2. FIRE TESTS

2.1. BACKGROUND

Most of the information used for the definition of fire design characteristics comes from fire tests. For example, much of the information on smoke and heat generation included in the PIARC report of the Brussels Congress [4] was based in the results of the fire tests conducted in the Ofenegg tunnel, in Switzerland.

Later, most of the information used for the description of fire design characteristics within the PIARC report "*Fire and Smoke Control in Road Tunnels*" [7] was collected from the reports of the large scale fire tests conducted recently, which included the EUREKA EU 499 – FIRETUN Project in Europe, the Memorial Tunnel Tests in the United States.

2.2. QUANTIFICATION AND DETERMINATION OF FIRE LOADS IN TUNNELS

The essential characteristic that describes quantitatively the "*fire size*" is the Heat Release Rate (HRR), normally expressed, in the context of a tunnel, in MW. Although theoretical estimations of HRR have been used, e.g. the Mont Blanc tunnel fire investigation, recent discussions on fire size are associated with large-scale fire tests, where HRR has obtained through in-situ measurements.

In general, two kinds of techniques are available to directly measure HRR: open-burning HRR calorimeters and compartment fire tests. In the first case, some experiments have been completed with car size vehicles, as cited later. However, most of the values of HRR used in the literature have been obtained through large-scale tunnel fires, and the values obtained by the following methods:

- The designer should consider the rate of fire development (peak heat release rates may be reached within 10 minutes), the number of vehicles that could be involved in the fire, and the potential for the fire to spread from one vehicle to another
- Temperatures directly above the fire can be expected to be as high as 1000 °C to 1400 °C (1832 °F to 2552 °F)
- The heat release rate can be greater than in the table if more than one vehicle is involved
- A design fire curve should be developed in order to satisfy each engineering objective in the design process (e.g. fire and life safety, structural protection, etc.)

As in all kind of measurements, different uncertainties can be expected depending on the method used, so it is common to use more than one procedure to evaluate HRR during large scale campaigns.

2.3. RESULTS OF FIRE TESTS IN ROAD TUNNELS

2.3.1. Car fires

Much work has been done on car fire size. An exhaustive collection of HRR results for car size fires has been collected by Ingason and Lönnermark,[18]. Zhao and Kruppa [19], in a study of behaviour of a car park steel structure under fire action, presented an allocation of European cars into five categories. These categories are based on the energy released during a fire based on the average mass and the energy released.

Based on these results, different attempts have been made, e.g. [20], to define heat release rate curves for car fires, expressed by analytical expressions. The authors cited report that the HRRs for single passenger car varies between 1,5 and 8 MW, with most being less than 5 MW. The HRR may rise to about 10 MW when two cars are involved. The time taken to reach peak HRR varies widely in the reported experiments, being between 10 and 55 minutes. Reports of other fire tests on vehicles can be found in references [21] to [25].

Hence, the results of these studies are generally in accord with prescriptive values normally assumed for the design fire size for passenger car fires.

2.3.2. Heavy Good Vehicles (real and simulated loads)

The number of large scale fire tests involving HGV in which measurements of HRR has been accomplished is not so numerous as for passenger cars. However, the most broadly referred are the following.

Eureka 499-Project

In the Eureka-project EU499 [8] full-scale tests were conducted in the disused Repparfjord Tunnel in Norway. The overall objective of the tests was to investigate parameters that affect the protection of people and preservation of property in the event of fires in underground transportation facilities.

The project consisted of 20 full-scale fire tests of road and rail transportation vehicles, wood cribs, and heptane pools. Extensive instrumentation was used to measure gas temperature and velocity profiles, tunnel surface, temperatures, heat fluxes, smoke obscuration, and gas composition at various distances in both directions from the location of the fire. Temperatures and mass loss of the burning object were also measured. Several approaches were used to determine the heat release rate of the burning object based on the available temperature, velocity, and gas composition data. *Table A2.1* summarises the main details.

TABLE A2.1. EUREKA TEST SUMMARY

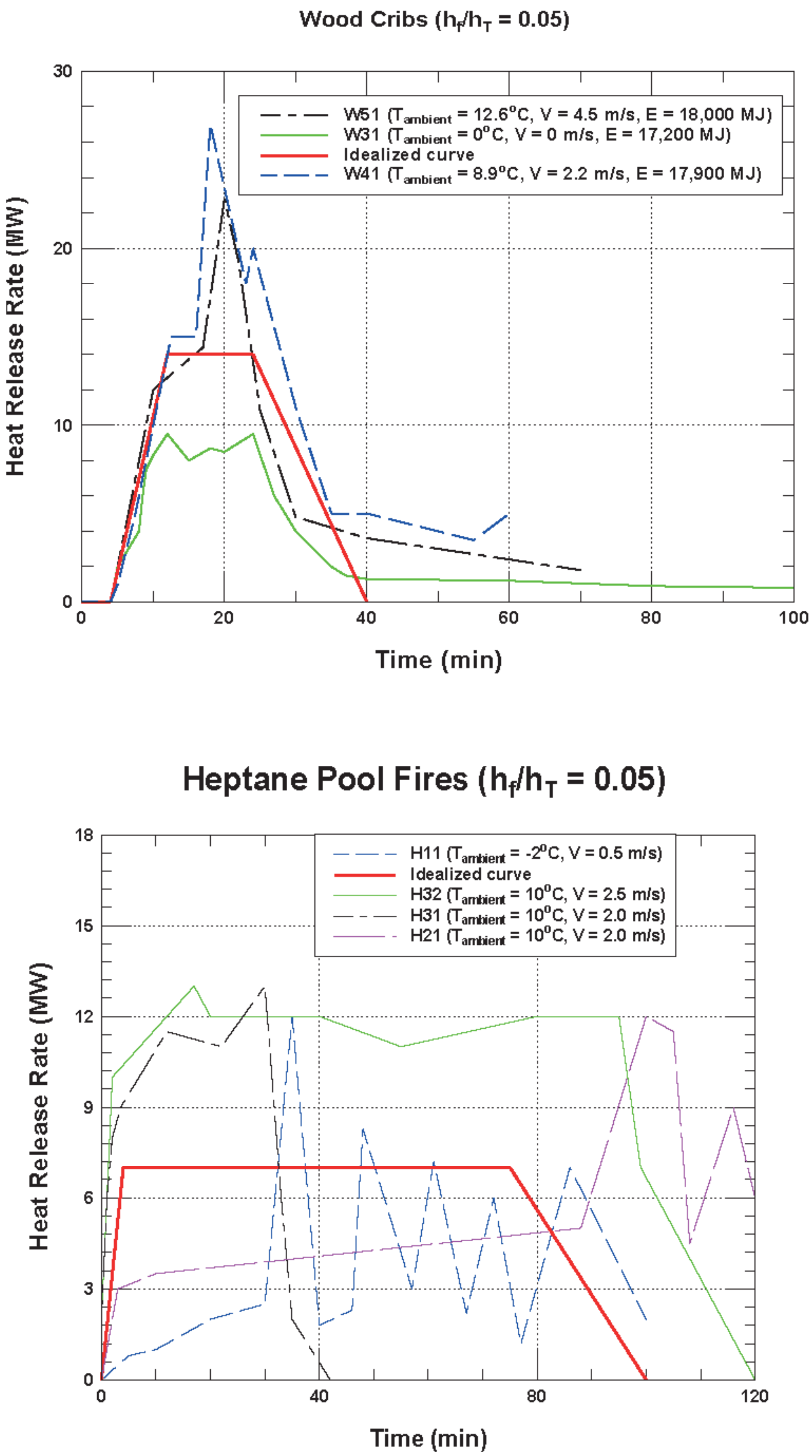
Tunnel Geometry	Fire Load	Test Parameters	Measurements
Length: 2.3 km **Slope:** 1% N-S **Cross-section:** Area = 34 m2 (±4 m^2) Horse-shoe rock cross-section with flattened ceiling and concrete floor **Isolation of walls:** Tunnel ceiling and walls in the immediate vicinity of the fire load (260 m – 345 m) were lined with a steel-fibre reinforced light-weight shotcrete	**Materials:** wood, plastics, heptane Type: Wood crib: “*WC*” Private car: “*PC*” Public bus: “*PB*” Heavy goods vehicle: “*HGV*” Heptane pool fire: “*HP*” Plastic vehicle: “*PV*” Lorry load (wood+tyres+plastic) “*MF*” **Humidity:** 80-95% **Blockage ratio:** WC: 2.4/5.5 = 0.44 HP: 0.3/5.5 = 0.05 PC: 1.45/5.5 = 0.26 PB: 3.2/5.5 = 0.58 HGV: 4.25/5.5 = 0.77 PV: 2.0/5.5 = 0.40 MF: 2.4/5.5 = 0.44 **Arrangement:** Fire load was arranged centrally with respect to the tunnel cross-section at 295 m from the north portal	**Ambient conditions:** Prevailing wind in the N-S and S-N directions in winter and summer, respectively. **Air velocity (m/s):** WC: 0.3-2.2 HP: 0.6-2.5 PC: 0.3 PB: 0.3 HGV: 3.4 – 6.8 PV: 0.5 MF: 0.5 FFFS: N/A	**Temperature:** 46 TC on/in the fire 9 TC on the walls 300 TC in tunnel cross-section 1 plate-type thermometer **Radiation:** 6 pyrometers **Air velocity:** 76 bi-directional probes and anemometers **Smoke:** 34 Opacimeters 6 optical density **Gases analysers:** 24 CO/CO$_2$/O$_2$/SO$_2$/C$_n$H$_n$/NO **Mass loss:** 1 weighing platforms for WC and ML tests **Observations:** 13 videos cameras (stationary & variable, infrared)

