline of 29 April 2014 for implementation of safety improvements
- Risk analysis required for innovative approaches
- No explicit requirement for any fire suppression systems

Recent UK Tunnel Projects

- New Tyne Crossing: first fire suppression system installed in UK road tunnel; decision based on a cost/benefit analysis
- Dartford Tunnels: high-pressure mist system installed
- A3 Hindhead Tunnel: capability for future fire suppression system installed
- A55 Conwy Tunnel: passive fire protection contractor selected

LTA Fire Suppression Tests

Research Programme

- Funded by the Land Transport Authority in Singapore
- Life safety and structural fire protection benefits of fire suppression
- Consideration of "compensation effects"
- Both large-scale tunnel tests and laboratory-scale tests undertaken

Fire Suppression Research undertaken by

F Tarada
Mosen Ltd

A D Lemaire, L M Noordijk
Efectis Nederland BV

M K Cheong, W O Cheong, K W Leong
Land Transport Authority of Singapore

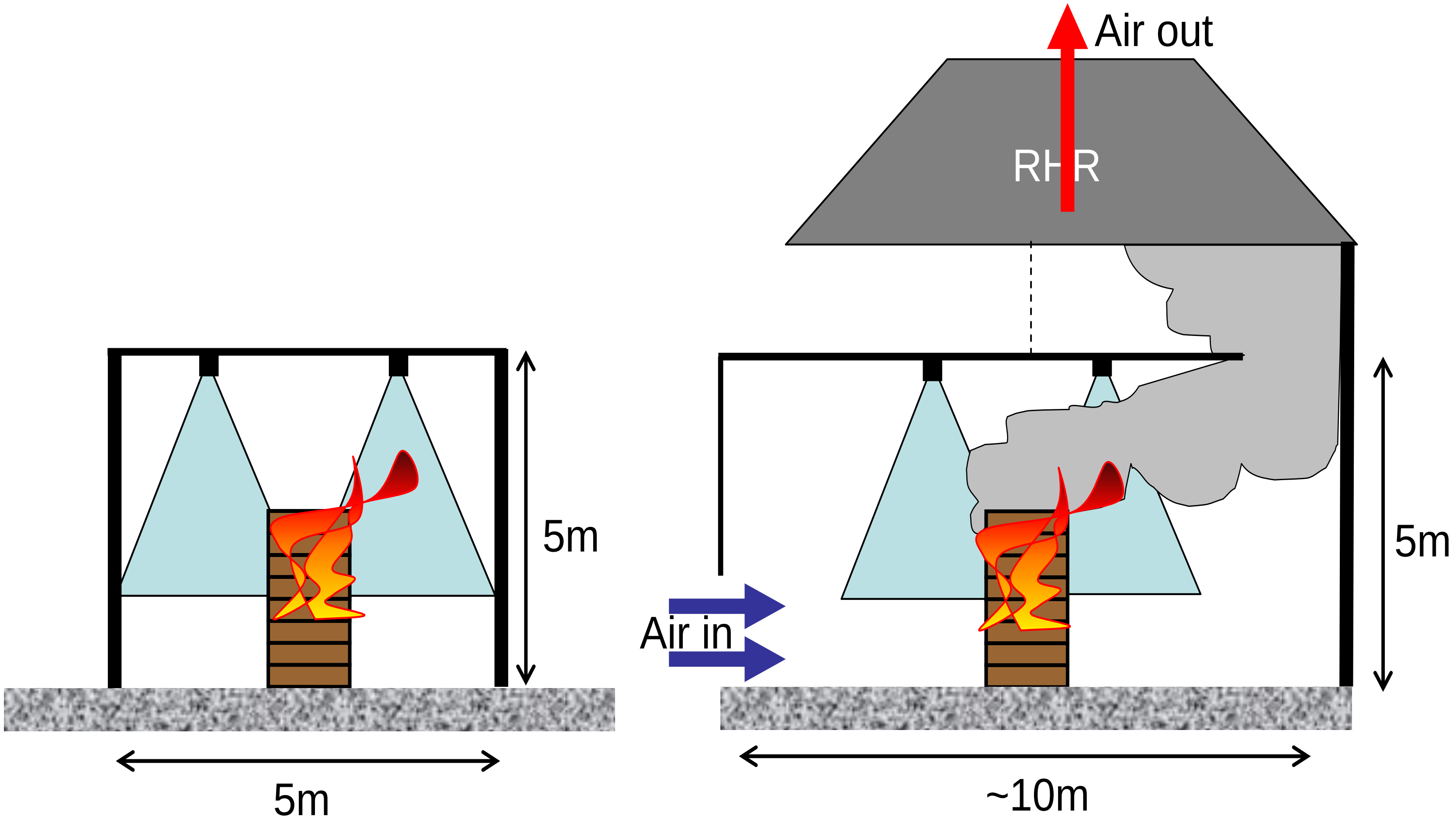
Reduced-Scale Fire Tests

Reduced-Scale Fire Tests

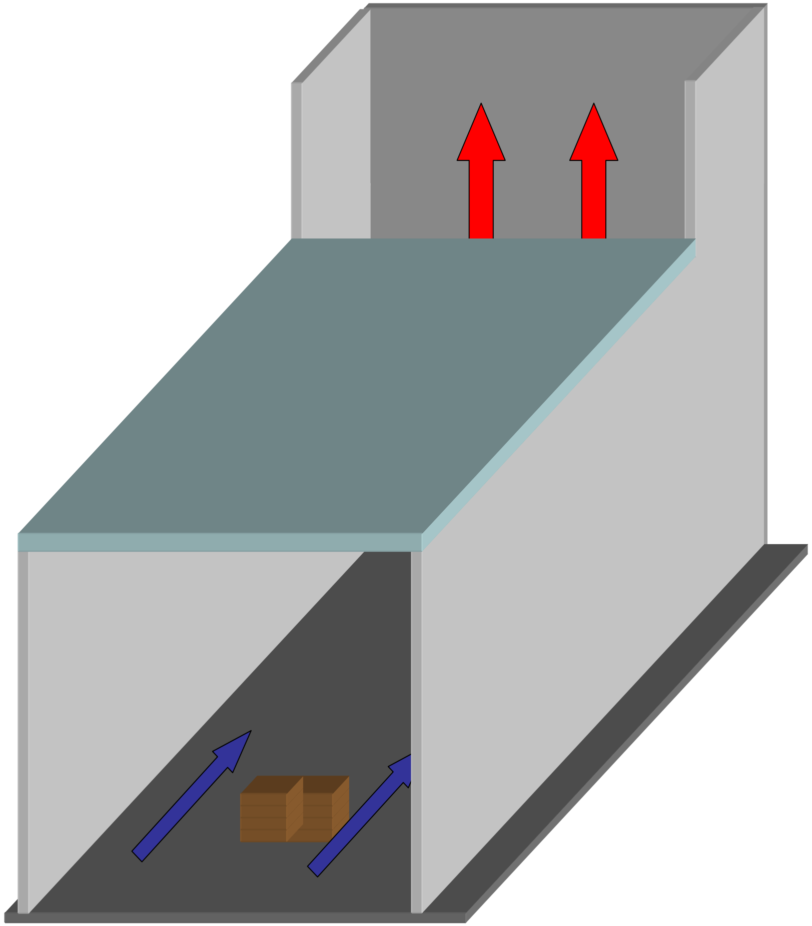
Objective:

- To gain additional understanding regarding the energy budget in suppressed tunnel fires

Test Set-Up



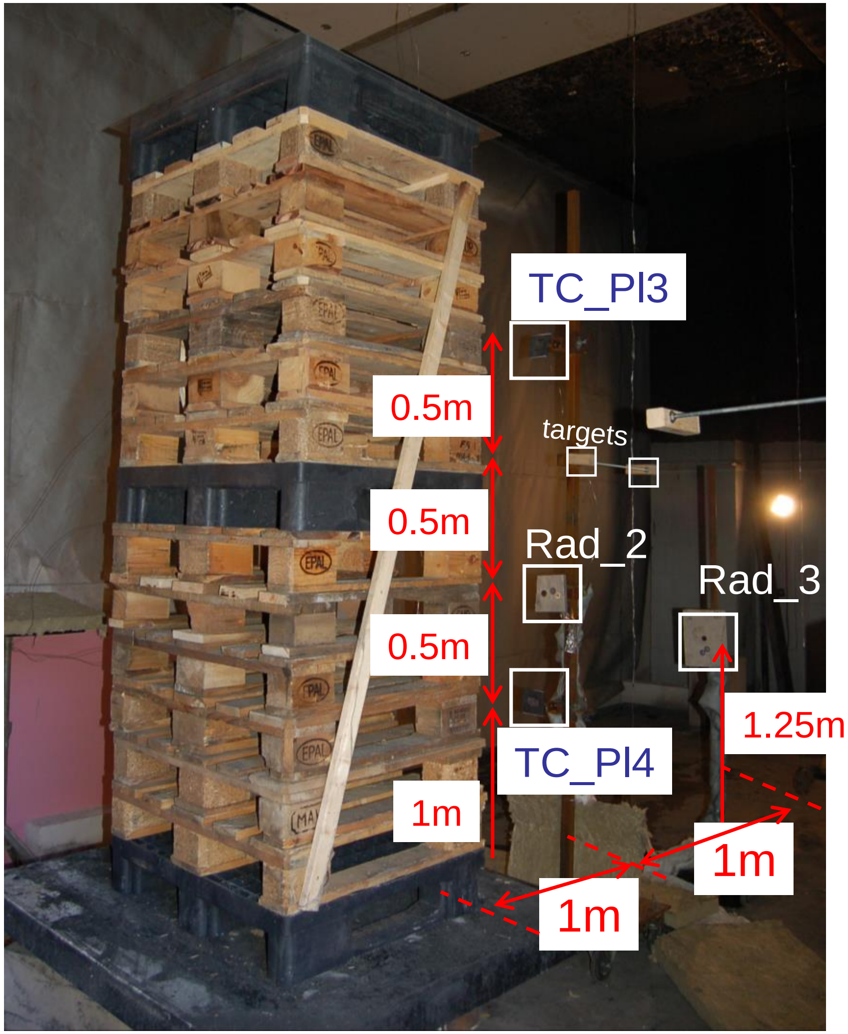
Test Set-Up



Fuel Type and Stacking

- 80% cellulosic (wooden) to 20% plastic pallets
- Pallet stack height: 3m
- Top of the pallet stack 2m below the sprinkler nozzles
- Early collapse of the pallet stack was prevented by fixing wooden strips to the pallet stack
- 1mm thick aluminium plate used to shield top of stack in some cases

