Chapter 3
Tunnel Fire Tests

Abstract This chapter gives a detailed overview of numerous large-scale fire tests carried out in different types of tunnels. Some important model scale tunnel fire tests are also included. The information given, sets the level of knowledge from this type of tunnel fire testing. The reason for doing tests is to obtain new knowledge about different phenomena. Although the focus is on large-scale testing, the fundamental knowledge is obtained both from large-scale and intermediate size tunnel testing as well as laboratory testing (For example, scale models). The aim is usually to investigate some specific problems such as influence of different ventilation systems on smoke and temperature distribution along the tunnel, the fire development in different type of vehicles, and the effect of heat exposure on the integrity and strength of the tunnel construction.

Keywords Fire tests · Measurements · Heat release rate (HRR) · Temperature · Flame length · Large-scale · Model scale

3.1 Introduction

Large-scale testing is generally costly as they are time consuming and logistically complicated to perform. This is one of the main reasons why the number of large-scale tests in tunnels is limited. The information obtained is sometimes incomplete and the instrumentation is often insufficient. There is a need, however, to perform large-scale tests in order to obtain acceptable verification in realistic scale. The data obtained from such large-scale tunnel fire tests, provides the basis for the technical standards and guidelines used for tunnel design today [1, 2].

An overview and analysis of large-scale tests performed in road and railway tunnels is given here. The analysis presented in this chapter is largely based on an overview given by Ingason [3]. The overview includes some additional information obtained since the overview was first published in 2007. The analysis of the large-scale experiment focus on presenting the following parameters:

- Measured maximum or peak heat release rates (HRR)
- Fuel mass loss rate

H. Ingason et al., *Tunnel Fire Dynamics,* DOI 10.1007/978-1-4939-2199-7_3

- Measured peak gas temperatures
- Flame lengths

In the second part, an overview of some model scale tests is given. It contains short description of the tests, and includes the main conclusions drawn. The main references are also included, both for the large-scale and model scale tests.

3.2 Overview of Large-Scale Tunnel Experiments

The variety of the large-scale tests is in the fire source, both type and HRR, instrumentation, technical documentation, tunnel geometry and ventilation conditions. A summation of all scientifically orientated large-scale tunnel fire tests that have been carried out worldwide since the beginning of 1960s until 2014, is given in Table 3.1. This summary excludes all commercial or legal orientated (reconstruction) large-scale testing and large-scale tunnel tests with fire suppression systems. The tests with fire suppression systems will be described in Chap. 16. These systems today, are termed as Fixed Fire Fighting Systems (FFFS). The data on HRR, temperatures, and flame lengths are given wherever possible.

The number of scientifically aimed large-scale fire test programs have been carried out to date is slightly more than a dozen. Most of the tests program included less than 30 tests, except for the Memorial test series which included 98 tests. The focus has mainly been on the heat and smoke spread and how different ventilation systems influence the parameters listed earlier. Nearly half of the test series included FFFS tests (sprinkler), which, as mentioned earlier, will be presented in more details in Chap. 16, but in this chapter the focus is on the results from free burn tests.

The quality of large-scale tests carried out in the 1960s–1980s varied considerably. The key fire hazard parameter, the HRR, has not been quantified in these tests. The boundary conditions such as wind at portals, air temperatures, lining surface etc. were usually not the most favorable for validation of advanced computer models. They were performed to fill a wide gap of nonexiting knowledge about influence of the ventilation systems on tunnel fires rather than to fulfill the need for advanced theoretical studies or validation of Computation Fluid Dynamic (CFD) fire models.

The first series of large-scale tunnel fire test were performed in the 1960s and the 1970s in Europe. They were mainly directed to solve the fire problems of road tunnels in Europe. Grant et al. [4] considered these tests as 'tantalizing snapshots' primarily due to the inadequate HRR data. The documentation on fuel mass loss rates, combustion efficiency, ventilation flow rates and wind, and pressure conditions was not sufficient to fully validate the functional relationships derived theoretically or in laboratory scale tests at that time.

Among these well-known large-scale tunnel fire test series in the 1960s and the 1970s in Europe are the Ofenegg (1965, 24 m^2, 190 m)[1] [5] series, the Glasgow

[1] (test year, cross section, tunnel length).

Table 3.1 Scientifically aimed large-scale fire tests performed since the middle of 1960s [3]

Test program, country, year	No of tests	Fire source	Tunnel cross section (m^2)	Tunnel height (m)	Tunnel length (m)	Measurements	Range of peak HRR (MW)	Comments
Ofenegg, Switzerland, 1965	11	Gasoline pool (6.6, 47.5, 95 m^2)	23	6	190	T, CO,O2,v, visibility	11–80	Single track rail tunnel, dead end, sprinkler
Glasgow, 1970	5	Kerosine pool (1.44, 2.88, 5.76 m^2)	39.5	5.2	620	T, OD	2–8	Disused railway tunnel
Zwenberg, Austria, 1974–1975	30	Gasoline pool (6.8, 13.6 m^2), wood and rubber	20	3.9	390	T, CO,CO2, NOx, CH, O2, v, OD	8–21	Disused railway tunnel
P.W.R.I, Japan, 1980	16	Gasoline pool (4, 6 m2), passenger car, bus	57.3	~6.8	700	T, CO, CO_2, v, OD, radiation	Pool: 9–14[a] Cars and buses un-known	Special test tunnel, sprinkler
P.W.R.I, Japan, 1980	8	Gasoline pool (4 m2), bus	58	~6.8	3277	T, CO, CO_2, O_2, v, OD, radiation	Pool: 9 Bus un-known	In use road tunnel, sprinkler
TUB—VTT, Finland, 1985	2	Wood cribs (simulate subway coach and collision of two cars)	24–31	5	140	HRR, T, m, CO, CO_2, O_2, v, OD	1.8–8	Disused cavern system
EUREKA EU499, Norway, 1990–1992	21	Wood cribs, heptane pool, cars, metro car, rail cars, HGV trailer and mockup	25–35	4.8–5.5	2300	HRR, T,CO, m,CO_2,O_2,SO_2,CxHy, NO, visibility, soot, m,v	2–120	Disused transportation tunnel
Memorial, USA, 1993–1995	98	Fuel oil (4.5–45 m2)	36 and 60	4.4 and 7.9	853	HRR, T, CO,CO_2,v, visibility	10–100	Disused road tunnel, sprinkler
Shimizu No. 3, Japan, 2001	10	Gasoline pool (1, 4, 9 m^2), cars, bus	115	8.5	1120	T, v, OD, radiation	2–30[a]	New road tunnel, sprinkler tests

Table 3.1 (continued)

Test program, country, year	No of tests	Fire source	Tunnel cross section (m^2)	Tunnel height (m)	Tunnel length (m)	Measurements	Range of peak HRR (MW)	Comments
2nd Benelux tunnel, The Netherlands, 2002	14	n-heptane + toulene, car, van, HGV mock up	50	5.1	872	HRR, T, m, radiation, v, OD, visibility	3–26	New road tunnel, sprinklers
Runehamar tunnel, Norway 2003, 2013	4	Cellulose, plastic, furniture, wood pallets	32–47	4.7–5.1	1600	HR, T,PT, CO, CO_2,O_2,HCN, H2O, isocyanates, OD, radiation	70–203	Disused road tunnel
Brunsberg, Sweden, 2011	2	Metro car	44	6.9	276	HRR, T,PT, CO, CO_2,O_2, OD, radiation	77	Disused rail tunnel
San Pedro tunnel, 2012	1	HGV mockup	37	5.2	600	HRR, T,PT, CO, CO_2,O_2, OD, radiation	150	Test tunnel
Carleton laboratory facility, 2011	2	Train and subway car	55	5.5	37	HRR, T, CO, CO_2,O_2	32–55	Laboratory facility

HRR heat release rate, *m* mass loss rate, *T* temperature, *PT* plate thermometer, *CO* carbon monoxide, *CO_2* carbon dioxide, *CH* hydrocarbon, *HCN* cyanide, *H_2O* water vapour, *v* velocity, *OD* optical density, visibility = cameras for smoke registration.