Illustration A2.1 shows the measured heat release rates versus time for tests conducted with wood cribs, a public bus, a plastic car, mixed fuel, heptane pool fire, and a heavy goods vehicle as the fuel sources.

For design purposes it may be useful to consider the fire behaviour in an idealized manner, representing the various stages of ignition, growth, steady state and decay. Such curves are also shown, for each type of fuel load, in *illustration A2.1*. The idealized curves for all tested fuel loads and the key data are shown in *illustration A2.2*.

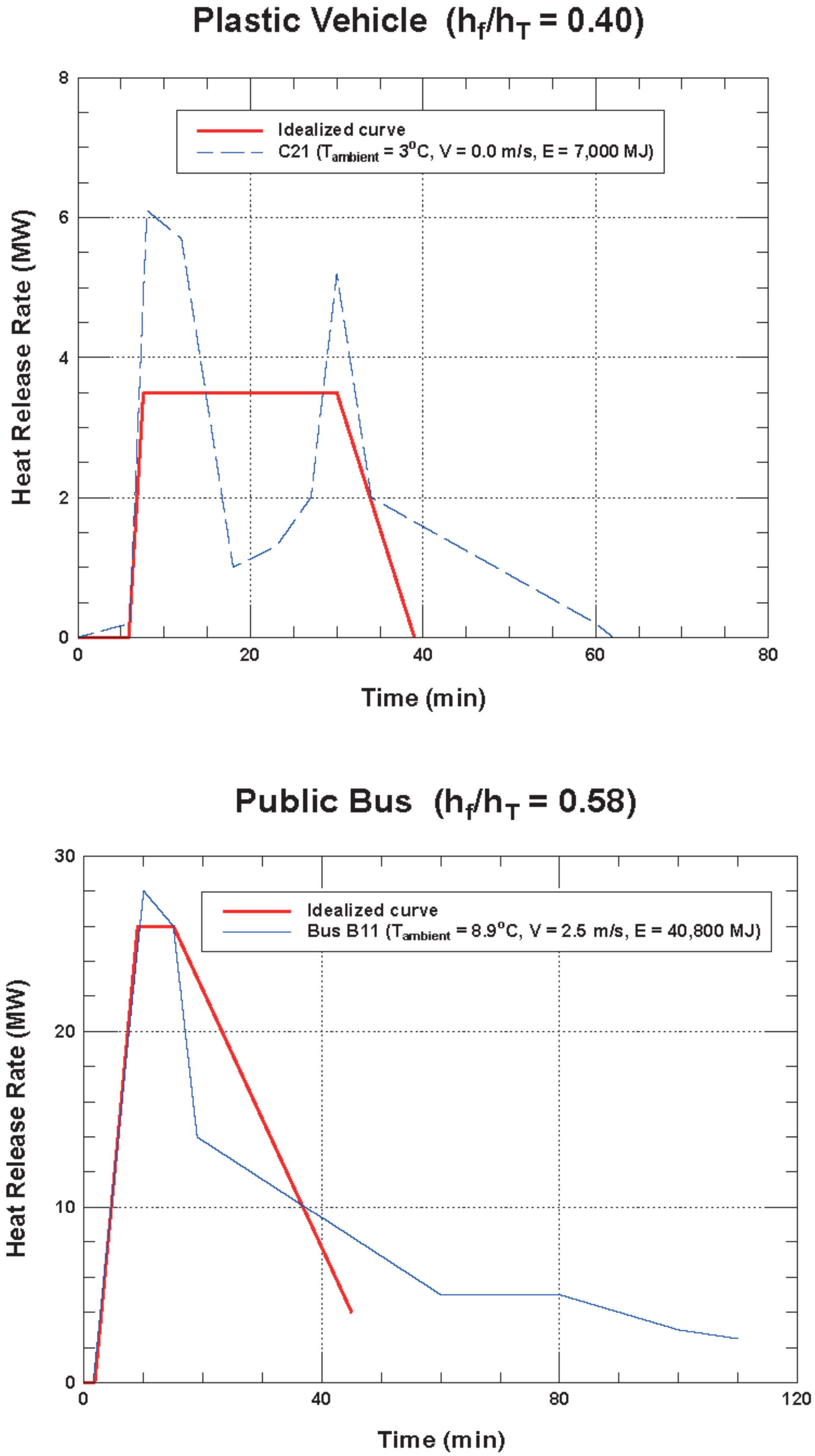
In developing these idealized curves, some constraints or criteria were respected. The total energy released, growth rate, and decay rate of the idealized curves were approximately maintained the same as the experimental data.

The fire HRR varies considerably even within a single vehicle class. No recommendation is made, therefore, for a single idealized curve for design use. The concept is presented, however, as a possible characterization of the design fire, the actual parameters being adjusted on a case-by-case basis.



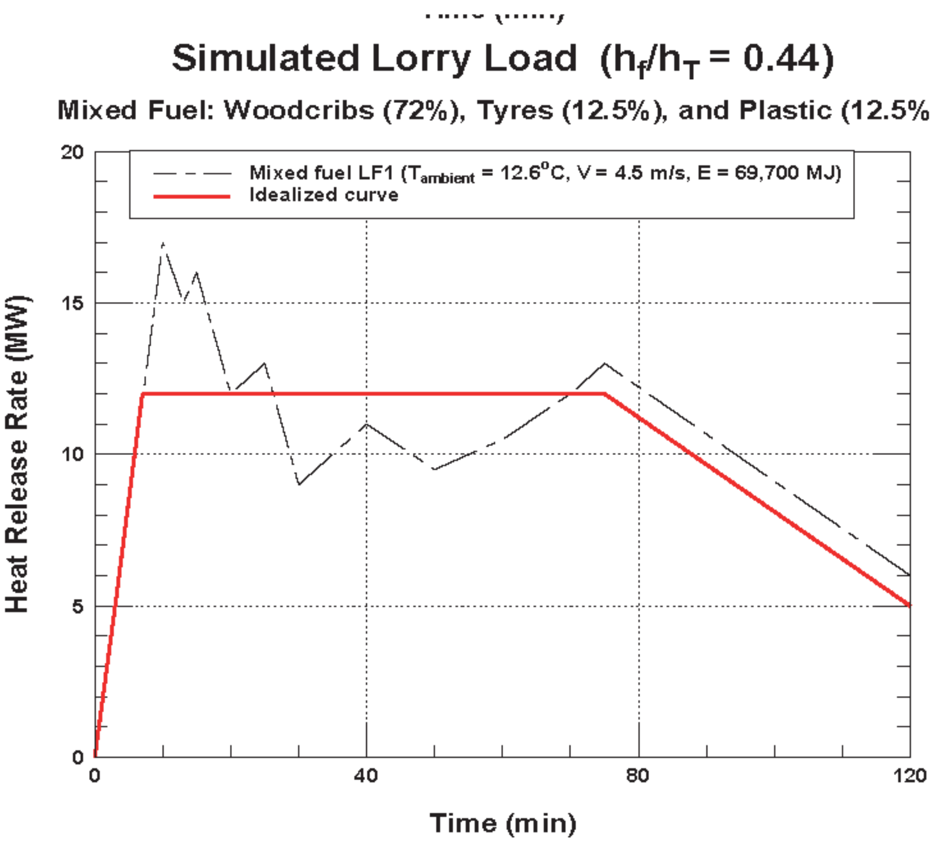
h_f: height of the fuel / h_T: height of the tunnel section