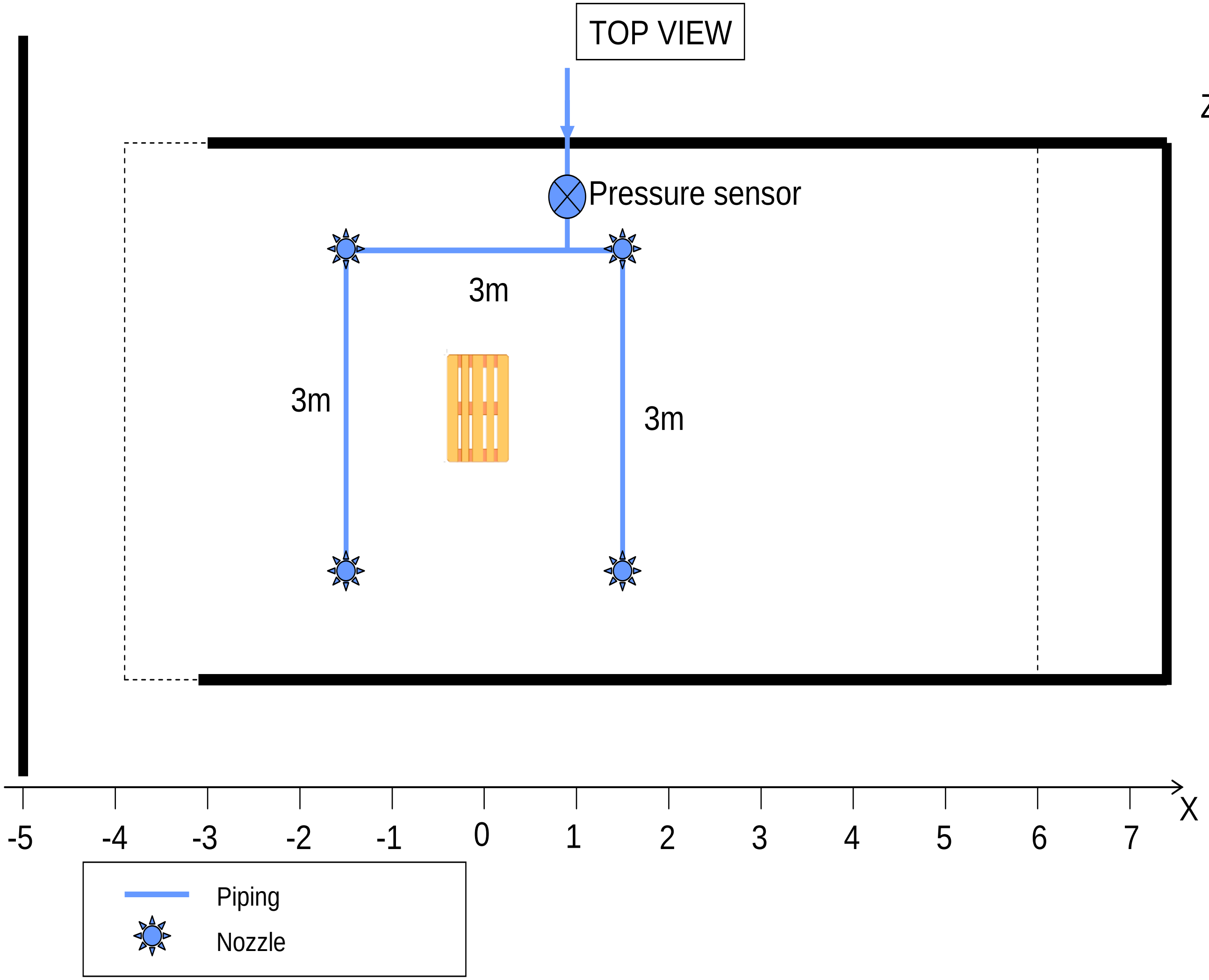
Fuel Stack



Fire Suppression System

- 4 nozzles in the ceiling for all tests
- The nozzles were installed in a 3m x 3m grid around the fire source
- Nominal water densities of 8 and 12 mm/min
- Standard and directional (110°, 180°) nozzles
- Activation time from 4 to 13 minutes

Nozzle Locations



Fire Tests

Test no.	Nozzle type	Discharge density (mm/min)	Activation at	# Pallets	Fire load shielding
0 (pre)	Standard	7	13 min	10 full width	Uncovered
1	Standard	11.2	Max HRR (6 min, 45 min)	19 full width	Uncovered
2	-	-	-	15 partial width	Covered
3	-	-	-	15 partial width	Uncovered
4	Dir. 180°	12.2	Max HRR (6 min)	15 partial width	Covered
5	Dir. 180°	12.2	Max HRR (6 min)	15 partial width	Uncovered
6	Dir. 180°	7.9	Max HRR (9 min 18 min)	15 partial width	Covered
7	Dir. 180°	7.9	4 min	15 partial width	Covered
8	Standard	7.9	4 min	15 partial width	Covered
9	Standard	7.9	Max HRR (8min 32s)	15 partial width	Covered
10	Dir. 110°	7.9	4 min	15 partial width	Covered
11	Dir. 180°	12.0	4 min	15 partial width	Covered

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Heat Release Rate

Measured using oxygen depletion factor:

$$\phi = \frac{X_{O_2}^{A^0}(1 - X_{CO_2}^{A}) - X_{O_2}^{A}(1 - X_{CO_2}^{A^0})}{X_{O_2}^{A^0}(1 - X_{O_2}^{A} - X_{CO_2}^{A})}$$

$$\dot{q} = \frac{\Delta H_c}{r_0} 1.1C \sqrt{\frac{\Delta p}{T_e}} \left(\frac{\phi}{1 - 1.105\phi}\right) X_{O_2}^{0}$$