[a] The bus was determined to be equal to 20 MW convective and 30 MW total

series (1970, 40 m^2, 620 m) [6] and the Zwenberg series (1974–1975, 20 m^2, 370 m) [7, 6, 8]. Both the Ofenegg [9] and the Zwenberg [8] test series have been reported with commendable detail on the test data and the test setup. A less known large-scale test series was carried out in Japan in the late 1970s and beginning of the 1980s [10] (P.W.R.I- Public Works Research Institute). The documentation in English is somewhat limited. The tests were carried out in a large-scale test tunnel (1980, 57.3 m^2, 700 m) built by P.W.R.I and in a full-size road tunnel; Kakei Tunnel (1980, 58 m^2, 3277 m). This was the first time cars and buses were used in large-scale test series in tunnels. As was the case in other tests in Europe at that time, no HRR measurements were carried out. Some weight loss estimations were, however, carried out.

The tests carried out in the 1960s and the 1970s did, and still have, a major influence on the standards and guidelines used for fire safety in tunnels.

The use of the Oxygen (O_2) Consumption Calorimetry [11, 12] made it possible to more easily and accurately measure the HRR in tunnel fires. By measuring the oxygen concentration in the fire smoke it was possible to determine the HRR. This was the start to a new era in large-scale tunnel fire testing in the 1980s and 1990s. There were other gas-based methods introduced as well. For example Tewarson [13] introduced another gas analysis technique, the Carbon Dioxide (CO_2) generation for measurement of HRR. This method was not as widely used in fire laboratories as the Oxygen Consumption Calorimetry but both these techniques found their way into the tunnel fire testing.

A German (Technische Universität Braunschweig (TUB)) and Finnish (VTT) cooperation [14, 15] (1985, 24–31 m^2, 140 m) lead to the performance of two large-scale tests in a tunnel using wood cribs as fuel to simulate fire in a subway car (80 GJ), and in two passenger cars (11.7 GJ) colliding in a tunnel. The original idea was to utilize the oxygen consumption technique, but due to large uncertainties in the oxygen and flow measurements it was never completed [16]. The cooperation between TUB–VTT developed and widened later into the EUREKA project EU499 (FIRETUN) (1990–1992, 25–35 m^2, 2300 m) [15] in the early 1990s. The oxygen consumption calorimetry was used for the first time in the EUREKA EU499 project and made it possible to measure the HRR from large vehicles with a relatively good accuracy, although not nearly as good as in fire laboratories.

The EUREKA EU499 tests were performed in the beginning of 1990s. They became a milestone concerning new valuable information for tunnel engineers. This was especially valid for the great variety in the HRR data for vehicle types such as cars, train coaches, subway coaches, and articulated lorry with furnitures [17–19]. The tests have resulted in significant improvements of information regarding HRR levels for single vehicles in tunnels. The EUREKA EU499 tests contain the most comprehensive fire testing of rail- and metro vehicles ever performed. In the EUREKA EU499 tests, there was very little consideration given to the risk of fire spread between vehicles, mainly because prior to and at the time of the performance of the tests, there had not been that many serious large fire accidents involving multiple vehicles as turned out to be the case in the late 1990s and in the beginning of 2000. The great majority of road tunnel fires consist of fires in one or two vehicles whereas large catastrophic fires can involve multiple vehicles.

Another milestone in large-scale tunnel fire testing was obtained in the Memorial tunnel test series (1993–1995, 36–60 m^2, 853 m) [20] carried out between 1993 and 1995. The fire source consisted of low sulfur No 2 fuel oil pans (diesel) and not real vehicles. The aim was to use a well-defined fire source in order to compare the performance of the different ventilation systems. In order to investigate the influence of vehicles on the ventilation flow, silhouettes representing vehicles were placed at different locations. A comprehensive instrumentation was located in both the upstream and downstream directions of the fire. There is no doubt that, the Memorial tests demonstrated very well the performance and control of different types of ventilation systems. The tests also provide a very important source for validation of Computational Fluid Dynamics (CFD) models. The memorial test data is the best-documented fire test results ever made available (CD-ROM).

The test results were used as a basis for the design of the ventilation system in the Boston Central Artery Tunnel (BCAT) project and they have already had a great impact on the design of smoke control systems worldwide. The usefulness of longitudinal- and exhaust-ventilation was clearly shown as well as the positive performance of foam sprinkler systems. A confirmation of the correlation between HRR and 'critical velocity' was established for the first time in a large-scale test, especially the HRR independence of longitudinal velocity over 3 m/s. To date, these fire experiments are the most comprehensive and most expensive large-scale tests ever performed. There is no doubt that the EUREKA tests and the Memorial tests are the most well-known and well reputed large-scale fire test series to date. They have already been established as the 'large-scale fire tests' and provide a new base for standards and knowledge in tunnel fire safety.

Since the beginning of the 21st century there have been to date some mediocre fire test series performed in large-scale tunnels. Large-scale tests were performed in the No. 3 Shimizu Tunnel (2001, 115 m^2, 1120 m) on the New Tomei Expressway, using gasoline pan fires, cars and a bus [21]. These tests included natural and longitudinal ventilation as well as water sprinklers. The main focus was on heat and smoke spread in a large-cross section tunnel (three lanes). In the Second Benelux tunnel in the Netherlands (2002, 50 m^2, 872 m, large-scale tests with cars and Heavy Goods Vehicles (HGVs) mock-ups using wood pallets were performed in 2002 [22]. Tests with natural- and longitudinal-ventilation and water sprinkler systems were also performed here. These tests provide very important results on the effects of longitudinal ventilation on HRRs in HGVs and on car fires. A large-scale test series was carried out in the Runehamar tunnel (2003, 47 m^2, 1600 m) [23, 24]. Four tests using a mock-up of HGV fire loads were carried out. These tests provide an important information on fire development in different types of ordinary hazard goods and show that this type of goods can create fires which are similar in size as a gasoline tanker fire. The initial fire growth rate is although not as fast or comparable to that of a petrol tanker fire. The tests showed clearly that, the maximum gas temperature levels from ordinary hazardous goods could easily be similar to those from of a tank fire. The results from the Runehamar tests have already had implications on design fires in road tunnels and the furnace testing of tunnel elements. Two large-scale tests series have been performed involving rolling stocks, that is, in the Brunsberg tunnel and Carleton laboratory. They show that the peak HRR is much higher than what has been used in design. The maximum in those tests ranged from 32 to 77 MWs.