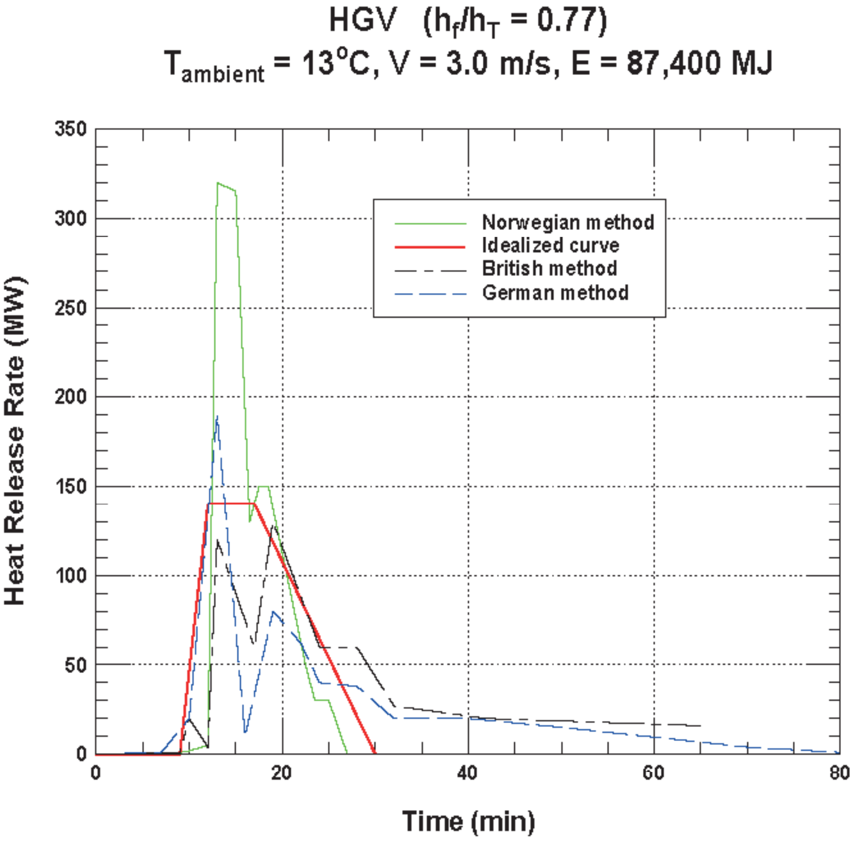
Illustration A2.1 - Measured total heat release (HRR) - 1/3



h_f: height of the fuel / h_T: height of the tunnel section

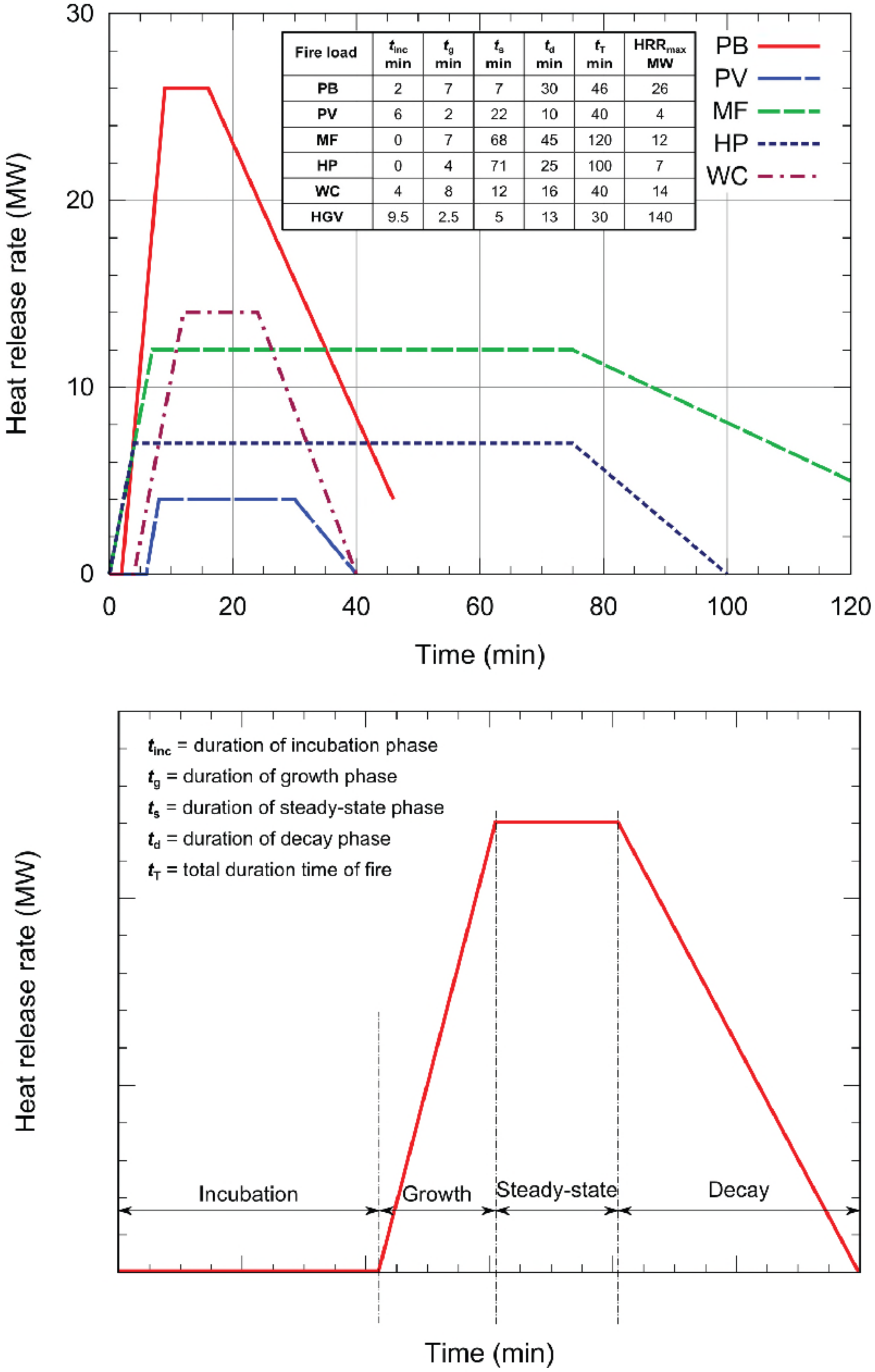
Illustration A2.1 - Measured total heat release (HRR) - 2/3





h_f: height of the fuel / h_T: height of the tunnel section

Illustration A2.1 - Measured total heat release (HRR) - 3/3



Fire load	t_{inc} min	t_g min	t_s min	t_d min	t_T min	HRR_{max} MW
PB	2	7	7	30	46	26
PV	6	2	22	10	40	4
MF	0	7	68	45	120	12
HP	0	4	71	25	100	7
WC	4	8	12	16	40	14
HGV	9.5	2.5	5	13	30	140

Illustration A2.2 - Idealized HRR-time curves

Referring to *illustration A2.2*, the defined timescales of the idealized curves illustrate:

t_{inc} : .....time from ignition until the fire is producing flame (smouldering region)
t_g : ....time from end of incubation to maximum heat release (fire growth region)
t_s : ....duration time of the steady-state region
t_d : ......time from the start of the decay of the HRR to the end of it (decay region)
t_T : ......duration time of the fire from ignition

It can be seen that the time for the fires to grow are between 7 and 12 minutes, relatively short durations in the context of evacuation and response. The duration of the fires varies considerably. The HGV fire has the shortest duration and was the most intense fire. However, it should be noted that the fire size was influenced by ventilation, the 140 MW being associated with a ventilation air velocity of 6 m/s. The influence of air velocity on fire size is discussed further below.

BENELUX tunnel tests

The Benelux tests [9] were performed in tube D of the 2nd Benelux tunnel near Rotterdam, Netherlands. The cross-section is approximately rectangular, with a width of 9.8 m and a height of 5.1 m. The ceiling was originally protected by an insulating material; extra insulation was added over a length of 75 m around the fire during the tests, on the ceiling, sidewalls and floor. A sand bed was also used to protect the floor and absorb spilt fuel.

For these tests, the HGV loads were simulated by means of a construction with a synthetic canvas and a stack of loading pallets underneath to achieve a rate of heat release of approximately 20 MW in conformity with that of a small HGV (4.5 m x 2.4 m x 2.5 m).