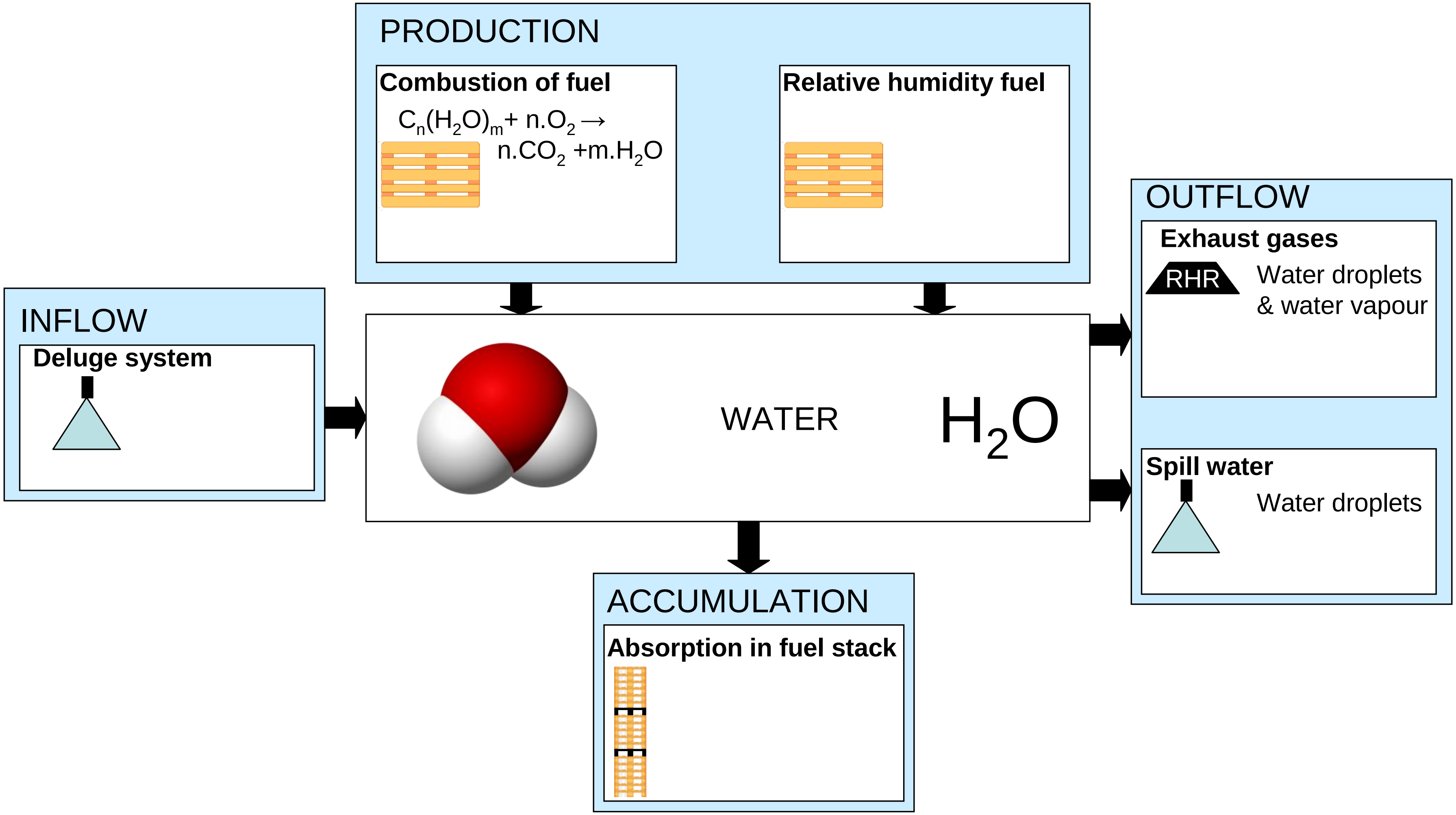
Mass Loss

- Pallet stack was placed on a balance
- Mass loss and the absorbed water from the fire suppression system measured

Water Flowrates and Temperatures

- Flow rate, temperature and pressure of the suppression system are measured in the piping
- Water temperatures in the basin are measured at two locations, about 1m and 2m downstream of the fire

Water Balance



PRODUCTION

Combustion of fuel

$C_n(H_2O)_m + n.O_2 \rightarrow n.CO_2 + m.H_2O$

Relative humidity fuel

INFLOW

Deluge system

WATER

H_2O

OUTFLOW

Exhaust gases

RHR

Water droplets & water vapour

Spill water

Water droplets

ACCUMULATION

Absorption in fuel stack

Moisture Content of Fuel

- Mass and volume of fuel determined by drying it to evaporate all water from the sample.
- Result showed a moisture content of the fuel samples of 12% to 17%.

Water Inflow

- The inaccuracy of the water inflow is estimated to be less than 1% due to the high accuracy of the measurement device
- Allowances were made for the water vapour in the inflowing air

Water Production

- Water produced as a product of combustion
- Estimated through a proportion of the consumed oxygen mass
- Corrections made for the water evaporated from the unburnt fuel, calibrated using the free burning tests

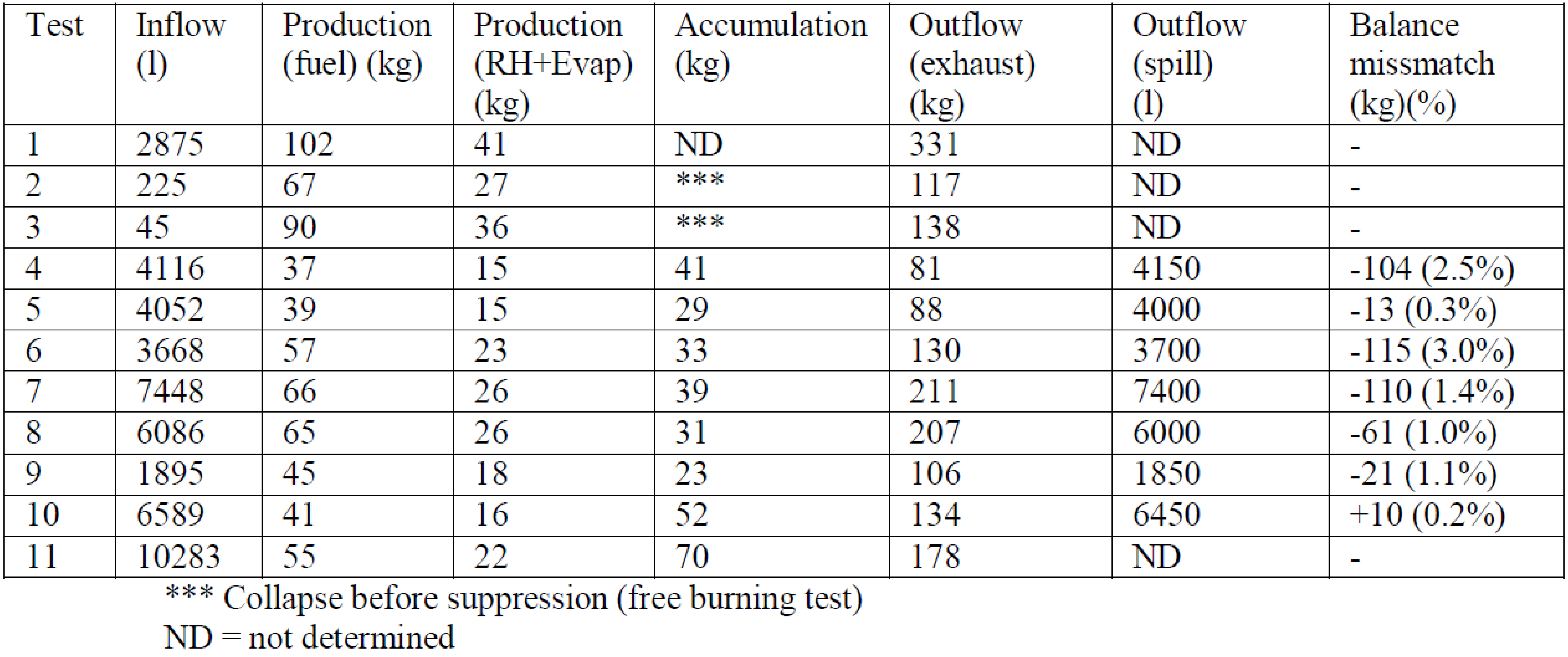
Water Accumulation

- Estimated from the “theoretical” mass of fuel burnt and the mass loss measurements.
- Corrections applied in case of stack collapse.

Water Outflow

- Measured using the moisture content, temperature and humidity of the exhaust gases.
- Correction made for the humidity of the incoming air.
- Contribution of spill water estimated through measurements of water levels.

Water Balance



Test	Inflow (l)	Production (fuel) (kg)	Production (RH+Evap) (kg)	Accumulation (kg)	Outflow (exhaust) (kg)	Outflow (spill) (l)	Balance missmatch (kg)(%)
1	2875	102	41	ND	331	ND	-
2	225	67	27	***	117	ND	-
3	45	90	36	***	138	ND	-
4	4116	37	15	41	81	4150	-104 (2.5%)
5	4052	39	15	29	88	4000	-13 (0.3%)
6	3668	57	23	33	130	3700	-115 (3.0%)
7	7448	66	26	39	211	7400	-110 (1.4%)
8	6086	65	26	31	207	6000	-61 (1.0%)
9	1895	45	18	23	106	1850	-21 (1.1%)
10	6589	41	16	52	134	6450	+10 (0.2%)
11	10283	55	22	70	178	ND	-

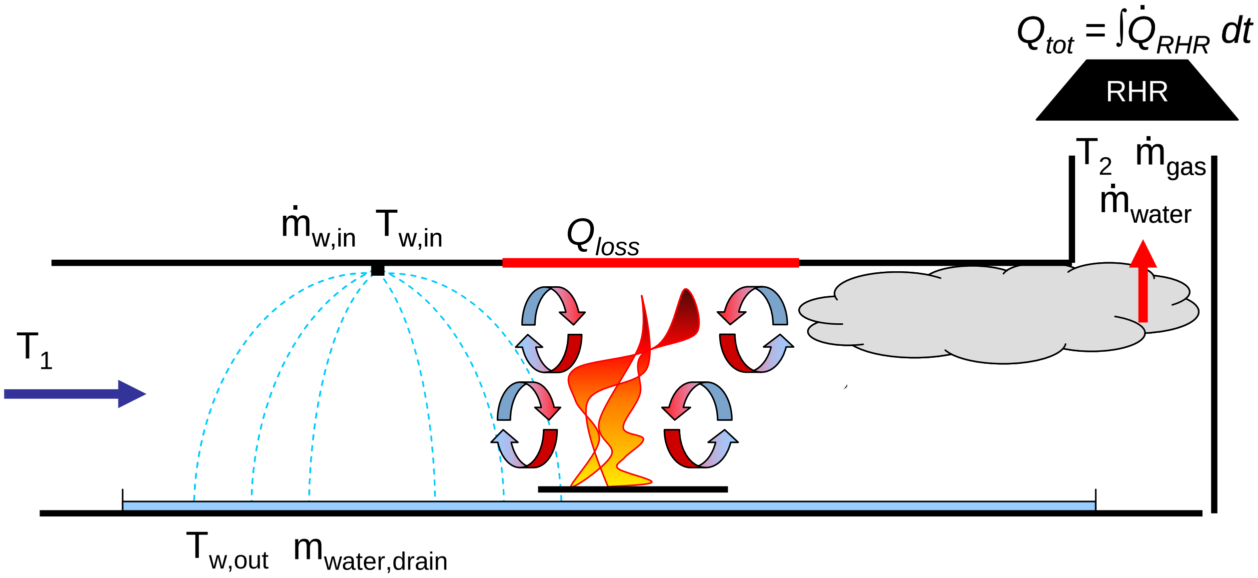
*** Collapse before suppression (free burning test)