There are numerous tests found in the literature that has been carried out in 'intermediate-sized' tunnels. The cross sections vary between 5 and 13 m^2, which can be compared to the cross sections of the large-scale tests series presented which varied between 25 and 115 m^2. Apte et al. [25] presented a detailed study of pool fires in a tunnel (1991, 13 m^2, 130 m) using longitudinal ventilation in a typical mine roadway. These experiments were used for validating a computational fluid dynamics (CFD) approach to modelling tunnel fires. They also show the effects of longitudinal ventilation on burning rate of pool fires. An extensive series of experiment were carried at the Safety Executive Laboratory (HSE) in Buxton, England (1992–1993, 5.4 m^2, 366 m) [26]. Both obstructed- and open-tunnel situations were considered in the HSE tests. The former included one-third scale models of a part of a HGV shuttle train from the Channel Tunnel and the latter used kerosene pools. In the second phase of the test program, even wood cribs were used. The HRRs were measured using the oxygen consumption calorimetry technique and mass loss rates combined with a value of combustion efficiency. The objective was to provide data for CFD simulation of interaction of longitudinal flow and a back-layering smoke flow. The results suggested that the value of the critical velocity tended to some near constant value with increasing HRR, and thus did not conform to the simple theory developed by Thomas [27]. This discovery was very important for the design of longitudinal ventilation systems, especially when this finding was verified in the Memorial tunnel test series. Ingason et al. (1995, 9 m^2, 100 m) [28] presented results from tests carried out in an intermediate sized tunnel tests. These tests were carried out using wood cribs, pool fires, and a passenger car. The aim of these tests was to establish a correlation between optical smoke density and gas concentrations [29] for use in CFD simulations. The CFD codes at that time were not able to predict with any good accuracy the optical smoke density but they could predict the concentrations of gas species. The experiments showed a good correspondence between the measured optical density (visibility) and the measured gas concentrations at different locations in the tunnel and accordingly that this was an accessible way to predict the smoke optical density or visibility.

There are many other tests performed in large-scale tunnels, the main purpose has either been commercial testing or testing of the ventilation systems of a specific tunnel before it is put into operation. The fire source can either consist of pan fires, wood crib fires or car fires. Examples of such tests can be found in [30, 31] and in the Handbook of Tunnel Safety [32].

Within the framework of the legal enquiry initiated after the catastrophic fire in the Mont Blanc tunnel in 1999, a series of large-scale tests were conducted in the same tunnel (2000, 50 m^2, 11,600) [33]. The objective was to investigate the consequence of the fire during the first half hour. The tests were carried out in two phases. Three tests with diesel pool fires of 8 MW, modifying the smoke control conditions for each test, were carried out in the first phase and in the second phase a test with a real HGV truck and a trailer similar to that which generated the fire 1999 but with a much smaller amount of transported goods. The longitudinal flow at the fire location was about 1.5 m/s. In order to limit the peak HRR tyres had been removed and fuel tank was emptied. Only 400 kg of margarine were stored in the trailer. The total calorific value of the truck and the trailer with its goods was estimated to be 76 GJ. This value can be compared to the real value, which was estimated to be 500–600 GJ. The HGV was ignited by setting on fire successively three small pools filled with a diesel oil and alcohol mixture, respectively place in the HGV driver's cab, behind the cab and between the cab, and the trailer. During the first 40 min, the HRR of the HGV fire remained lower than that of the pool fire, about 6 MW. Then the HRR reached a level of 23 MW, which can be related to the extensive burning of the HGV trailer.

3.3 Large-Scale Tunnel Fire Tests

In the following more detailed information is given for each of the tests listed in Table 3.1. Most of the tests are without interaction of FFFS (deluge water spray systems or deluge sprinkler system). For these test, wherever possible, information of maximum HRRs ($\dot{Q}_{\max}$), fuel mass loss rate ($\dot{m}''_f$), ambient (T_0) and maximum ceiling temperatures (T_{max}), and maximum horizontal flame lengths (L_f) along the ceiling is given. The maximum horizontal flame lengths along the ceiling is based on the ceiling temperature measurements, assumed flame tip at 600 °C as proposed by Rew and Deaves [34]. In case of interaction with FFFS short information is given in this chapter, but more detailed information is given in Chap. 16.

3.3.1 Ofenegg 1965

The first large-scale tunnel fire test series to obtain scientific and engineering information was carried out in the Ofenegg tunnel in Switzerland, in1965 [5]. These tests were carried out in order to study the ventilation capacities (natural, longitudinal[2], semitransverse[3]) in the case of a fire, especially in case of a gasoline tank fire. The tests were expected to give information on the hazardous level for tunnel users, possibilities to rescue people and the impact on tunnel construction and installations. Also the influence of a FFFS (deluge sprinkler nozzles) was investigated. This type of information was urgently needed in Switzerland due to the large road tunnel projects carried out in the 1960s. The tunnel used for these experiments was a single track railway tunnel (23 m^2, 3.8 m wide and 6 m high), with wall located 190 m from the one portal and the ceiling was 6 m high with a rounded top. By closing the

[2] Longitudinal ventilation consists of fans blowing in outside air through the rear end duct system with an air quantity of 39 m^3/s, that is, a longitudinal velocity of 1.7 m/s.

[3] Semitransverse system have air inlets at low levels but either no extraction or extraction at only a few points, so that the air and vehicle exhaust gases flow along the tunnel, at a velocity which increases along the tunnel length. The fresh air supply equal to 0.25 m^3/s, m.

cross section the test tunnel became a dead end tunnel of 190 m in length. A total of 11 tests were performed using gasoline pool fires on a concrete trough with the edge placed 131.5 m from the open entrance. The other end (190 m) was bricked up. The sizes of the pools used were 6.6, 47.5 and 95 m^2, respectively, with the smallest representing the contents of the fuel tanks of two cars and the largest a substantial spill from a gasoline tanker. The width of the trough (fuel pan) was 3.8 m and the length of the trough varied; 1.7, 12.5 and 25 m, respectively.

The experiments showed that large quantities of smoke were generated in all the tests. The smoke front travelled along the tunnel at speeds of up to 11 m/s and the visibility deteriorated in most cases 10–20 s after the start of the fires. Generally, the greater the fuel quantity, the worse the conditions [35]. It was found that the heat evolution was a decisive factor for the possible escape of people. With a semi-transverse ventilation system supplying up to 15 m^3/s the burning rate was virtually unchanged compared to no ventilation. With a longitudinal ventilation system giving an air velocity along the tunnel of about 1.7 m/s, averaged over the cross-section of the tunnel, the burning rate of a 47.5 m^2 fire was about twice that for the 47.5 m^2 fire with no ventilation.

An estimation of the HRR was made by Ingason [3] and the results are presented in Table 3.2. The estimation, which is based on the measured fuel flow rates for each test [5] and an assumed combustion efficiency of 0.8 in the tunnel and a heat of combustion of 43.7 MJ/kg, show that the average HRR was 2.1 MW/m^2 for the 6.6 m^2 fuel, 0.95 MW/m^2 for the 47.5 m^2 fuel, and 0.35 MW/m^2 for the largest one (95 m^2). In the open the HRRs is in the order of 2.4 MW/m^2 (0.055 kg/(m^2 s) and $\Delta H_c = 43.7$ MJ/kg [36]). It is clear that the burning rate per square meter in these tests is highly influenced by the ventilation rate and the test setup. The poor accessibility of the oxygen to the fuel bed as the troughs (pans) used was nearly as wide (3.8 m) as the tunnel (4.2 m) is one of the reasons. In a wider tunnel the results may have been quite different. In the case where the longitudinal ventilation was used the burning rate increased dramatically, especially for the large fire (test no 7a, 47.5 m^2), since the oxygen was more effectively mixed with the fuel. Compared to gasoline fire in the open, the burning rate became slightly less per square meter when the fire was small (6.6 m^2). The maximum ceiling temperature obtained was 1325 °C and the average HRR was estimated to be 70 MW. With a natural-ventilation or semitransverse-ventilation the temperatures were slightly lower or about 1200 °C and the average HRR was between 33 and 39 MW. In general, we see that the maximum ceiling temperature varies between 450 and 1325 °C for average HRRs between 12 and 70 MW. Clearly, the temperatures are not only dependent on the level of the HRR but also by the ventilation conditions.