The cargo area, also referred to as ‘aluminium HGV hood’, consisted of a steel sheet floor with a self-sustaining hood made up of aluminium sheets. The side and front walls of the hood consisted of nine flanged sheets that were assembled by means of a bolt connection. The cargo area was loaded with 4 stacks each having 9 wooden Euro-pallets (in total 36 pieces) and a car tyre on top of each stack. The load was ignited by lighting two small bowls of petrol that were placed in the middle of the cargo floor between the wooden stacks.

An additional test (number 14) comprised two rows each having four wooden stacks placed on the weighing platform. Each stack consisted of nine wooden Euro-pallets. In total 72 pallets were burned in order to realise a maximum rate of heat release of approximately 40 MW. In order to have extra smoke developing, 6 car tyres were added. Schematics of the test setups are given in *illustration A2.3*.

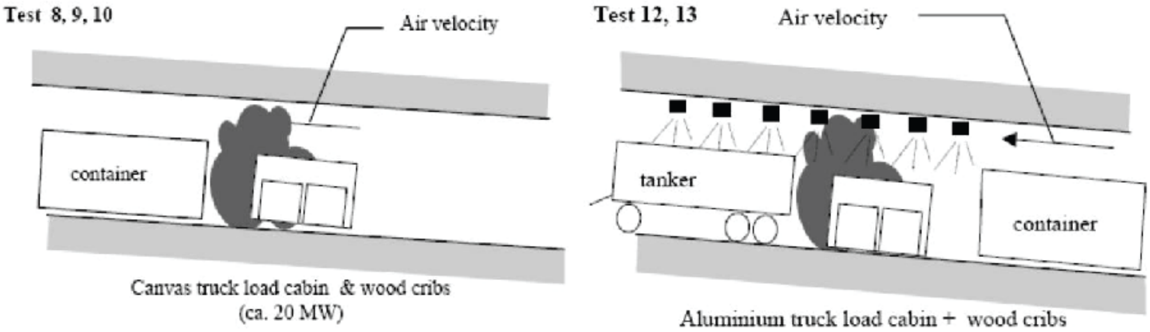


Illustration A2.3 - Benelux test setup

TABLE A2.2. SUMMARY OF BENELUX TESTS

Test #		Fire load	Intended HRR (MW)	Intended air velocity (m/s)	Ventilation	Sprinkler
Smoke spread ventilation tests	1	Pool	5	0 – 1	Off	
	2a	Pool	5	0 then 6	Switched on with a delay	
	2b	Pool	5	0 to 6	Progressive build-up	
	3a	Pool	5	0 – 1	Off	
	3b	Pool	20	0 then 6	Switched on with a delay	
	4	Pool	20	0 to 6	Progressive build-up	
Effet du courant d'air sur la puissance	5	Passenger car	5	0 – 1	Off	
	6	Passenger car	5	0 – 1	Off	
	7	Passenger car	5	6	On	
	8	Canvas hood, 36 pallets, 4 tyres	20	0 – 1	Off	
	9	Canvas hood, 36 pallets, 4 tyres	20	6	On	
	10	Canvas hood, 36 pallets, 4 tyres	20	6	On	
Essais d'aspersion	11	Van with 18 pallets	10 – 15	1	On	Delayed activation
	12	Aluminium hood, 36 pallets, 4 tyres	20	3	On	Immediate activation
	13	Aluminium hood, 36 pallets, 4 tyres	20	0 – 1	Off	Delayed activation
	14	72 pallets, 6 tyres	35	0 – 1	Off	Delayed activation

Illustration A2.4 compares the fire tests with potentially higher loads and without fire suppression influencing the HRR, specifically tests 9, 10, 11 and 14.

Tests 9 and 10 both have 36-pallet stacks under a canvas, with a longitudinal airflow of about 6 m/s. The results compare well with each. The growth rate is a bit higher in test 9, and so is the peak HRR; the ventilation system was working at full capacity during the growing phase, whereas it was only at 50% in the first minutes of test 10. Both tests show an incubation time of about 4 minutes.

Test 14 involved a pallet stack about twice as large as in 9 and 10, with almost no longitudinal air flow. A sprinkler system was tested but according to the report, it was only activated after 22 minutes in the fire region, at a time when the fire was almost out. A sprinkler system was actually operated earlier further downstream of the fire, over a tanker that served as fire target. The idea was to investigate the cooling efficiency of the sprinkler system on the tanker while keeping the fire HRR high. The behaviour of this fire is very similar to the previous ones. The incubation time is a bit longer (5-6 minutes), perhaps due to the weak ventilation; the growth rate is similar in the linear phase (about 7 MW/min). The decay is a little faster. From this comparison, the repeatability of pallet stack fires seems good, and the qualitative behaviour is consistent regardless of the ventilation conditions. Strong ventilation reduces the incubation time and maybe accelerates growth.

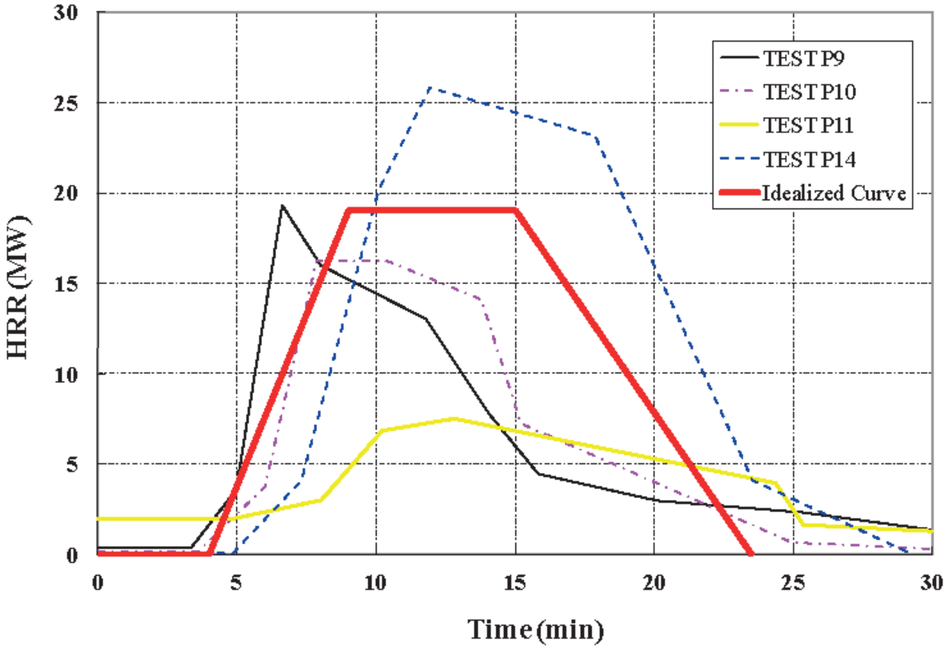


Illustration A2.4 - BENELUX tunnel test results

Test 11, a van loaded with 18 pallets and a weak longitudinal air flow (1 m/s), with late activation of the sprinkler system. This test is quite difficult to interpret. In contrast with the other tests described, the van is set on fire using a small petrol bowl placed on the driver's seat. However, the HRR is 2 MW from the very beginning of the test, which is probably a measurement error. If we regard this HRR as zero, the incubation time is quite long (6-7 minutes) and the growth is slow. The activation of the sprinkler system after 13 minutes probably prevents the HRR from reaching a peak higher than 7 MW, a value that seems moderate regarding the load.

Runehamar tests

The Runehamar large-scale fire tests were conducted in 2003 in an abandoned tunnel in Norway. The 1600 m tunnel has a cross section at the fire site of about 9 meters wide and 6 meters high. The area was reduced to about 50 m2 due to the installation of a steel structure that supported the fire protection boards.

In total four tests were performed with a fire in a semi-trailer set-up. In three tests mixtures of different chosen cellulose and plastic materials were used, and in one test a "*real*" commodity consisting of furniture and fixtures was used. In all tests the mass ratio was approximately 80% cellulose and 20% plastic. A polyester tarpaulin covered the cargo.

Illustration A2.5 shows the test configurations. *Table A2.3* provides the main details of the test results and *illustration A2.6* shows the variation of HRR with time for the tests.