ND = not determined

Energy Components

- **Qtot** - The total chemical energy released by the fire due to the combustion - measured by the oxygen depletion calorimetry.
- **Qconv** – Energy transferred away from the fire source by convection. Includes the latent heat of evaporation.
- **Qwater** – Energy absorbed by liquid suppression system water
- **Qloss** – Heat losses, mainly the radiative heat transfer from the fire source (can be positive or negative)

Energy Balance



$Q_{tot} = Q_{conv} + Q_{water} + Q_{loss}$ → $Q_{loss} = Q_{tot} - Q_{conv} - Q_{water}$

$Q_{tot} = \int \dot{Q}_{RHR}\, dt$

$Q_{conv} = Q_{conv,gas} + Q_{conv,water} = \int \dot{m}_{gas} C_{p,g} \Delta T\, dt + \int m_{water} C_{p,w}(T) \Delta T^{\cdot} dt + \int m_{water} H_v\, dt$

$Q_{water} = m_{water,drain} C_{p,w} (T_{w,out} - T_{w,in})$ $\Delta T = T_2 - T_1$ or $\Delta T = T_2 - T_{w,in}$

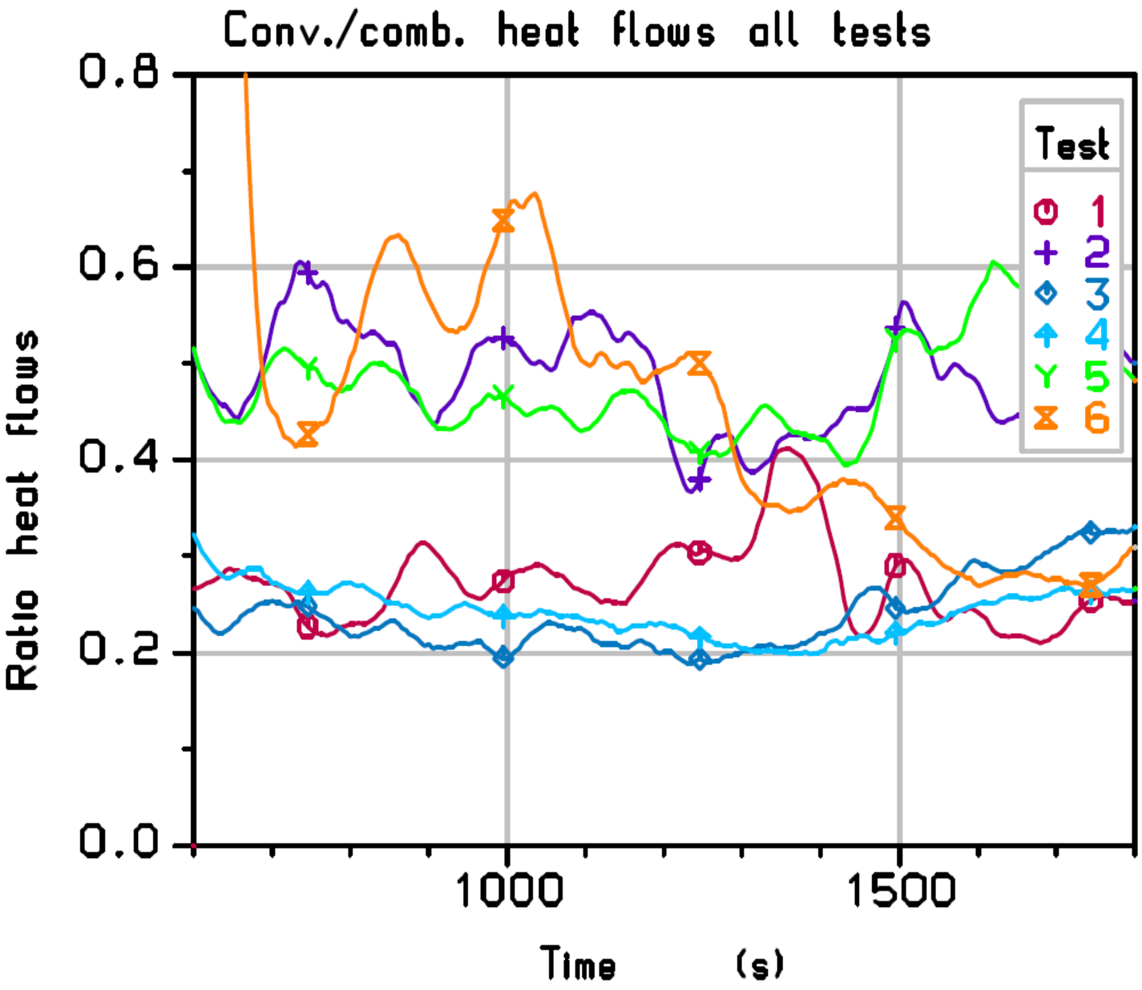
Energy Balance

Test	**Q_{RHR}**	**$Q_{ConvGas}$**	**$Q_{ConvEvap}$**	**$Q_{WaterBasin}$**	**Q_{Loss}**
4	256	115 (45%)	119 (46%)	75 (29%)	-61 (-24%)
5	313	129 (41%)	141 (45%)	165 (53%)	-133 (-43%)
6	411	190 (46%)	165 (40%)	188 (46%)	-145 (-35%)
7	1423	632 (44%)	460 (32%)	362 (25%)	-79 (-6%)
8	1441	621 (43%)	454 (31%)	340 (24%)	-22 (-2%)
9	269	**136 (51%)**	133 (49%)	108 (40%)	-118 (-44%)
10	772	377 (49%)	267 (35%)	245 (32%)	-140 (-18%)
11	1080	**274 (25%)**	372 (34%)	594 (55%)	-180 (-17%)
Average		**43%**	**39%**	**38%**	**-23%**

Energy Balance - Summary

- Convective heat transfer represents 25 % to 51% (average 43%) of the released fire heat release rate

Results from Full-Scale Fire Tests



Typical Example

- A typical unsuppressed HGV fire heat release rate may be set at **100 MW**
- If a deluge-type fire suppression system is properly designed, installed and maintained, and is activated shortly after fire detection, it may be possible to limit the fire heat release rate to **30 MW**
- If the assumption is made that only 50% of the fire heat release rate is convectively transported, this equates to **15 MW**

Conclusions from reduced-scale tests

- Low-pressure deluge systems can be very effective in reducing fire heat release rates in tunnels
- As an additional bonus: the convective heat release rates are disproportionately reduced
- Time to review the convective heat release rates for design calculations?