In Table 3.2, an estimation of the flame length, L_f, from the centre of the trough is given as well. The flame length is given both towards the portal where most of the air flow was directed and towards the end of the tunnel. It is calculated from the centre of the pool fire and it is based on linear interpolation of the peak gas temperatures measured in the 0.5 m below the ceiling and represent the 600 °C temperature front [34]. Here the size of the pool in combination with the ventilation conditions plays an important role whether the temperatures become high or low.

Table 3.2 Relevant data from the Ofenegg tunnel tests in 1965 [3]

Test no	A_f(m^2)	Type of ventilation	FFFS	Air supply ventilation (m^3/s)	T_0 (°C)	Velocity at portals at max conditions (2 min) (outflow/inflow)	$\dot{m}''_f$ lower-upper (kg/(m^2 s))	HRR lower-upper[a] (MW)	Average HRR (MW)	Average HRR per square meter fuel area (MW/m^2)	T_{max} (°C)	L_f towards portal (m)	L_f towards end (m)
1	6.6	Natural	No	0	16	2.2/1.5	0.062–0.074	14–17	16	2.4	710	18	0
2		Semitransverse	No	15	17.5	2.2/2.3	0.046–0.062	11–14	12	1.8	830	23	0
2a		Longitudinal	No	39	11	4.2/1.1	0.046–0.062	12–16	14	2.1	450	NA	NA
3		Natural	Yes	0	16	1.9/2.7	NA	NA			950	21	0
5	47.5	Natural	No	0	10	4.8/2.3	0.021–0.026	35–43	39	0.8	1200	66	11
6		Semitransverse	No	15	10	NA	0.019–0.021	32–35	33	0.7	1180	100	11
7a		Longitudinal	No	39	11.3	5.8/0.5 (out)	0.032–0.043	60–80	70	1.5	1325	74	7
7		Natural	Yes	0	11.3	–	NA	NA			995	58	11
9	95	Natural	No	0	4.6	4.6/3	0.010–0.011	33–37	35	0.4	1020	79	23
10		Semitransverse	No	6	9	5/2	0.009–0.010	30–33	32	0.3	850	82	23
11		Natural	Yes	0	11.2	4.1/2.8	NA	NA	NA		800	NA	NA

[a] $HRR = \eta \dot{m}''_f A_f \Delta H_c$ where η is the combustion efficiency, $\dot{m}''_f$ is the burning rate per square meter, A_f is the fuel area and ΔHc is the heat of combustion. We assume η=0.8 in tests with natural and semitransverse ventilation and η=0.9 in the tests with longitudinal ventilation. The heat of combustion ΔHc is assumed to be equal to 43.7 MJ/kg and the fuel density is assumed to be 740 kg/m^3 [36]. *NA* Not Available

In the tests with the 6.6 and 47.5 m^2 pool fires the temperature in the ceiling increased rapidly, and reached a maximum after about 2 min from the ignition. Shortly after reaching the maximum, the temperature dropped rapidly down and after about 10 min from ignition the temperature was in all cases without FFFS less than 200 °C. In the case with the largest pool fire (95 m^2) and no FFFS, the temperature was relatively constant at its high temperatures for about 8–10 min. The oxygen measurements indicated that all the oxygen was consumed. This indicates that the 95 m^2 pool fire was ventilation-controlled. That the fire was ventilation controlled could explain the large difference in HRR data per square meter and temperature data compared to the smaller pool fires.

These tests were very valuable for design of the tunnel ventilation systems at that time. Much effort was put into analyzing data in order to relate it to the conditions of evacuation. These tests had also, a major impact on the view of using FFFS in Europe. It was not found feasible to use FFFS in tunnels due to some adverse effects of the system. The FFFS were able to extinguish the fire, but the visibility was reduced in the vicinity of the fire and after the fire was extinguished in the gasoline, fuel vapour continued to evaporate. In the last test the critical concentration (20 min), that is fuel concentration in the vapor phase within the flammable limits was obtained and due to hot particles in the fire zone the vapor cloud ignited. The deflagration created resulted in a velocity of 30 m/s.

3.3.2 Glasgow 1970

The Building Research Establishment (BRE) (former Fire Research Station (FRS)) in the UK carried out in collaboration with the Glasgow fire brigade five experimental fires in a disused railway tunnel in Glasgow [35]. The purpose of the tests was originally not tunnel related. The tests were actually carried out to investigate smoke spread in an enclosed shopping mall. A disused railway tunnel was used because it was a reasonable approximation to certain features of such a building [35]. The disused railway tunnel was 620 m long, 7.6 m wide and 5.2 m high. Fires of one, two or four trays of kerosene were burnt. The trays were square with side length of 1.2 m, or area of 1.44 m^2 with a fuel load of 45-L kerosene. The estimated HRR in each tray was 2 MW [35], or 1.39 MW/m^2.

The experimental instrumentation was scattered inside the tunnel. The smoke layer height and the time of arrival of the smoke front were measured at 20 different locations with human observers using breathing apparatus. According to Heselden [35] there were some temperature and smoke obscuration measurements done, but no details are given. Observations from the tests show that smoke layer was actually quite flat (horizontal) during the tests. Heselden [35] describes thoroughly the smoke conditions within the tunnel after ignition;

"In all the tests the bulk of the smoke formed a coherent layer, which was initially 1–2 m thick depending on the size of the fire, and which gradually deepened as the test progressed, reaching 3–4 m deep for the largest fire 10 min after ignition.

The velocity of advance of the layer was in the region of 1–1.5 m/s, discounting the initial 1/2 minute when the burning rate was building up to an equilibrium value. In two tests the smoke nose was followed to the end of the tunnel, a distance of 414 m from the fire. The smoke layer was then quite well defined even though it would have been only some 5°C above the air beneath. It was found that, a layer or plug of smoke reaching to ground level often formed at the tunnel entrance probably due to the mixing and cooling produced by a cross wind; this plug tended to be drawn back into the tunnel with air current induced by the fire. The air below the main smoke layer was not perfectly clear. Although the bulk of the smoke formed a layer, some optically thinner smoke tended to build up in the clear layer below even before the ceiling smoke layer had reached the end of the tunnel. This may have been due to some mixing of smoke downwards at the smoke nose, which was more turbulent than the layer following it, or to mixing at obstructions (which were very few), or to wisps of smoke cooled by contact with the wall, clinging to the wall, and moving downwards where they were swept up by and mixed into the main air flow to the fire."

The Glasgow tests have not been widely referred to in the tunnel literature, most likely due to the scattered data obtained from these tests and the fact that the tests were not originally performed to improve tunnel fire safety. More detailed information about these tests can be found in reference [37].

3.3.3 The West Meon Tests in Early 1970s

The FRS was also involved in other large-scale tunnel testing in collaboration with local fire brigades. Heselden [35] reports briefly on the tests carried out in Hampshire in UK in early 1970s without giving any further references. These tests were carried out in connection with proposals for the channel tunnel, which opened for traffic in 1994. The FRS in collaboration with the Hampshire Fire Brigade and British Railways carried out an experimental fire in a disused railway tunnel near West Meon, Hampshire. The tunnel was 480 m long, 8 m wide and 6 m high and the cars to be burnt were placed 45 m from one of the tunnel portals. During the burning of one car a smoke layer up to 3 m thick formed under the roof but observers were able to remain near the fire without any ill effects except headaches afterwards. The flow of the smoky hot gas was controlled by the wind of about 2 m/s that was blowing through the tunnel.