Illustration A2.5 - Illustration of runehamar test setup

TABLE A2.3. RUNEHAMAR TEST DATA

FIRE LOAD	**Test 1**	**Test 2**	**Test 3**	**Test 4**
Materials	Wood pallets and plastic (Polyethylene) pallets (11010 kg)	Wood pallets and mattresses (Polyurethane) 6853 kg	Furniture and fixtures + rubber tires (7530 + 800 kg)	Plastic cups (Polystyrene) in cardboard boxes on wood pallets (2849kg)
Arrangement	A trailer load with total 11,1 ton wood (82%) and plastic pallets (18%). 360 wood pallets measuring 1200 800 150mm, 20 wood pallets measuring 1200 1000 150mm and 74 PE plastic pallets measuring 1200 800 150mm—122m^2 polyester tarpaulin.	A trailer load with total 6.8 ton wood pallets(82%) and PUR mattresses (18%). 216 wood pallets and 240 PUR mattresses measuring 1200 800 150mm—122m^2 polyester tarpaulin	A trailer with 8.5 ton furniture, fixtures and rubber tyres. Furniture and fixtures (tightly packed plastic and wood cabinet doors, upholstered PUR arm rests, upholstered sofas, stuffed animals, potted plant (plastic), toy house of wood, plastic toys). Ten large rubber tyres-122m^2 polyester tarpaulin	A trailer mock-up with 2.85 ton corrugated paper cartons filled with plastic cups (19%). 600 corrugated paper cartons with interiors (600mm 400mm 500mm; L W H) and 15% of total mass of unexpanded polystyrene (PS) cups (18,000 cups) and 40 wood pallets (1200 1000 150mm)—10m^2 polyester tarpaulin
FIRE LOAD PLATEAU (GJ)	244	135	179	62
Growing time (Time from ignition to peak HRR (min))	18.5	14.1	10	7.4
Maximum HRR value (MW)	201.9	156.6	118.6	66.4
Peak Temperature (°C)	1365	1282	1281	1305

Referring to *illustration A2.6*, it can be seen that the incubation time is about 4-6 minutes and the growth time, from developed fire to peak HRR, ranges from 4 to 10 min. The growth rate varies from 15 to 30 MW/min. Ventilation effects were also noted in these tests. In tests 1 and 2 a pulsation of the fire was observed which " *created a pulsating flow situation at the measuring station, where the measurements showed that the maximum velocity was pulsating in the range of 3 to 4 m/s down to a minimum in the range of 1 to 1.5 m/s*" [11].

It is interesting to compare the test configurations of the Benelux and Runehamar tests. The arrangements for Benelux tests 8 and 10 are qualitatively similar to that of Runehamar test 1 with the following quantitative differences:

- Runehamar T1 involved 380 wood pallets and 20 plastic pallets; the fire load was therefore about 11 times larger than in the Benelux tests.
- The Runehamar tunnel cross-section was significantly smaller (dimensions between the protection boards: width 7.1 m, maximum height 5 m)

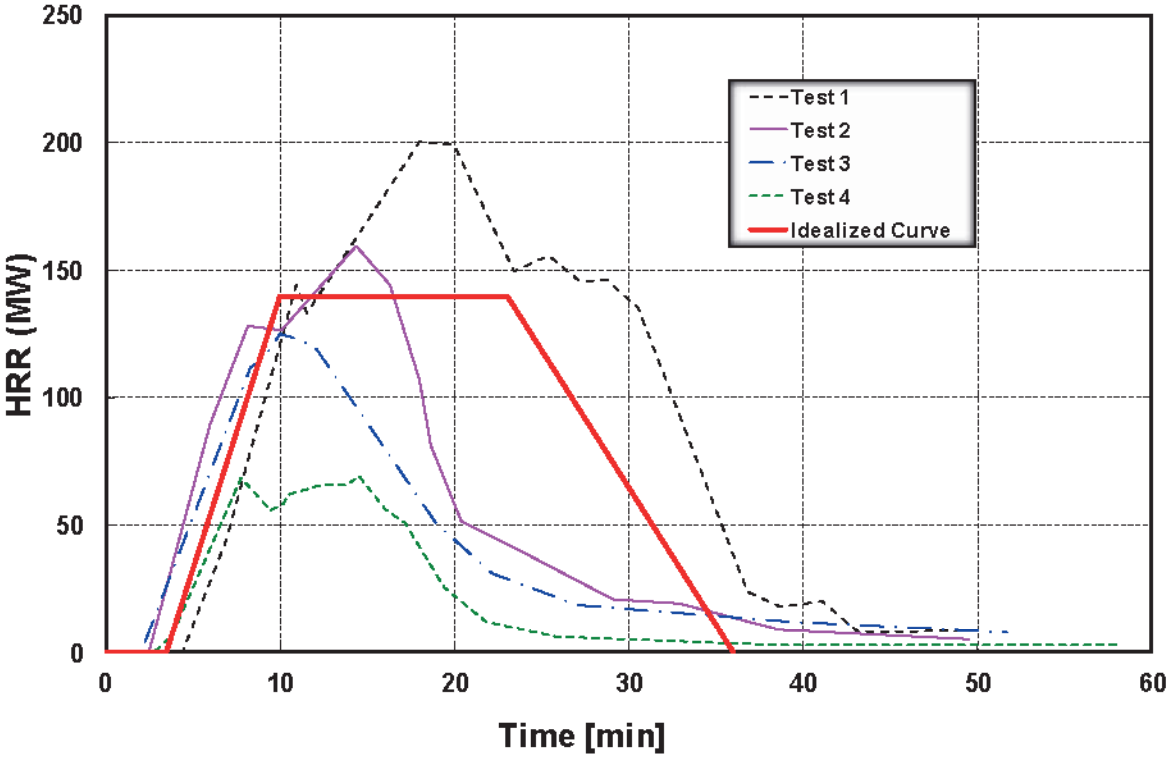


Illustration A2.6 - Runehamar test results [12]

Memorial tunnel fire ventilation test program
Other large-scale fire tests have been conducted to evaluate the fire and smoke behaviour in tunnels using pool fires. In most of them, measurements showed a clear correlation between the pool surface and maximum HRR. Nevertheless, due to the immediate development of the flashover phase, no interesting findings can be stated on this topic. One of the most complete large-scale fire test campaigns involving pool fires was the Memorial Tunnel.

The Memorial Tunnel Fire Ventilation Test Program (MTFVTP) [13] consisted of a series of full-scale fire tests conducted in an abandoned road tunnel. Various tunnel ventilation systems and configurations of such systems were operated to evaluate their respective smoke and temperature management capabilities. These tests generated a significant database relevant to the design and operation of road tunnel ventilation systems under fire emergency conditions.

The Memorial Tunnel is located near Charleston, West Virginia. This is a two-lane, 2800-foot long, mountain tunnel having a 3.2% grade. In preparation for the MTFVTP, the tunnel was modified and instrumented to allow operation and evaluation with the following ventilation system configurations:

- Full Transverse Ventilation
- Partial Transverse Ventilation
- Partial Transverse Ventilation with Single Point Extraction
- Partial Transverse Ventilation with Oversized Exhaust Ports Point Supply and Point
- Exhaust Operation Natural Ventilation
- Longitudinal Ventilation with Jet Fans

The tunnel was equipped with instrumentation and recording equipment for data acquisition. Sensors measuring air velocity, temperature, carbon monoxide (CO), and carbon dioxide (CO2) were installed at various tunnel sections. Data from these sensors were recorded. Smoke generation and movement and the resulting effect on visibility was assessed using seven remote-controlled television cameras with associated recording equipment.

Ventilation system effectiveness in managing smoke and temperature movement was tested for the following fire sizes: 10, 20, 50, and 100 megawatts (MW). The heat release of a 20 MW fire is approximately equivalent to a bus or truck fire, and a 100 MW fire is equivalent to a flammable fuel spill feeding a pool approximately 44.6 m2 (480 sq ft) in area.

In addition to varying the fire size, systematic variations were made in airflow quantity, longitudinal air velocity near the fire, and fan response time for each ventilation system. Tests were also conducted to assess the impact of longitudinal air velocities on the effectiveness of a foam suppression system.

In the MTFVTP, various smoke management strategies and combinations of strategies were employed, including extraction, transport, control direction of movement, and dilution to achieve the goals of offsetting buoyancy and external atmospheric conditions and to prevent backlayering. A total of 98 tests were conducted.