LTA Large-Scale Fire Tests

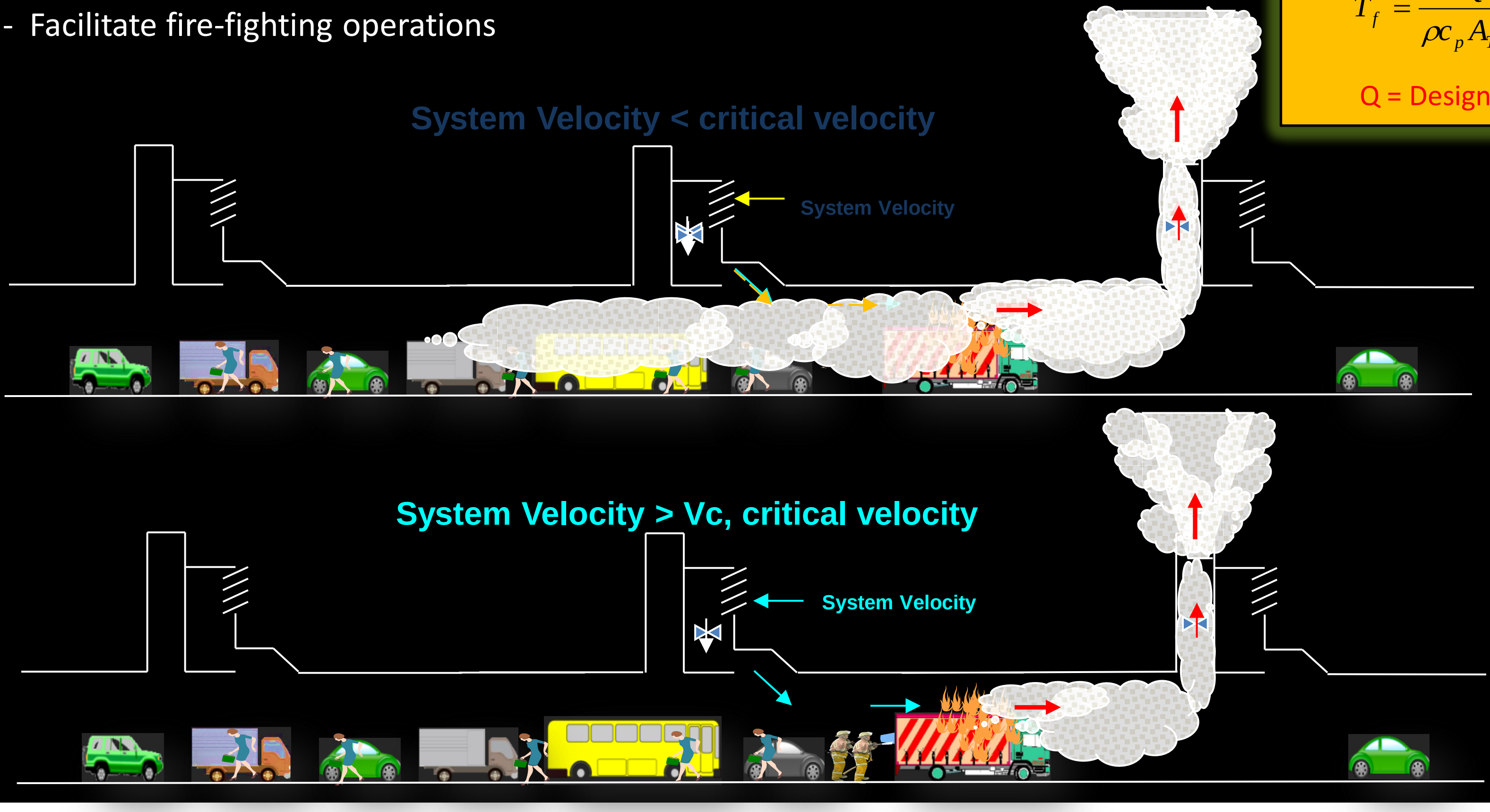
Tunnel Ventilation System

1. Provide an effective means of controlling smoke flows during fire emergencies such that:
   - Motorists could evacuate safely
   - Facilitate fire-fighting operations

$$V_c = K_1 K_g \left(\frac{gHQ}{\rho c_p A_T T_f} \right)^{1/3}$$

$$T_f = \frac{Q}{\rho c_p A_T V_c} + T$$

Q = Design fire



Singapore Traffic Act

General prohibitions in road tunnels

a) A vehicle which carry any flammable materials or petroleum
b) A vehicle overall height is 4.5 metres or above
c) A vehicle whose overall width is exceed 2.5 metres
d) A vehicle whose overall length exceed 13 metres
e) A trailer conveying a standard container
f) A tanker carrying petroleum fuel

Measure to enforce regulation

a) Hazmat Transport Vehicles Tracking System (HTVTS) installed in HTV
b) HTV only can travel on designated route
c) Movement monitor by fire service
d) Fire service has the ability to immobiliser these vehicle remotely

Type of vehicles in Singapore road tunnels

Vehicles Description

- Motorcycles
- Private Cars or Taxis
- Buses
- Light Goods Vehicles
- Heavy Goods vehicles


Motorcycle


Car


Taxi


Bus


Light Goods Vehicles


Heavy Goods vehicles

Vehicles prohibitions in road tunnel

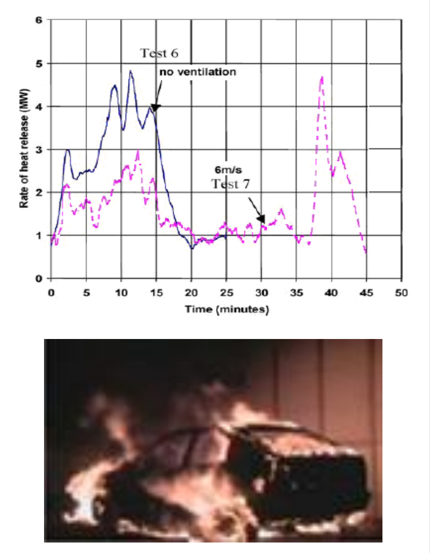

Petrol Tankers

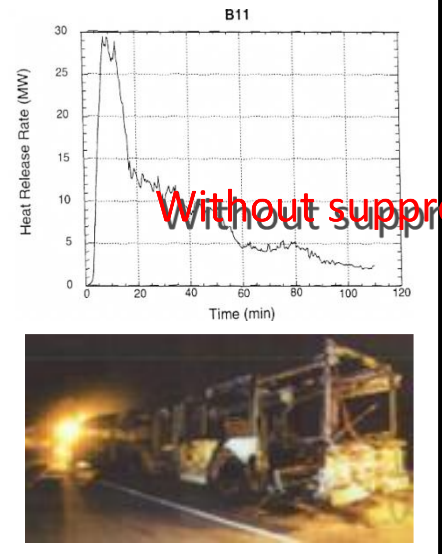
Trailer

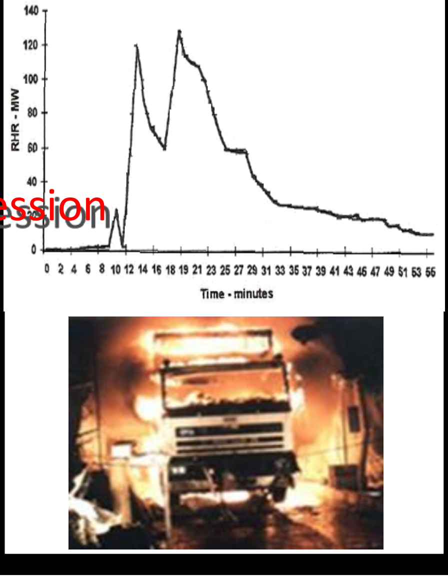
Design Fire

The design fire sizes use are generally based on NFPA standard

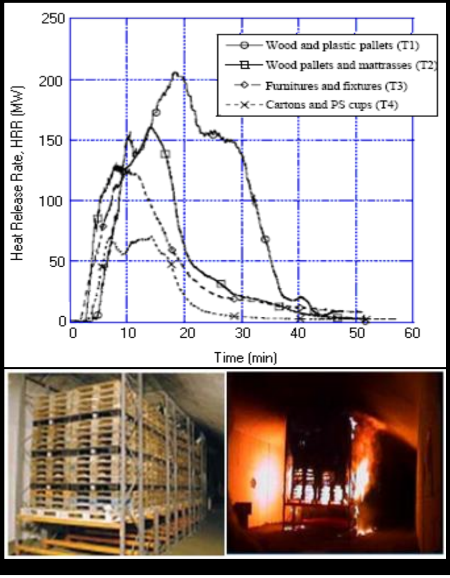
Vehicles	Peak heat release rate
Car	: 5 to 10 MW (multiple cars 10-20 MW)
Bus	: 20 to 30 MW
Heavy goods truck	: 70 to 200 MW
Tanker	: 200 to 300 MW







Without suppression



Singapore Fire Test Programme

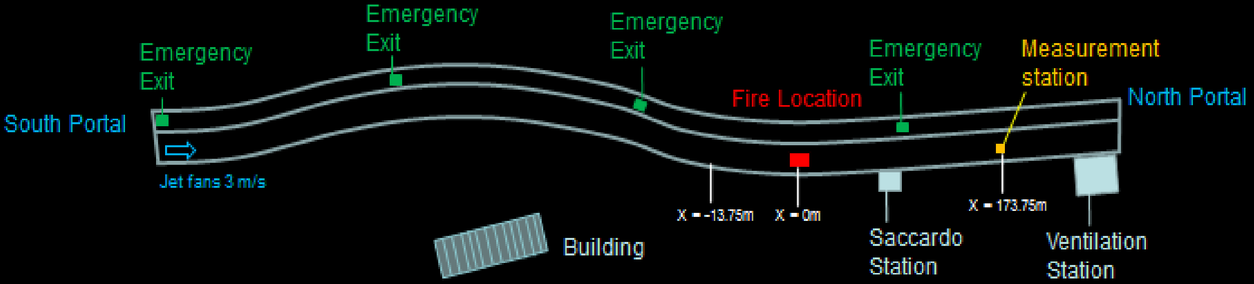
i) In 2011, LTA Singapore commissioned Efectis to conduct a fire test programme

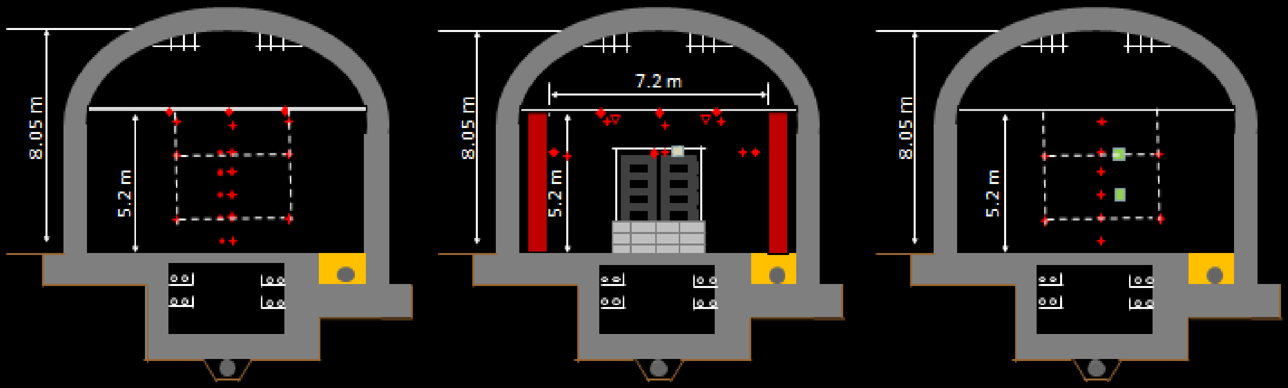
ii) The aim of this fire tests programme is investigate
  a) effects on the HRR with and without fire suppression system
  b) effect of fire suppression system on tunnel velocity
  c) acquire information on the appropriate design parameters to adopt
    (e.g nozzle type, discharge density and activation time)

iii) A total of 7 large scale fire tests was conducted in this fire test programme.