3.3.4 Zwenberg 1975

A decade after the Ofenegg tunnel tests, a new test series was carried out in the Zwenberg tunnel in Austria 1975 [7]. The reason for these tests was similar as for the Ofenegg tests. Large road tunnel projects were planned in the early 1970s in Austria. The aim was to investigate the effects of different types of ventilation (longitudinal, semitransverse and transverse ventilation[4] on the distribution of smoke (visibility), heat and toxic gases, and the effects of heat on the ceiling construction and the exhaust fans. The Ofenegg tests concentrated on studying the conditions during fire with more or less unchanged ventilation pattern, whereas the main objective of the Zwenberg tests was to investigate how changing the ventilation pattern could influence conditions inside the tunnel. For the operation of tunnel ventilation the following two major questions had to be answered [6]:

1. What quantities of fresh air shall be supplied in order to provide the best conditions in case of tunnel fire?
2. What influence has forced longitudinal ventilation on the conditions inside the tunnel?

Beyond that, the scope of the research project was to study the effects of a tunnel fire on evacuees. In order to do that, the gas temperatures, content of toxic gases and oxygen in the tunnel, the visibility in the smoke, and the fire duration was measured. The aim was also to find ways to improve the situation in the tunnel by using different types of tunnel ventilation. The focus was also on the effects of the fire on the tunnel structure and technical equipment within the tunnel.

The tests were carried out in an abandoned railway tunnel owned by the Austrian Railways. The tunnel was 390 m long with a cross section of 20 m^2 (traffic space) and a ventilation duct of 4 m^2. The tunnel gradient was 2.5 % from the south to the north portal. The tunnel height up to the ventilation duct was 3.8 m and the tunnel width was 4.4 m. Fully transverse ventilation system was installed in the test tunnel, designed for a supply of 30 m^3/s of fresh air and for the same quantity of exhaust air. An injection fan installed near the southern portal was designed to provide a longitudinal flow up to 7 m/s in the traffic space. Every 6 m alternately a fresh air opening and a polluted air opening were installed.

The fire source was located 108 m from the south portal. It consisted of 12 individual concrete trays in two rows with a total volume of 900 L liquid (gasoline, diesel) corresponding to a surface area of 20 m^2 where the internal measures of each tray was 1 m wide and 1.7 m long. Only four trays (beside each other) were used in the standards test (6.8 m^2) and six in the large tests (13.6 m^2). A total of 46 measuring points for temperature were mounted, 11 for air and gas velocities, 19 for gas sampling (O_2, CO_2, CO, CH and NOx) and seven for visibility observations. Total of 30 tests, see Table 3.3, were performed using gasoline pools of 3.4, 6.8, and 13.6 m^2, respectively. The majority of the tests, 23 'standard fire' tests, were run using four trays with a fuel area of 6.8 m^2 and 200 L of fuel. This fire size was found to be sufficient to obtain useful data and avoid damages on the installation. In the tests with the 'standard fire' following parameters were varied:

1. Location of the fresh air supply (from below or above)
2. Quantity of polluted air to be exhausted

[4] Transverse ventilation system has both extraction and supply of air. Fully transverse ventilation have equal amount of exhaust and supply air.

Table 3.3 Relevant data from the Zwenberg tunnel fire tests in 1975 [3]

Test no.	Identification code of test[a]	Test conditions[a]	Fuel (litre, area, fuel type)	T_0 (°C)	$\dot{m}''_f$ (kg/(m^2 s))	Average HRR[b] (MW)	T_{max} (°C)	L_f towards north portal (m)	L_f towards south portal (m)
101	U-1-1-7-F	TOF	100, 3.4 m^2, gasoline	NA	0.064	8	NA	NA	NA
102	U-1-1-2.5-F	TOF	200, 6.8 m^2, gasoline	NA	0.051	12	NA	NA	NA
103	U-1-1-0-F	FTV		12	0.044	10	904	19	6
104	U-1-1/3–0-F			10	0.052	12	1240	14	60
105	X-1-0-0-F	EO		12	0.054	13	1320	11	12
106	0-1-1/3-0-F			8	0.049	12	1222	15	12
107	0–1-1–0-F	FTV		10	0.035	8	1080	17	10
203	U-1-1-0-A	FTV		8	0.041	10	856	21	6
204	U-1-1/3-0-A			10	0.041	10	1118	16	11
205	X-1-0-0-A	EO		10	0.051	12	1254	17	14
206	0-1-1/3-0-A			8	0.049	12	1318	20	20
207	0-1-1-0-A	FTV		10	0.033	8	1134	19	10
208	U-0-1-0-A	STV		12	0.035	8	822	23	7
209	U-1-1-2-A	FTV		14	0.048	13	663	15	0
210	U-1-1/3–2-A			12	0.045	12	563	5	0
211	U-1-1-2-F	FTV		12	0.044	12	670	16	0
212	X-0-0-2-A	PLV		14	0.044	12	623	12	0
213	X-0-0-4-A	PLV		12	0.045	12	312	10	0
214	X-0-0-0-A	EO		16	0.040	9	1000	23	0
215	0-1-1–2-F	FTV		12	0.044	12	612	10	0

Table 3.3 (continued)

Test no.	Identification code of test[a]	Test conditions[a]	Fuel (litre, area, fuel type)	T_0 (°C)	$\dot{m}''_f$ (kg/(m^2 s))	Average HRR[b] (MW)	T_{max} (°C)	L_f towards north portal (m)	L_f towards south portal (m)
216	0-0-1-0-A	STV		13	0.037	9	893	26	5
217	0-0-1/3–0-A	STV		11	0.032	8	1165	26	10
218	0-1-1/3–2-A			10	0.040	11	623	12	0
219	X-1-0-2-A	EEO		6	0.040	11	675	16	0
221	X-1-0-2-A	EO		8	0.028	7	723	4	0
220	X-1-0-0-A	EO	200, 6.8, diesel	8	0.041	10	643	13	0
301	X-1-0-0-A	EO	400, 13.6, gasoline	6	0.042	20	1332	59	12
302	0-1-1/3-0-A			6	0.035	17	1320	46	31
303	0-0-1/3-0-A			8	0.044	21	1330	60	21
2000	U-0-1-0-A	STV	Wood, rubber	NA	NA	NA	NA	NA	NA

NA not available

[a] *TF* test of facility (preliminary tests), *FTV* fully transverse ventilation, *EO* extraction only, *STV* semi transverse ventilation, *PLV* pure longitudinal ventilation, *EEV* enlarged extraction opening

[b] We assume in tests with natural and semitransverse ventilation and in the tests with longitudinal ventilation. The heat of combustion is assumed to be equal to 43.7 MJ/kg and the fuel density is assumed to be 740 kg/m^3 [36]

3. Quantity of air supply
4. Forced longitudinal ventilation in traffic space
5. Conditions in the traffic space (open or obstructed)

The selected combination of different test parameters can be obtained from the second column in Table 3.3.

As an example the identification code of test 210, that is, U—1–1/3–2– A is given according to the following system:

U	Location of fresh air supply
	U = from below
	O = from above
	X = no supply
1	Quantity of exhausted air
	1= nominal quantity 30 m^3/s
	1/3 = 10 m^3/s
1/3	Supplied quantity of fresh air
	1 = nominal quantity 30 m^3/s
	1/3 = one third of 30 = 10 m^3/s
2	Longitudinal flow in the traffic space (2 m/s)
A	Condition in the traffic space
	F free cross section
	A test models in the traffic space

The ventilation arrangement, the pool size, the length of the tunnel, and that no FFFS were used, are the main parameters that differ these tests from the Ofenegg tests. The average burning rate per square meter varied between 0.032 kg/(m^2 s) and 0.064 kg/(m^2 s) with an average value of 0.043 kg/(m^2 s), whereas in the Ofenegg tests it varied between 0.009 kg/(m^2 s) and 0.074 kg/(m^2 s). In the open a corresponding value for large pool fires is 0.055 kg/(m^2 s) [36], see Chap. 4. The burning rates in the Zwenberg and the Ofenegg tests are not based on any weighted results, it was calculated as the total fuel consumption divided by an estimated burning time. This will lead to conservative values since the burning rate varies with time, especially in the beginning of the test and during the period when the fire starts to decrease. In between these periods it should be relatively constant. As shown earlier the variation in the burning rates per square meter in these tests is much less than in the Ofenegg tests. The main reason is probably that the fire size was not nearly as large as in the Ofenegg tests and also that the tunnel was open in both ends and the total width of the pool (two trays beside each other ~2.5 m) was much less than the width of the tunnel (4.4 m).