The basic findings to date are summarized below:

- The ASHRAE criteria of 0.155 m3/s per line-meter (100 cubic feet minute per lane-foot) of tunnel for emergency road tunnel ventilation has been used as a minimum design basis for many years. However, there had been no validation of this value. The tests showed that longitudinal airflow near a fire affects the required extraction rate for temperature and smoke management. Hence, specifying a ventilation rate for temperature and smoke management, solely on its extraction capabilities, is an insufficient design criteria.
- Longitudinal ventilation using jet fans was shown to be capable of managing smoke and heat resulting from heat releases up to 100 MW. The required longitudinal air velocity to prevent backlayering in the Memorial Tunnel was approximately 600 feet per minute (3 m/s) for a 100 MW fire. Since the longitudinal velocity generated by jet fans will manage temperature and smoke only on one side of the fire, to the detriment of smoke and temperature conditions on the opposite side, such systems should be applied only in road tunnels with uni-directional traffic flow.
- Jet fans positioned downstream of, and close to, the fire were subjected to temperatures high enough to cause failure. Accordingly, this condition needs to be considered in the system design and selection of emergency operational modes.
- Full transverse ventilation systems can be installed in single-zone or multi-zone configurations and can be operated in a balanced or unbalanced mode. Single-zone, balanced (equal flow rates for supply and exhaust air) full transverse systems indicated very limited smoke and temperature management capability. Ventilation-rates of 0.155 m^3/s per line-meter (100 cfm/lf) exhaust capacity did not manage conditions resulting from heat release rates of 20 MW and greater, unless the system was operated in an unbalanced mode (reduced supply airflow). Single-zone full transverse systems operated in the unbalanced mode had improved temperature management capability. However, even 0.155 m^3/s per line-meter (100 cfm/lf) exhaust capacity provided only limited temperature and smoke management for a 20 MW

heat release rate. Multiple zone full transverse systems have the inherent capability to manage smoke and temperature by creating longitudinal airflow.

- Partial transverse ventilation systems can be installed in single-zone or multi-zone configurations and can be operated in supply or exhaust mode. Single-zone partial transverse systems capable of only supplying air (no possible reversal of fans to exhaust air) were relatively ineffective in smoke or temperature management. Single-zone partial transverse systems which can be operated in the exhaust mode provided a degree of smoke and temperature management.
- Longitudinal airflow is a significant factor in the management of smoke and heat generated in a fire. Ventilation systems which effectively combine extraction and longitudinal airflow can significantly limit the spread of smoke and heat. Multiple-zone ventilation systems allow control over the direction and magnitude of longitudinal airflow, and can effectively manage smoke and temperatures in the tunnel. Two-zone partial transverse ventilation with 0.155 m^3/s per line-meter (100 cfm/lf) effectively managed 20 MW heat release rates.
- Single point extraction (SPE) is a ventilation system configuration capable of extracting large volumes of smoke from a specific location through large, controlled openings in a ceiling exhaust duct, thus preventing extensive migration of smoke. These openings range from 9.3 to 28 m^2 (100 sq ft to 300 sq ft) in size and are generally spaced on 91.5 m (300 ft) distributed along the tunnel. The SPE transverse type system effectively managed smoke and temperature conditions for a 20 MW fire with ventilation rates lower than 0.155 m^3/s per line-meter (100 cfm/lf). SPE systems are applicable to bi-directional traffic flow, with a degree of dependency, however, on the location and spacing of the SPE openings. Smoke and heat being drawn from the fire to the SPE opening could pass over or possibly around stalled traffic and vehicle occupants.
- Oversized exhaust ports (OEP) are a modification to transverse type systems which provides smoke extraction capability in the immediate location of a fire. The concept consists of 2.8 m^2 (30 sq ft) oversized exhaust ports spaced approximately 9 m (30 ft) and designed to fully open when subjected to the heat of a fire. Significant improvements in temperature and smoke conditions were obtained using OEPs relative to the basic transverse ventilation system using conventional size exhaust ports. The OEP enhancement is also applicable to tunnels with bi-directional traffic.
- Natural ventilation resulted in extensive spread of heat and smoke upgrade of the fire. However, the effects of natural buoyancy are dependent on the fire size and the physical characteristics of the tunnel.
- Fan response time, the interval between the onset of a fire and ventilation system activation, should be minimized since hot smoke layers can spread quickly, e.g., up to 490 to 580 m (1600 to 1900 ft) in the initial two minutes of a fire.
- The maximum temperature experienced at the inlet to the central fans (closest location to the fire approximately 213 m (700 ft) was 163 °C (325 °F) for a 100 MW fire, 124 °C (255 °F) for a 50 MW fire, and 107 °C (225 °F) for a 20 MW fire.
- The restriction to visibility caused by smoke occurs more quickly than does a temperature high enough to be debilitating. Carbon monoxide (CO) levels near the roadway never exceeded the guidelines established for the Test Program.
- The effectiveness of the foam suppression system was not diminished by operation in strong longitudinal airflow. In the MTFVTP, the system was operated and tested in conditions with 4 m/s (800 fpm) longitudinal air velocity.
- Adequate quantities of oxygen to support combustion were available from the tunnel air. The possible increase in fire intensity resulting from the initiation of ventilation did not outweigh the benefits.

Table A2.4 presents a summary of the actual measurements for the different tests examined.

TABLE A2.4. SUMMARY OF TEST MEASUREMENTS

Test Program	Fire Load	Test	t_{inc}	t_g	t_T	v	HRR_{max}	E_T	h_f/h_T	Growth Rate MW/min
			min	min	min	m/s	MW	GJ		
Eureka	Woodcrib	W31	4	8	100	0.0	9.5	16	0.47	1.2
		W41	4	14	60	2.5	27	32	0.47	1.9
		W51	4	16	70	4.5	22.8	26	0.47	1.4
	Heptane	H11	0	35	100	0.5	12	22	0.04	0.3
		H21	0	100	120	2.0	12	38	0.04	0.1
		H31	0	30	50	0.0	13	22	0.04	0.4
		H41	0	17	120	1.5	13	73	0.04	0.8
	Vehicles	Plastic (C21)	6	8	62	0.0	6.1	7	0.39	0.8
		Bus (B11)	1.5	8.5	110	0.0	28	56	0.62	3.3
		Mixed (LF1)	2	8	120	0.0	17	76	0.47	2.1
	HGV	HGV-GER	7	13	80	13.0	190	115	0.83	14.6
		HGV-NOR	8	13	27	13.5	320	116	0.83	24.6
		HGV-BR	9	10	65	14.0	130	131	0.83	13.0
Benelux	HGV	P9	4	6.5	30	6.0	19	10	0.00	3.0
		P10	4	8	30	6.0	16	10	0.00	2.0
		P14	6	11.9	29	0.0	26	19	0.00	2.2
Runehamar	HGV	Test 1	4.5	13.5	49	3.0	201	258	0.20	14.9
		Test 2	2.5	11.5	49	3.0	159	149	0.20	13.9
		Test 3	2	8	52	3.0	125	117	0.20	15.6
		Test 4	3	5	58	3.0	69	61	0.20	13.9

RWS fire suppression tests – Runehamar 2008

In January 2008 RWS conducted full scale fire test [14] on the water based fire suppression system designed for use in the A74 Roermond Tunnels in the Netherlands. The tests were carried out in the same location, and under similar conditions to, the earlier full-scale fire tests carried out at Runehamar by the Swedish Fire Research establishment. The objectives were to demonstrate the ability of a water mist fire suppression system to reduce significantly the heat output from a solid fire, and the ability of the system to extinguish a large flammable liquid fire.

The test layout is shown in *illustration A2.7* and comprised 3 sections of 25 m in length, spray nozzles every 2 meters a flow 3.000 l/min pressure 50 bar and AFFF mixing units.