Singapore Fire Test Programme

- Tunnel Safety Testing, Pola de Siero, Spain
- 600 m long test tunnel
- 5.2m high
- 7.2- 9.5m wide





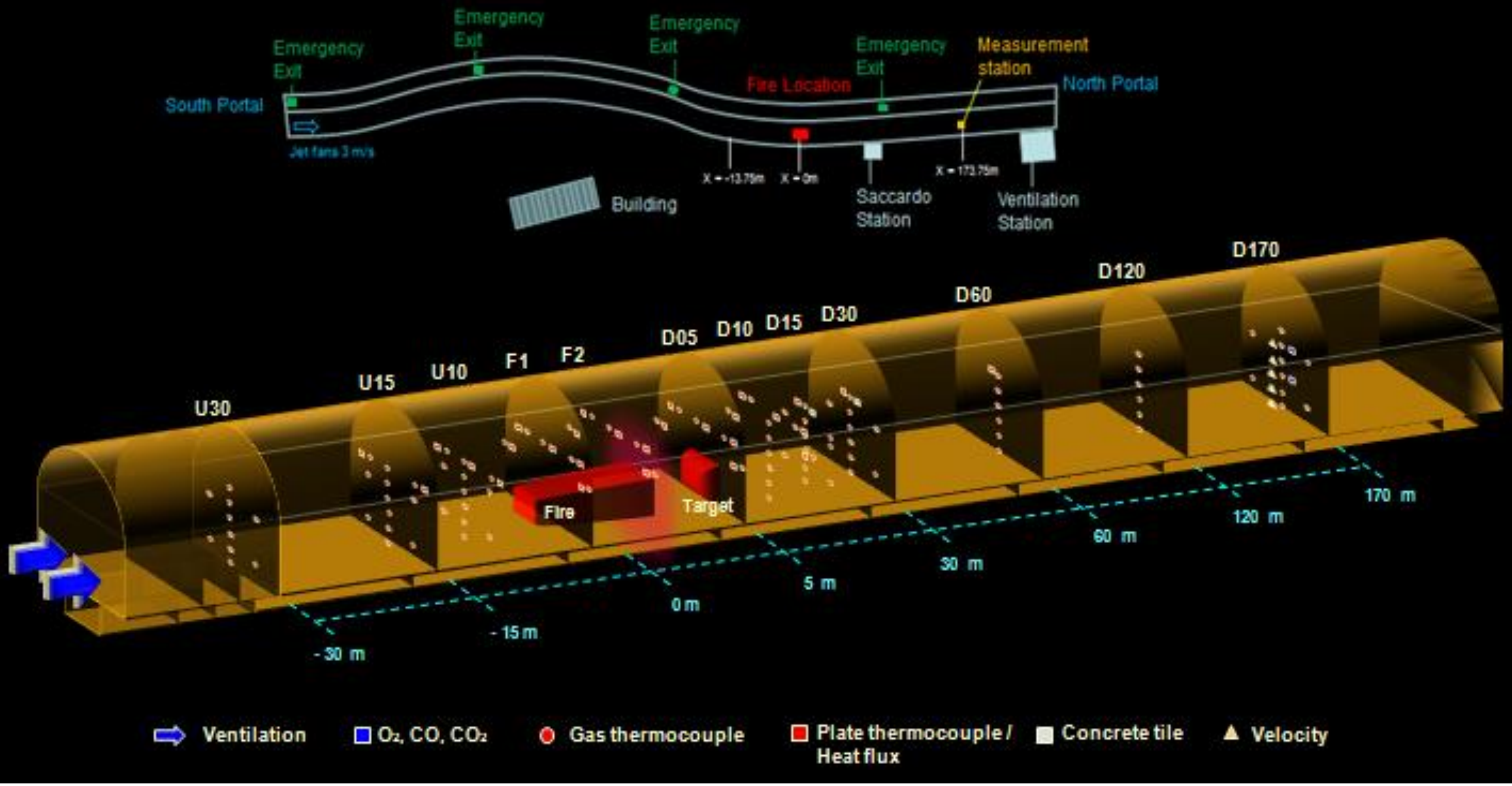
U10 Location X = -13.75m

Fire location, X = 0m

Location = D170, X = 173.75m

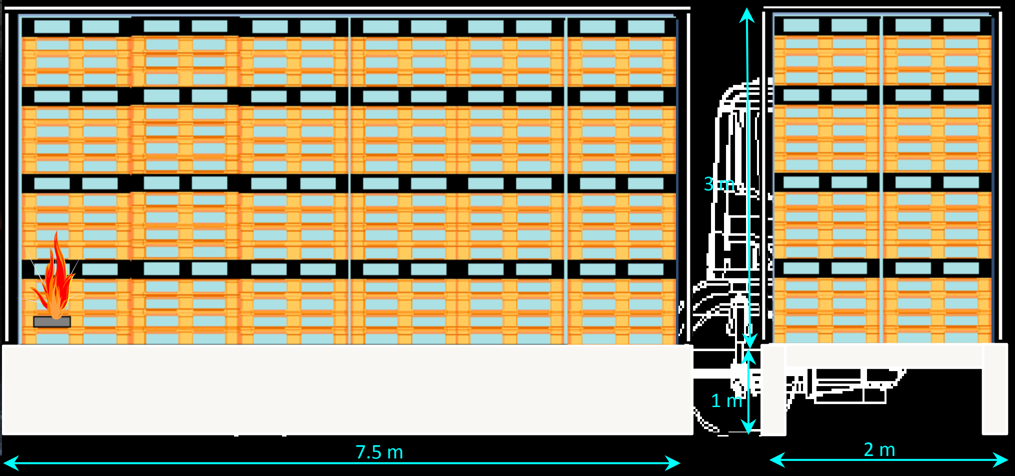
🟩 O_2,CO,CO_2 ▽ Deluge Nozzle + Gas thermocouple ▫ Heat flux sensor • Velocity ✦ Plate thermocouple

Test Setup - Instrumentation



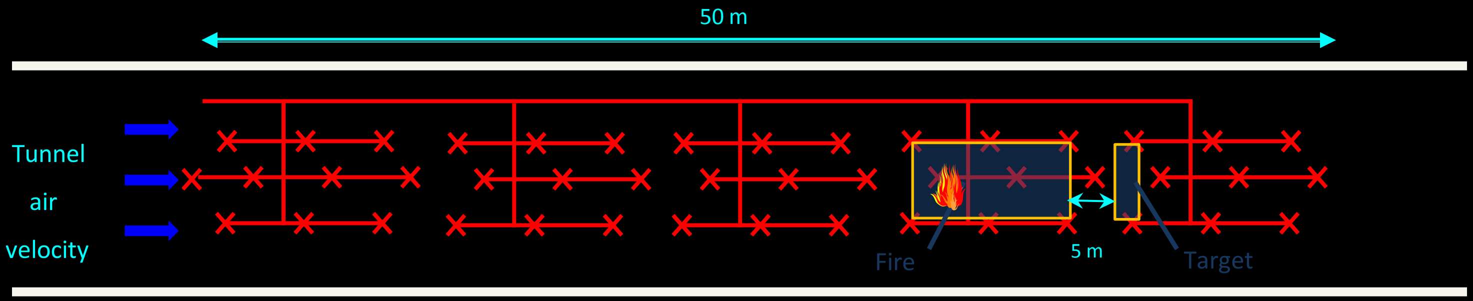
Fuel Load:

- 228 wooden (80%) and plastic (20%) pallets
- 3 m/s ventilation velocity
- Without and with deluge operation



Target:

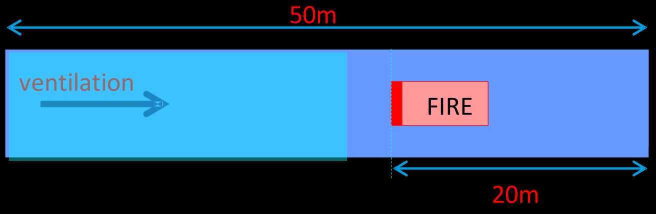
Deluge System:



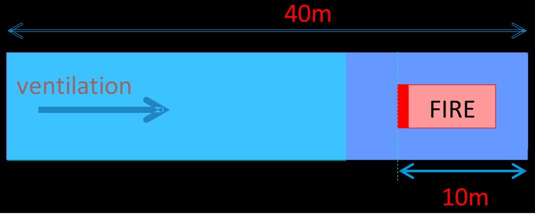
Large Scale Fire Test Schedule

Test	Test description (variation)	Discharge density (mm/min)	Nozzle type	Activation time (min)	Fuel load in zone
1	Base case	12	Directional 180º spray nozzle	4	Position A
2	Low suppression	8	Directional 180º spray nozzle	4	Position A
3	Nozzle	12	Pendant standard spray nozzle	4	Position A
4	Nozzle*	12	Pendant standard spray nozzle	4	Position A
5	Reduced cooling	12	Pendant standard spray nozzle	4	Position B
6	Late activation	12	Pendant standard spray nozzle	8	Position A
7	Unsuppressed	-	-	-	Position A