Feizlmayr reports [3] that two classes of danger areas were used when analysing the results of the Zwenberg tests; class 1 areas with fatal effects and class 2 areas of potential danger. This type of classification was used in the Ofenegg tests as well. The criteria for class 2 used were the following; 80 °C temperature, 4.3 % CO_2 and 1000 ppm (0.1 %) of CO at heat level. The results of the Zwenberg tests showed that the extension of the danger area and smoke area (visibility) could be influenced to a great extent by the system of ventilation. The fully transverse ventilation (FTV), when properly designed air flow supply (throttle), was found to offer the best conditions for getting the fire situation under control. With semitransverse ventilation (STV) with only fresh air supply the system gave only modest improvements of the conditions within the tunnel. It was recommended to throttle the fresh air supply in order to improve the conditions. New STV installations should be designed so that in case of fire a quick change over from fresh air supply to air extraction could be achieved. In tunnels with bi-directional traffic, it was found that the FTV or STV (if properly designed) would be more effective in case of fire than the longitudinal ventilation system due to possibility of smoke extraction. Based on the Zwenberg tests, it was strongly recommended that longitudinal ventilation should be shut down in case of fire with exception that meteorological conditions require other measure to prevent the longitudinal flow. In tunnels with uni-directional traffic it was found that longitudinal ventilation system could protect the people on the upstream side of the fire, assuming that the vehicles were not trapped on the downstream side of the fire. The recommendations given after the Zwenberg tests have been a guide for the design of ventilation systems world-wide.

3.3.5 P.W.R.I 1980

The Public Works Research Institute (P.W.R.I.) in Japan performed two series of large-scale tests [10]. The first test series were carried out in P.W.R.I's own full-scale test tunnel facility and the second test series was carried out on the Chugoku Highway in the Kakeitou Tunnel. The full-scale tunnel at P.W.R.I. site has a total length of 700 m, a cross sectional area of 57.3 m^2 (H=6.8 m) and is equipped with ventilation system and FFFS. The Kakeitou tunnel has a total length of 3277 m, a cross sectional area of 58 m^2 (H=6.7 m), and is equipped with ventilating and FFFS. The majority of the experiments were conducted in the full-scale tunnel at P.W.R.I. but also in the Kakeitou tunnel. The main purpose of using the long tunnel was to determine the environment for people evacuating from tunnels.

The fire source consisted of gasoline pool (gasoline) fires, passenger cars, and large-sized buses. Gasoline pool fires of 4 and 6 m^2 were used to generate a HRR equal to the fire for large-sized vehicle, large-sized buses, and passenger cars. The pool fires were applied in order to accomplish steady and repeatable fires, which may not be the case in tests using real motor vehicles. Several real motor vehicles were, although used for confirmation of the results. Four to six sets of gasoline fire pools (trays) were arranged for fires, each having four 0.25 m^2 (a total of 1 m^2 fuel surface area) fire trays in one set. Further, 18 L of gasoline was uniformly placed in each fire tray in order to maintain almost the same burning rate for about 10 min after ignition. In the tests with passenger cars, doors of the driver's seat were left half-opened, while other doors and windows were closed. Approximately, 10–20 L of gasoline were put in the fuel tank of the passenger cars. For large-sized buses, the entrance door, exit doors, and the window next to the driver's seat were fully opened, and 50 L of light oil was put in the fuel tank. With respect to passenger cars and buses, pieces of cloth soaked in advance in a small amount of gasoline were placed on the rear seats and ignited. A comprehensive instrumentation was used in these test series. The gas temperatures (84 points in the Kakei tunnel), concentrations of smoke (78 points in the Kakei tunnel), gas velocities (5 points), concentrations of O^2, CO gases (1 and 3 points, respectively), radiation (1 point), and burning velocity (mass loss rate) were measured.

No HRR measurements were carried out in these tests. The fuel mass loss rate of the pool fires was measured as a reduction in the level of fuel. It is reported that at 1 m/s longitudinal velocity the mass fuel rate was 0.63 cm/min (0.078 kg/(m^2 s) assuming 740 kg/m^3 for gasoline) and 1.24 cm/min (0.153 kg/(m^2 s)) at 4 m/s. The authors refer to outside door test yielding 0.42 cm/min (0.052 kg/(m^2 s)). These burning rates can be compared to values given in Table 3.2 (Ofenegg) and Table 3.3 (Zwenberg). At low velocities the values are in the same order, whereas at high wind velocity it is about factor of two higher. On passenger cars the burning rate was reported to be 7.4 kg/min (0.15 kg/s) at 1 m/s and 10 kg/min (0.17 kg/s) at 4 m/s. Assuming an average heat of combustion of 30 MJ/kg this would correspond to 4.4 and 5 MW, respectively. The burning rate of the seats in the buses was reported to be 6.9 to 8.1 kg/min (0.11 kg/s and 0.14 kg/s).

The ventilation system was able to create a longitudinal flow up to 5 m/s. The FFFS facilities were set so that comparisons could be made between the presence and absence of FFFS under the same fire sources and the same longitudinal flow. Duration of FFFS was set at about 20 min. The area of FFFS was that area directly above the fire source. In some tests the FFFS was used downstream from the fire source in order to check the water cooling effect on hot air currents. The amount of water discharge was set at about 6 L/(min m^2) on road surface. In order to review the possibility of fire spread to following vehicles congested during the fire, an experimental case was carried out using cars which were arranged longitudinally and transversely.

The influence of the temperature due to the fire was found to be only limited to the nearby areas of the fire. In Table 3.4 a summary of all peak HRRs and ceiling temperatures is given. The data show clearly the effects of the longitudinal flow on the peak temperature in the ceiling. Higher velocity tends to lower the ceiling temperature due to dispersion of the hot air. It was not possible to extract any information about the flame lengths from the information available. An estimation of the free flame height for the pool fires used in this test series indicates that the flames were not impinging on the ceiling. The ceiling temperatures given in Table 3.4 confirm these calculations.

It is pointed out in the report [10] that it is extremely important to determine the behaviour of smoke and to control smoke when considering the evacuation possibilities during a tunnel fire. It was concluded that in the case of a 4 m^2 gasoline fire or a large-sized bus fire, the conditions for evacuation could be maintained near the road surface for about 10 min and over a distance of 300–400 m, if the longitudinal velocity was lower than 2 m/s. However, if the wind velocity increased, the smoke spread over to the entire section was such that any type of evacuation would become difficult.