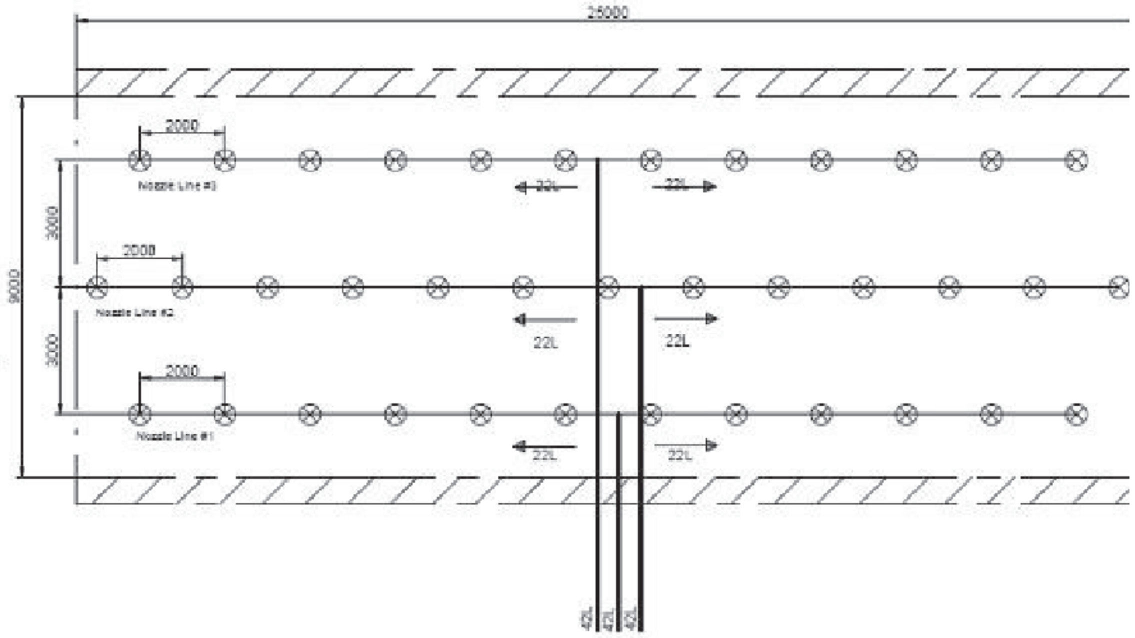


Illustration A2.7 - Fire suppression test layout

The test program considered solid and liquid fuel fires in the range anticipated range of 50 to 200 MW, as follows:

TABLE A2.5. RWS FIRE SUPPRESSION TESTS	
50 MW Solid (with AFFF)	To verify the requirements
200 MW Liquid (with AFFF)	
200 MW Liquid (without AFFF)	To investigate the system boundaries
200 MW Liquid (with bioversal)	
200 MW Solid (without AFFF)	

The flammable solid fires were similar to the 2003 full-scale fire tests, representing loaded trucks with wooden and plastic pallets. The flammable liquid fires utilised a 100 m^2 diesel pool. Ventilation air speeds were up to 5 m/s.

Temperature measurements are shown in *illustration A2.8*, showing that one minute after activation of the watermist the solid fire temperatures are reduced to less than 50 °C 20 m upstream and less than 280 °C 5 m down-stream. The liquid fire is extinguished.

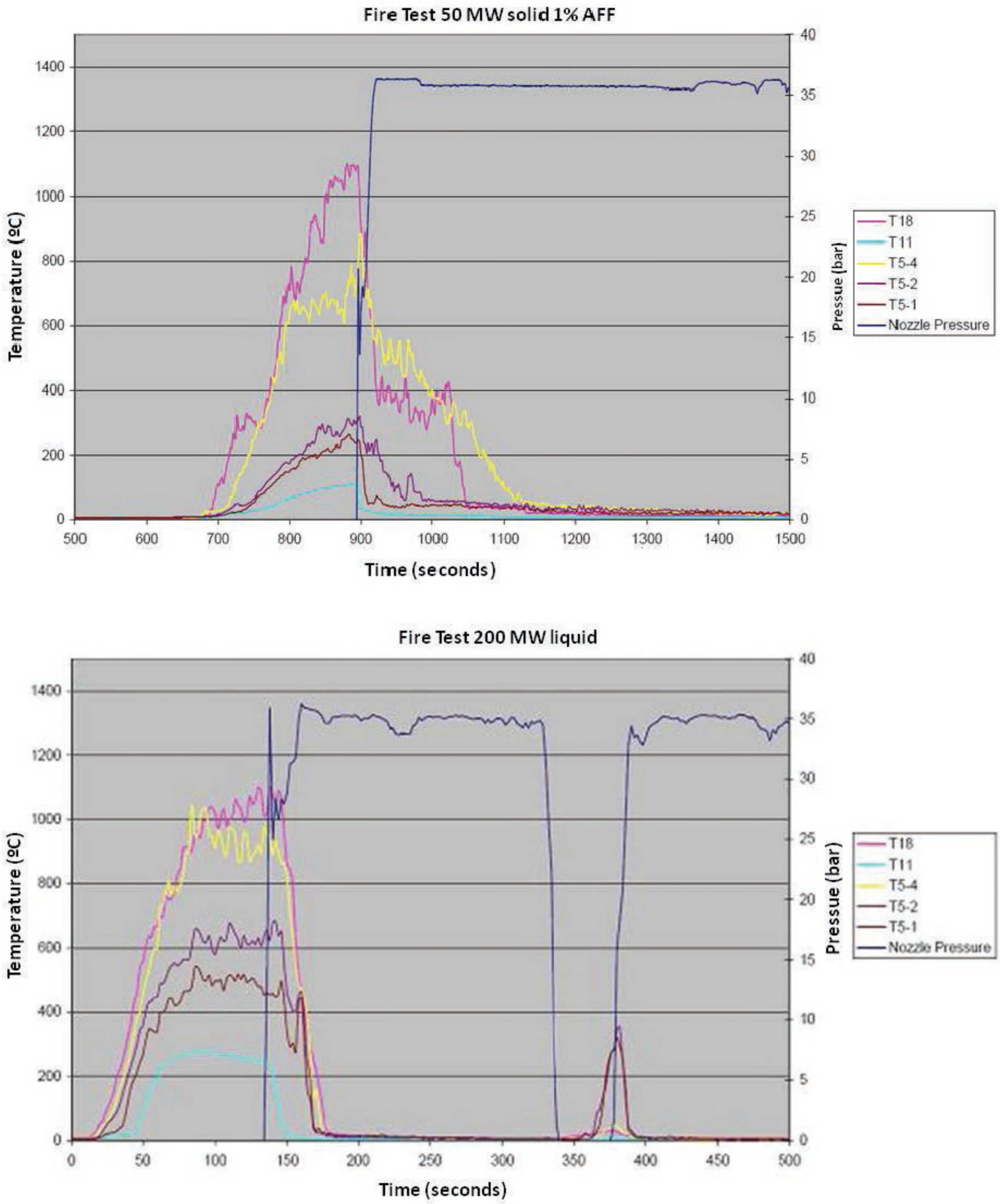


Illustration A2.8 - RWS suppression tests - temperature measurements

Tenability tests were also undertaken to determine conditions 20 and 300 m down stream of the fire, the parameters measured were temperature, CO concentration and visibility. *Illustration A 2.9* show the results at 300 m. It is clear that the conditions are untenable prior to the activation of the suppression system, but are restored afterwards.