Position A



Position B



Nozzle Specifications:

- K-factor: 80 lpm/bar$^{0.5}$

-Operating pressure: 1-2 bar, 8-12mm/min

-Detection

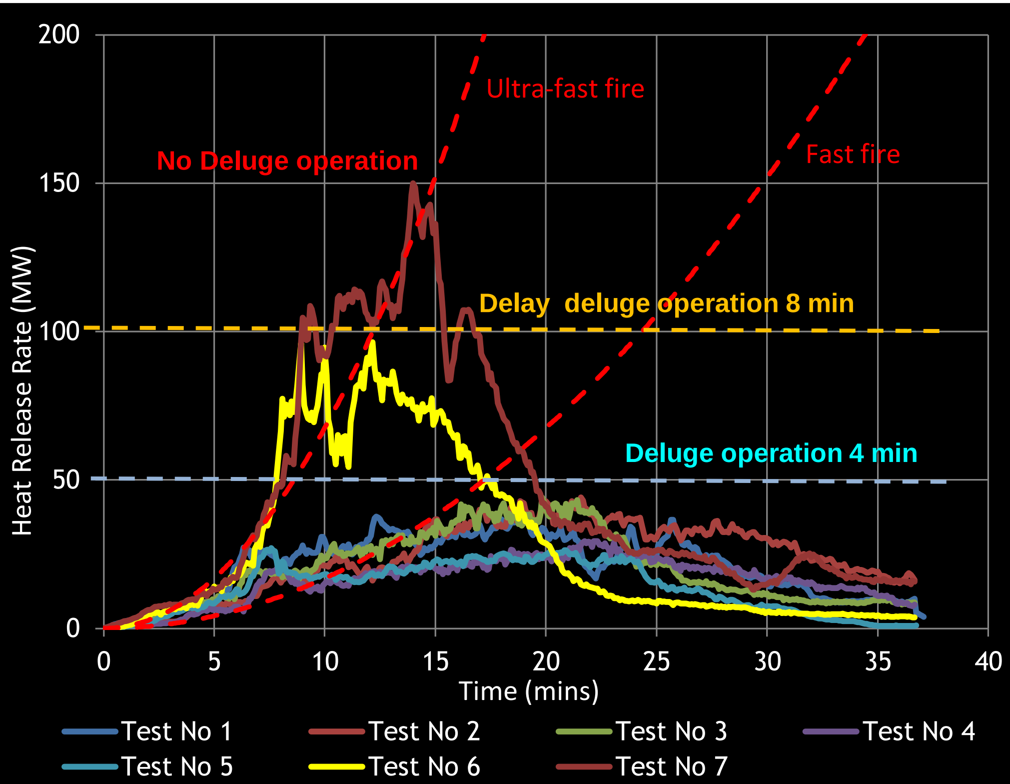
-Gas thermocouples on ceiling level is measured

-“Detection” is defined as 60°C gas temperature

System activation

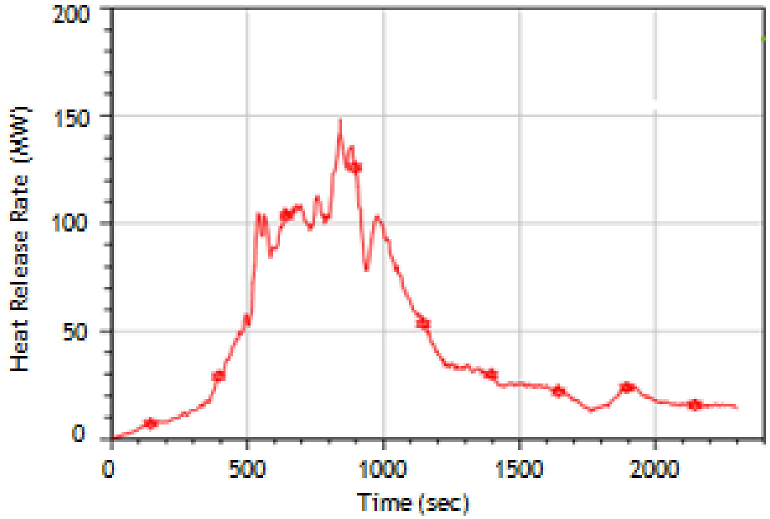
- Fixed time after “Detection”: 4 min

Heat Release Rate

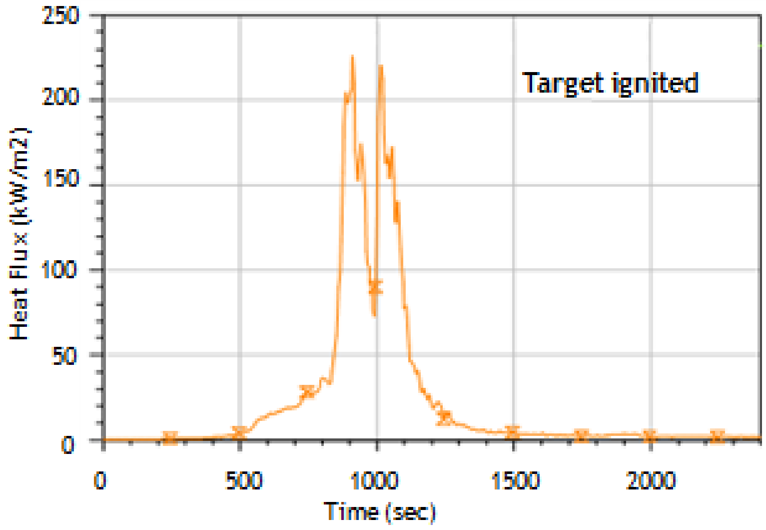


Free burning (Test 7)

Heat Release Rate

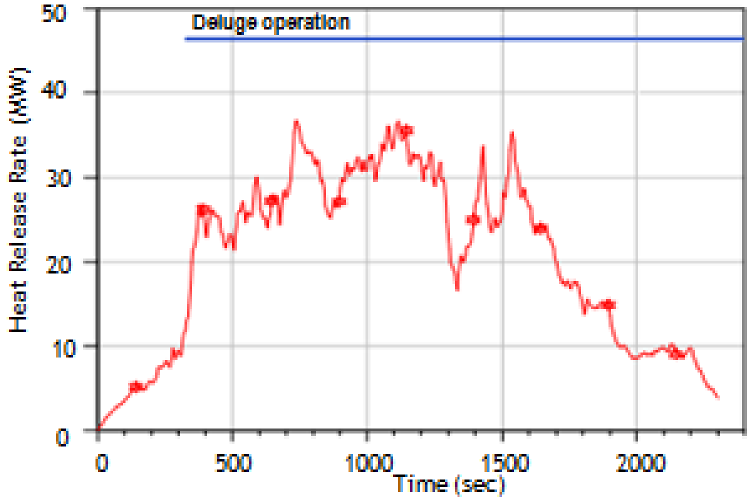


Heat Flux (5m downstream of fire)

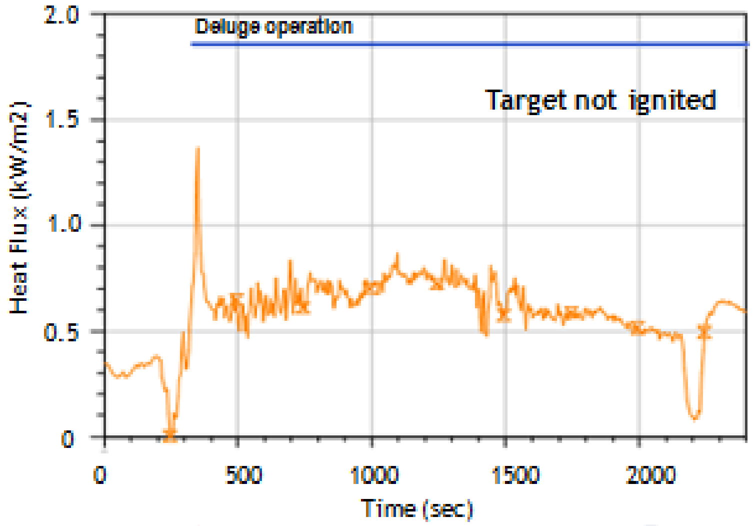


With deluge system (Test 1)

Heat Release Rate

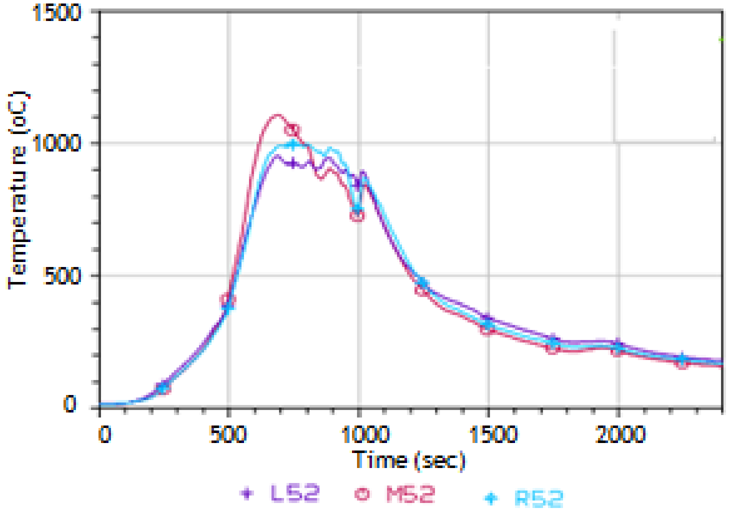


Heat Flux (5m downstream of fire)