Table 3.4 The test programme for the P.W.R.I. test series in Japan 1980 [3, 10]

Test no.	Test tunnel	Fire source (m^2, litre fuel)	u (m/s)	FFFS discharge time after ignition (min)	$\dot{Q}_{max}$ (MW)[a]	T_{max} (+5 m from centre) (no FFFS) (°C)
1	P.W.R.I. 700 m	4 m^2, 288 L	0.65	–	9.6	252
2	″	4, 288	5	–	9.6	41
3	″	4, 288	0.65	3	9.6	NAs
4	″	4, 288	5	3	9.6	NAs
5	″	6, 432	2	–	14.4	429
6	″	6, 432	2	0	14.4	NAs
7	″	Passenger car	1	–	NA	62
8	″	Passenger car	3	–	NA	NA
9	″	Passenger car	5	–	NA	NA
10	″	Passenger car	1	2.4	NA	NAs
11	″	Passenger car	3	2.4	NA	NAs
12	″	Passenger car	5	2.4	NA	NAs
13	″	Large-sized bus	5	–	NA	166
14	″	Large-sized bus	0.65	1.4	NA	NAs
15	″	Large-sized bus	2	10.5	NA	NAs
16	″	Large-sized bus	5	1.37	NA	NAs
17	Kakei 3277 m	4, 288	0	–	9.6	511
18	“	4, 288	2	–	9.6	199
19	“	4, 288	5	–	9.6	69
20	“	4, 288	0	3	9.6	NAs
21	“	4, 288	2	3.16	9.6	NAs
22	“	4, 288	5	3	9.6	NAs
23	“	Large-sized bus	0	–	NA	186
24	“	Large-sized bus	0	2.5	NA	–

NA not available, *NAs* not available temperature due to the FFFS.
[a] Based on estimation and not measurements. Due to the good ventilation condition we assume free burning conditions that is 2.4 MW/m^2 for gasoline (0.055 kg/(m^2 s) and 43.7 MJ/kg [36])

It was also found that the wind velocity in order to prevent back-layering was 2.5 m/s and that increasing the wind velocity would influence the fire so that the amount of heat and smoke would increase. It was found that the FFFS facilities of the present scale were not able to extinguish gasoline fire and roofed motor vehicles, but they were able to lower the nearby temperature and prevent fire spread to nearby motor vehicles. It was also shown that the FFFS may cause the smoke to descend and deteriorate the evacuation environment near the road surface, and therefore precautions should be taken concerning the method of operation sprinkling facilities.

3.3.6 TUB-VTT Tests 1986

As a part of German–Finnish cooperation on tunnel fires, the Technische Universität Braunschweig (TUB) in Germany and the Technical Research Centre of Finland (VTT) performed two large-scale tunnel fire test in 1985 in Lappeenranta in South Eastern part of Finland. This cooperation developed and widened later into EUREKA project EU499.

Two pilot tests were carried out in a tunnel in a limestone quarry 45 m below ground. The tunnel was 140 cm long, 6 m wide and 5 m high (30 m^2), and had natural calcite rock surfaces which were unprotected and without reinforcements. The first experiment was designed to simulate a fire in a subway car stalled in a tunnel. The second experiment simulated the case when one car in a queue of cars in a tunnel catches fire. Forced ventilation of fresh air at the rate of 7 m^3/s was used. This generated a longitudinal flow of 0.2–0.4 m/s over the cross section prior to ignition. At the maximum HRR an inflow of 0.3 m/s were measured in the lower part of the cross section and outflow of about 6 m/s in the upper part of the cross section at same location that is 19 m inside the exit portal. The fire load was made of wood cribs (moisture 17 %) nailed together in a way that allowed an air space of 50 % of the total volume. Temperatures of air, rock surface of the walls and the ceiling and temperatures of the steel, and concrete columns placed on the floor were recorded on several locations. Also, concentrations of O_2, CO_2 and CO, and air flow velocities were measured close to the exit of the tunnel. Fuel burning rate was determined by measuring the mass loss of wood on a weighing platform. The original idea was to utilize the oxygen consumption technique, but due to large uncertainties in O_2 and flow measurements it was never completed [16]. Smoke level and visibility were observed visually close to the exit.

In the first test (F1–1) the fire load of 7600 kg was distributed over an area of 3.2 × 48 m (spread as a layer on light concrete blocks 0.47 m above ground). After ignition at the upstream end of the fire load the wood cribs burned without flashover with a constant velocity of 0.66 mm/s for 21.5 h.

In the second test (F1–2) the fire load consisted of eight separated piles (cluster) of wood cribs, 1.6 × 1.6 m of area and 0.8 m of height each with a mass of 500 kg. The free space between the piles was 1.6 m and the lower end of the wood cribs was 0.5 m over the tunnel floor. Two adjacent piles were ignited simultaneously at the upstream end of the fire load. The fire growth rate was quite steep and reached a peak HRR of 8 MW after about 15 min into the test and then started to decay. The two wood piles burned out since it never spread to the adjacent wood piles. Therefore, a new ignition was done at the other end (downstream side) of the wood crib cluster. The fire growth rate was slower this time and reached a HRR of about 3 MW after about 20 min. The HRR was relatively constant at 3 MW (except one short peak at 4 MW) for about 45 min. The main difference between the first ignition and the second ignition is that the fire spreads downwind after the first ignition and upwind in the second ignition. The highest gas temperature in the ceiling after the first ignition was obtained after about 20 min into the test (F1–2); 679 °C and in the second ignition it was 405 °C obtained after about 26 min from the second ignition.

The experience from the tests shows that a spalling of the rock was a major problem. During the both experiments (F1-1 and F1-2) 10–20 cm thick layers of rock scaled off the walls and the ceiling in regions close to the fire, causing problems for safety of people carrying out the experiments, and also destroying some of the gauges during fire. One of the main conclusions from these experiments was that the theoretical calculations based on existing room fire codes did not reliably predict occurrence of flashover.

3.3.7 EUREKA EU499 Tests 1990–1992

The EUREKA EU499 test program was performed in an abandoned tunnel named Repparfjord Tunnel in northern Norway. The tunnel was 2.3 km long with a gradient less than 1 %, running north south from the main portal to a vertical shaft of 90 m height (cross section of the shaft was 9 m^2). The cross section of the tunnel was horseshoe shaped to rectangular with a flattened roof. The tunnel is approximately 5.3–7.0 m wide with a maximum height in the centre between 4.8 and 5.5 m.

The test programme included 21 large-scale tests, which were carried out in 1990, 1991, and 1992. The majority of the tests were performed in year 1992 as can be observed in Table 3.5. The main objectives of the EUREKA EU499 test program were to investigate the fire behavior of different type of fuels including real road and rail vehicles. Also to seek the possibilities of escape and rescue, and fire extinguish to see the damage of tunnel structure. The fire behavior of trains and HGVs revealed by these tests has had major effects on many design studies of large tunnel projects today.

The main results of the EUREKA EU499 project relates to the unique data of measured HRR for real vehicles where the oxygen consumption calorimetry was applied for the first time in large-scale tunnel tests. It also contained well-defined fire sources such as wood cribs and heptane pool fires, which are very valuable for scientific analysis. The wood crib tests showed a tendency of increased fire growth rate with increased ventilation rate, whereas it was not as apparent for the peak HRR. Results showed that generally the temperature of vehicles with body structure, which can melt away, for example, the aluminum subway coach and the school bus (GFRP), could reach ceiling temperatures from 800 to 1060 °C and HRR of 29–43 MW (tests 7, 11, and 14). For trains with steel body structure the HRR was less than 19 MW, fire duration longer and the ceiling temperatures tended to be lower than 800 °C (tests 4, 5, 12, and 13). For the passenger car, the highest temperature was between 210 and 480 °C and the HRR was up to 6 MW (tests 3 and 20). The same tendency about the influence of the body type on the results is found for the plastic car and the steel body passenger car. The estimated flame lengths are given in Table 3.5 as towards the portal and towards the vertical shaft. It is based on

Table 3.5 Relevant data from the test program for the EUREKA EU499 test series [3]