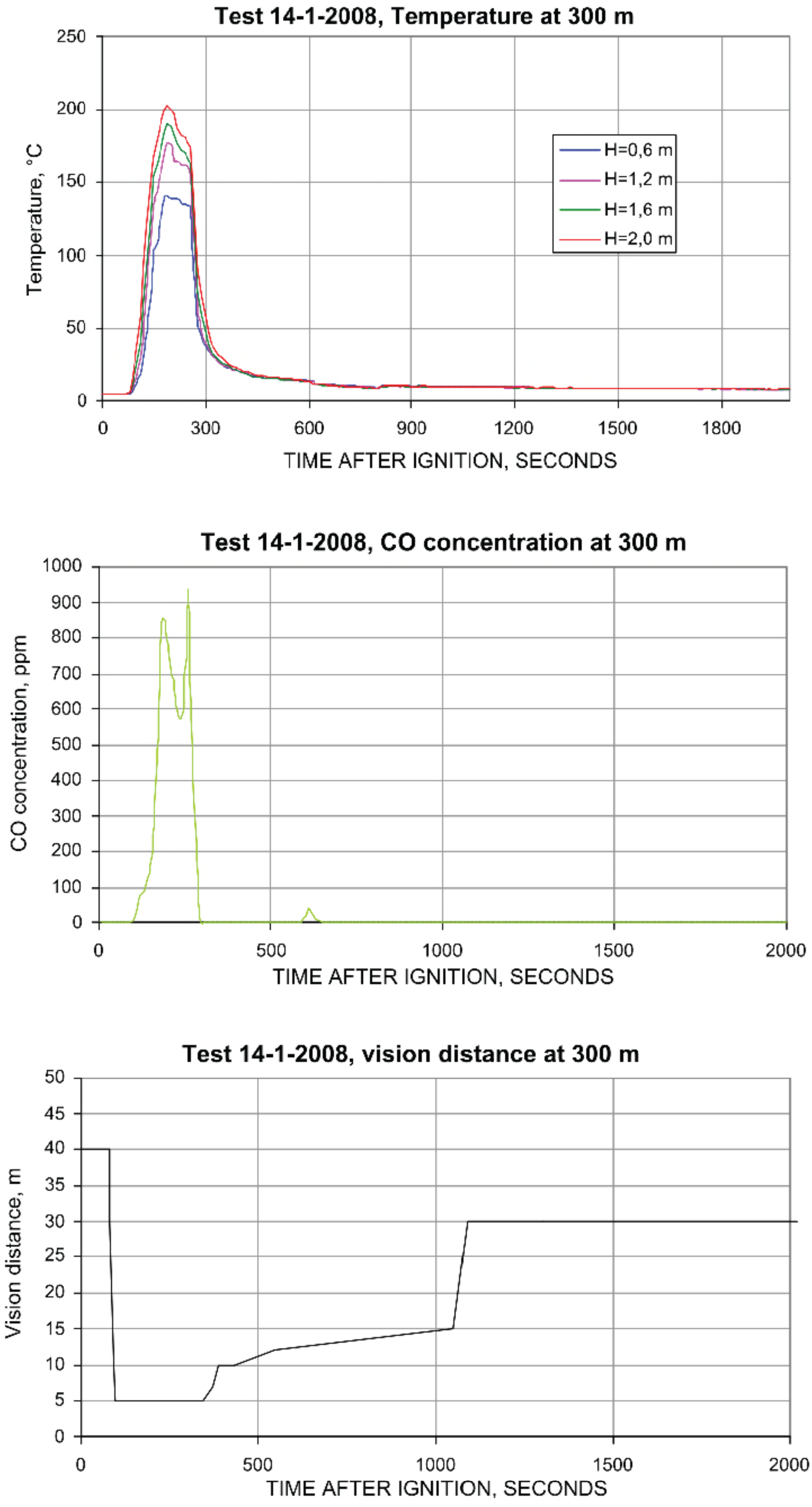


Illustration A2.9 - RWS suppression tests – tenability

2.4. DISCUSSION

The tests presented provide a useful database with regard to the form of the fire curve, considering the incubation period of the fire, the subsequent growth and peak value of HRR, and the decay time. The tests also show some specific correlation between some of the characteristics apparent in a tunnel and the aforementioned fire characteristics, such as the correlation between the fire load (combustible energy) and the peak heat release rate, and the impact of the air velocity in the tunnel and the fire growth and peak HRR. This effect was observed in the Runehamar test and, probably, on the EUREKA 499 Fire tests. This is important to consider, especially for narrow tunnels.

Fire growth and peak HRR, for open fires, show a substantial increase in conditions of higher air velocity. This is also in line with what would be expected, since it is well known that air forced over a fire increases the burning rate. The reason is twofold: more oxygen is transported to the fuel, increasing the combustion rate, and the deflection of the flame increases fire spread and consequently the fire growth rate. However fires in enclosed vehicles, where the air velocity is not able to contact the fire centre, do not behave in the same way as for open fires.

The fire tests in the Benelux tunnel indicated a fire growth rate twice as fast with an air velocity of 4-6 m/s compared with the fire growth rate without ventilation. The same test showed about 1.5 times the peak HRR rate at an air velocity of 4-6 m/s than without ventilation.

The increase in fire growth when increasing the air velocity can be estimated to be about 3.5 – 5.5 times higher if the air velocity is increased from zero up to 4-6 m/s. In the Benelux Test 9, the increase in fire growth rate was about 5.5 and in test 10 about 3.5. A study comparing results from full scale and small-scale tests verifies that the impact of air velocity on the fire growth almost follows a linear correlation, *illustration A2.10*, reference [26].

The impact of air velocity on the peak HRR is also demonstrated in the EUREKA HGV fire test with varying ventilation condition, 6m/s, 0m/s and 3m/s. The heat release rate was reduced from 120 MW at a forced air velocity of 6 m/s to nearly 42 MW without forced ventilation, i.e. a factor of three. When the fan was restarted with an air velocity of about 3 m/s, the heat release rate increased rapidly up to about 128 MW.

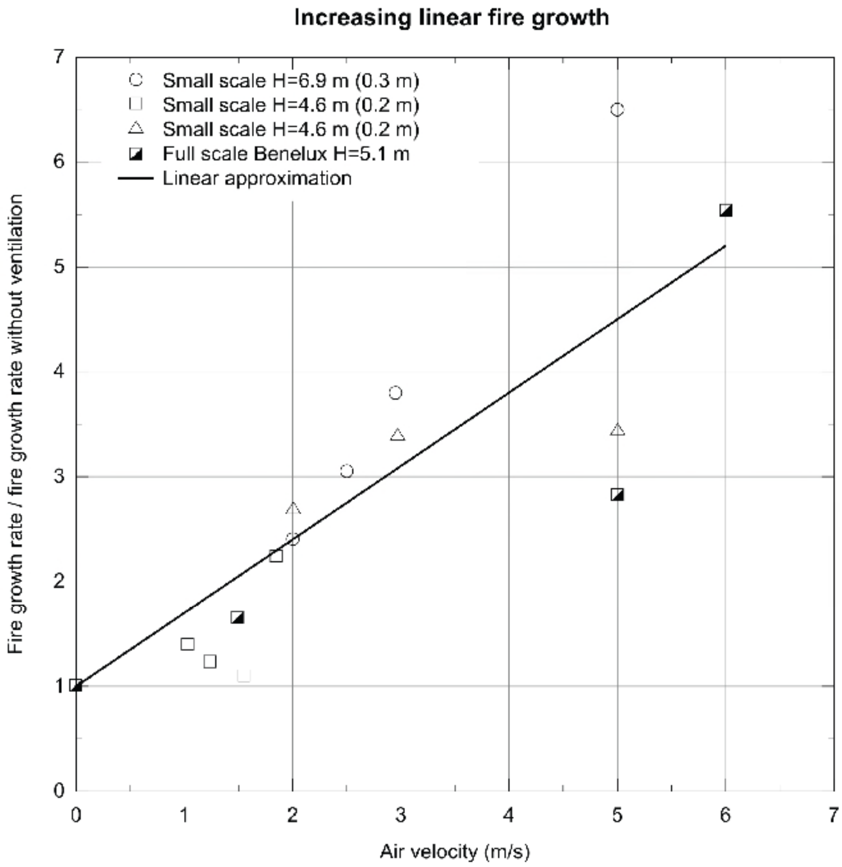


Illustration A2.10 - The relative impact of air velocity on the fire growth [26]

TABLE A2.6. SOME SPECIFIC FIRE CHARACTERISTICS MEASURED OR EVALUATED FROM FULL SCALE FIRE TESTS

Full scale fire tests	Fire Load (GJ)	Long. air velocity (m/s)	HRR (vicinity fire)	Linear fire growth rate (MW/min)
Benelux – test 8 – 36 wood pallets	10	0	N.A.	2,6 3,5
Benelux – test 9 – 36 wood pallets	10	4-6	N.A.	14,4
Benelux – test 10 – 36 wood pallets	10	6	N.A.	9
Benelux – test 14 – 72 wood pallets	19	1-2	26	3,6
EUREKA 499 School bus	41	0,3	29	N.A.
EUREKA 499 HGV	87	6 0 3	120 42 128	N.A.
Runehamar – test 1	247	3	202	20.1
Runehamar – test 2	135	3	157	26,3
Runehamar – test 3	179	3	119	16,4
Runehamar – test 4	62	3	66	16,9

Since the ventilation operating conditions influence the growth rate and HRR, it follows that the tunnel section characteristics, such as ceiling height and cross sectional area, must also influence the fire development. Therefore, the impact of these characteristics on the fire growth and fire size should be considered in the assessment of test results. In the Runehamar Test 1 the rock tunnel cross section area was about 50 square meters. At the location of the fire an additional inner tunnel was set up to function as protection of the rock tunnel. That inner tunnel cross-section area was about 32 square meters. In that section, stacks of wood and plastic pallets, simulating a loaded truck, were placed.

The distribution of the fire load is also likely to influence the test results. The Runehamar test (T1) exceeded higher heat release rates than the EUREKA HGV's 100-120 MW, but it is important to consider that the test setup with wood and plastic pallets was extraordinarily well ventilated due to the free air flow through the open pallets and accordingly gave an ideal combustion situation. The Runehamar test (T3) with upholstered furniture, fixtures, plastic and wood cabin doors and rubber tyres showed that fire development in an early phase was faster but did not reach the high HRR as test (T1) although the fire load was almost the same. The most significant difference between these two tests was the shape of the combustible material and the exposed surface area accessible for oxygen and burning. A more compact set up of fire load leads to less surface area per kg of combustible material and accordingly a lower HRR. The HRR measured in test (T3) correspond better with the EUREKA HGV test.