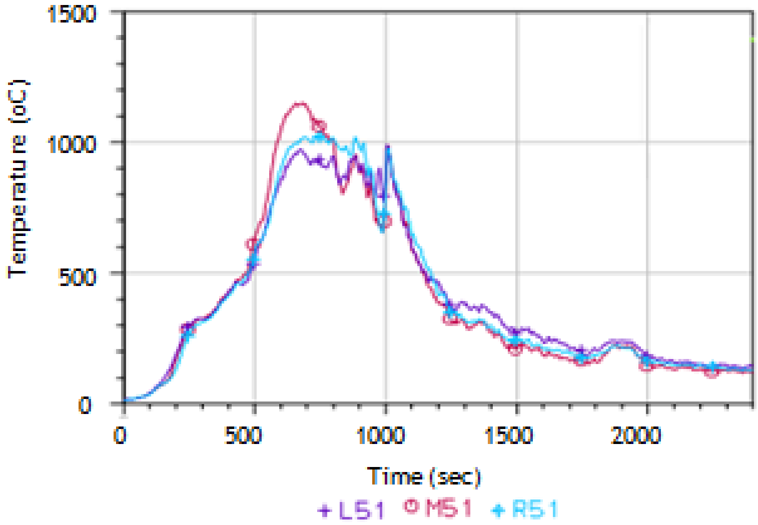


Free burning

Ceiling surface temperature (10m downstream of fire)

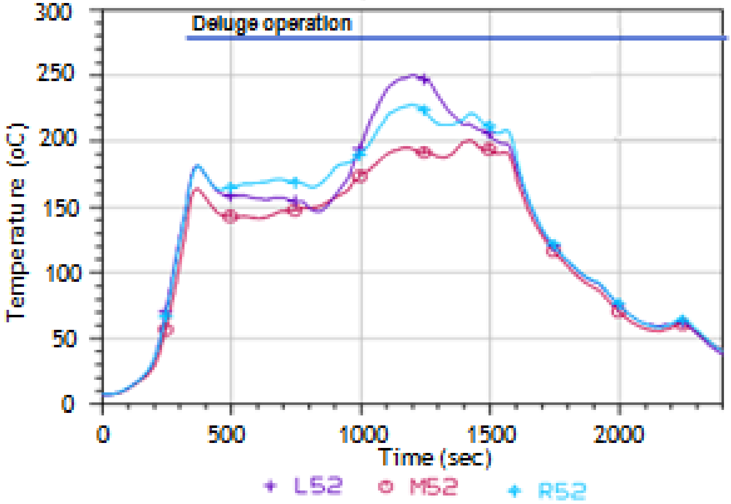


Gas temperature (10m downstream of fire)

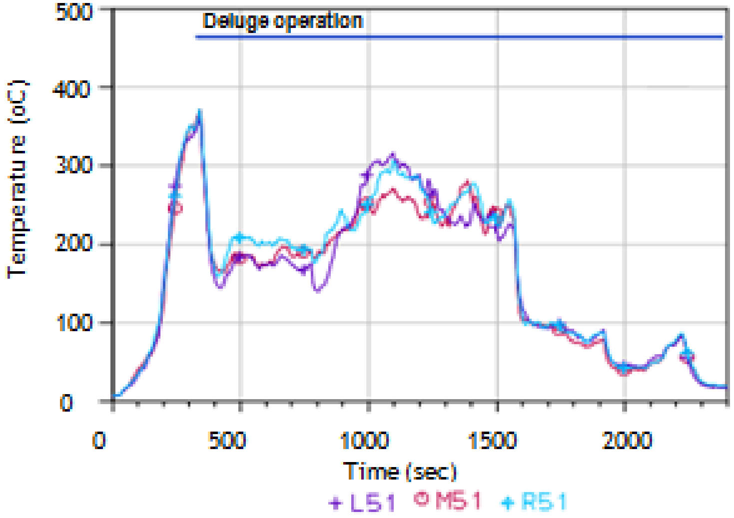


With deluge system

Ceiling surface temperature (10m downstream of fire)



Gas temperature (10m downstream of fire)



Conclusions from large-scale fire tests

- Peak heat release values reduced by 70 to 80% due to fire suppression (with 4 minute delay in activation)
- With delayed deluge operation to 8 minutes, the peak heat release rate is only reduced by 35%
- All the tests with deluge operation within 4 minutes are controlled below a peak heat release rate of 50 MW

Passive fire protection to tunnels

EU Directive Requirement

- “The main structure of all tunnels where a local collapse of the structure could have catastrophic consequences, e.g. immersed tunnels or tunnels which can cause the collapse of important neighbouring structures, shall ensure a sufficient level of fire resistance”

Issues

- Definition of “catastrophic consequences”?
- Do all immersed tube tunnels require passive fire protection?
- What is a “sufficient” level of fire resistance?

Catastrophic Consequences

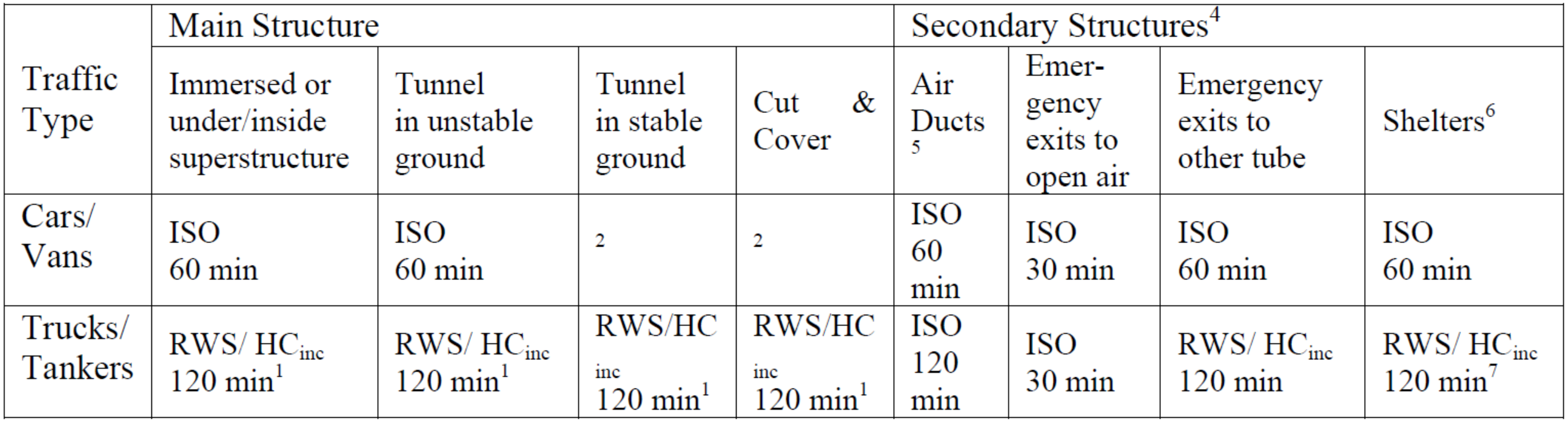
Possible interpretations:

- Structural damage
- Large-scale loss of life
- Traffic interruption leading to socio-economic damage

Immersed Tube Tunnels

- Potential vulnerability at tunnel joints
- Risk of inundation
- Long remediation / reconstruction timescales

World Road Association / International Tunnelling Association Recommendations (2004)



Traffic Type	Main Structure				Secondary Structures[4]			
	Immersed or under/inside superstructure	Tunnel in unstable ground	Tunnel in stable ground	Cut & Cover	Air Ducts [5]	Emer-gency exits to open air	Emergency exits to other tube	Shelters[6]
Cars/ Vans	ISO 60 min	ISO 60 min	[2]	[2]	ISO 60 min	ISO 30 min	ISO 60 min	ISO 60 min
Trucks/ Tankers	RWS/ HC_{inc} 120 min[1]	RWS/ HC_{inc} 120 min[1]	RWS/HC_{inc} 120 min[1]	RWS/HC_{inc} 120 min[1]	ISO 120 min	ISO 30 min	RWS/ HC_{inc} 120 min	RWS/ HC_{inc} 120 min[7]

Time for Reviewing the Recommendations?

- Requirements unnecessarily onerous?
- Not related to safety, but to asset protection
- Subject to benefit/cost assessments
- Influence of mitigation measures such as fire suppression?
- New task group to update recommendations

Typical Design Solutions

- Mineral fire boards – most used solution, e.g. Jack Lynch Tunnel, Cork
- Composite steel and cement panels
- Spray or trowel applied cementitious passive fire protection
- Polypropylene fibres – for new builds only; may be within sacrificial layer only

Palm Jumeirah Tunnel, Dubai

Palm Jumeirah Tunnel, Dubai

Review

- Recent Tunnel Fires
- UK Road Tunnel Context
- LTA Fire Suppression Tests
- Passive Fire Protection to Tunnels

Thank You

Dr Fathi Tarada

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