Test no.	Date of test	Fire load	u (m/s)	E_{tot} (GJ)	$\dot{Q}_{max}$ (MW)	T_0 (°C)	T_{max} (0 m) (°C)	T_{max} (+10 m from the centre) (°C)	L_f Towards portal (m)	L_f Towards shaft (m)
1	7.12.1990	Wood cribs no 1	0.3	27.5	NA	~5	NA	500	NA	NA
2	24.07.1991	Wood cribs no 2	0.3	27.5	NA	~5	NA	265	NA	NA
3	8.8.1991	Private car (steel body)	0.3	6	NA	~5	210	127	NA	NA
4	19.8.1991	Metro car F3 (steel)	0.3	33	NA	4.5	480	630	NA	~17
5	29.8.1991	Half rail car F5 (steel)	0.3	15.4	NA	1.7	NA	430	NA	NA
6	4.9.1991	Half rail car F6 (steel)	0.3	12.1	NA	4	NA	NA	NA	NA
7	23.8.1992	School bus (GFRP)	0.3	40.8	29	3	800	690	0	~17
8	28.8.1992	Wood cribs no 3	0.3	17.2	9.5	~8	NA	480	NA	NA
9	30.8.1992	Wood cribs no 4	3–4	17.9	11[a]	8.2	NA	440	NA	NA
10	31.8.1992	Wood cribs no 5	6–8	18	12[a]	10.4	NA	290	NA	NA
11	13.9.1992	1.5 rail cars F2Al+F7 (Aluminium+steel)	6–8/3–4	57.5	43	3.3	980	950	0	~20
12	25.9.1992	Rail car F2St (steel)	0.5	62.5	19	4.7	650	830	0	~20
13	7.10.1992	Rail car F1 (steel)	0.5	76.9	13	2.2	450	720	0	~20
14	14.10.1992	Metro car F4 (Aluminium)	0.5	41.4	35	1.6	810	1060	~11	~22

Table 3.5 (continued)

Test no.	Date of test	Fire load	u (m/s)	E_{tot} (GJ)	$\dot{Q}_{max}$ (MW)	T_0 (°C)	T_{max} (0 m) (°C)	T_{max} (+10 m from the centre) (°C)	L_f Towards portal (m)	L_f Towards shaft (m)
15	23.10.1992	Mixed load simulating truck load	0.5	63.3	17	~0	NA	400	NA	NA
16	27.10.1992	1 m^2 heptane pool no 1	0.6–1.0	18.2	3.5[b]	~0	NA	540	–[c]	–
17	28.10.1992	1 m^2 heptane pool no 2	1.5–2.0	27.3	3.5[b]	~0	340	400	–	–
18	29.10.1992	3 m^2 heptane pool no 3	1.5–2.0	21.2	7[b]	~0	NA	NA	–	–
19	29.10.1992	3 m^2 heptane pool no 4	2.0–2.5	54.5	7[b]	~0	NA	NA	–	–
20	4.11.1992	Private car (plastic)	0.5	7	6	0	480	250	NA	NA
21	12.11.1992	Heavy Goods Vehicle (HGV) with furnitures	6–8/3–4	87.4	128	~0	925	970	~19	38

[a] Fuel mass loss rate times where = 17 MJ/kg for wood
[b] Measured average burning rate 78 g/m^2 s multiplied with = 44.6 MJ/kg and 1 m^2
[c] minus (−) sign indicate that there were no horizontal flame lengths, L_f, registred by the thermocouples

600 °C flame tip obtained from maximum temperature graphs as a function of the distance from the centre of the fire given by Ekkehard [38].

The EUREKA EU499 tests show the importance of the glazed windows on the fire growth in the steel body trains. The fire growth rate is apparently governed by the sequence and timing of the window cracking. This can be shown by analyzing the temperature development inside the train compartments. The type of interior material (former or new design) appears not to be as eminent for the fire growth as expected. The type of body and the quality of the windows appears to be more important than the type of interior materials. For a heavy goods load (furniture's), which is not contained by any steel or aluminum body, the corresponding data were about 1000 °C and a HRR of 120–128 MW. The propagation speed of smoke front was constant along the tunnel, implying that the behavior smoke propagation was similar to the movement of gravity currents.

3.3.8 Memorial Tunnel Tests 1993–1995

The Memorial Tunnel Fire Ventilation Test Program (MTFVTP) consisted of a series of large-scale fire tests carried out 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. The Memorial Tunnel test program was performed in a two-lane, 853 m long and 8.8 m wide road tunnel built in 1953, taken out of traffic 1987 and was a part of the West Virginia Turnpike. The tunnel has a 3.2 % upgrade from south to north portal. The tunnel was originally designed with a transverse ventilation system, consisting of a supply fan chamber at the south portal and an exhaust fan chamber at the north portal. An overhead air duct, formed by a concrete ceiling 4.3 m above the roadway, was split into supply and exhaust section by a vertical concrete dividing wall. In some of the tests, the horizontal ceiling was removed in order to put in place 24 reversible jet fans in-group of three equally spaced, over the tunnel. The cross section changed from rectangular shape with cross sectional area of 36.2 m^2 to more of a horseshoe shape with an height of 7.8 m and a cross sectional area of 60.4 m^2. These fans had a 56 kW motor and an outlet velocity of 34.2 m/s and a volume flow of 43 m^3/s. They were designed to withstand air temperatures of about 300 °C.

The test programme consisted of 98 tests where the type of ventilation, fuel size and FFFS were changed. The ventilation systems was modified and run with the following system configurations:

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

Table 3.6 Relevant data from the Memorial Tests program with different type of ventilation system. In the case of the mechanical ventilation the peak temperature and flame lengths are obtained after the start of the ventilation [3]

Test Id.	Type of ventilation	u (m/s)	T_0 (°C)	H (m)	Nominal $\dot{Q}_{max}$ (MW)	T_{max} (°C)	L_f toward north portal (m)	L_f toward south portal (m)
101CR	Full Tranverse		21	4,4	10	574	–	–
103	Full Tranverse		19	4.4	20	1361	10	10
113A	Full Transverse		20	4.4	50	1354	37	0
217A	Partial Tranverse (PTV)		13	4.4	50	1350	45	6
238A	PTV-Two Zone		23	4.4	50	1224	21	13
239	PTV-Two Zone		21	4.4	100	1298	54	15
312A	PTV-Single Point Extraction		13	4.4	50	1301	42	7
318A	Point Supply and Point Extraction		11	4.4	50	1125	22	20
401A	PTV-Oversized Exhaust Ports		21	4.4	50	1082	21	12
605	Longitudinal	2.2	6	7.9	10	180	–	–
607	Longitudinal	2.1	6	7.9	20	366	–	–
624B	Longitudinal	2.3	14	7.9	50	720	–	21
625B	Longitudinal	2.2	15	7.9	100	1067	–	85
501	Natural ventilation		13	7.9	20	492	–	–
502	Natural ventilation		10	7.9	50	923	27	–

minus (−) sign indicate that there were no horizontal flame lengths, L_f, registred by the thermocouples

The tunnel was equipped with instrumentation and recording equipment for data acquisition. Sensors measuring air velocity, temperature, carbon monoxide (CO), carbon dioxide (CO_2), and total hydrocarbon content (THC) were installed at 12 cross sections along the tunnel. In total there were approximately 1400 measuring points, each point was recorded once every second during the test (the test time ranged from about 20 to 45 min). Smoke generation and movement and the resulting effect on visibility was assessed using seven remote-controlled television cameras with associated recording equipment.

It is not possible to present all the tests data from the Memorial Tunnel tests due to the large amount of tests performed (in total 98 tests). An extract of data for T_0, $T_{max,}$ and L_f is given in Table 3.6. The data is collected after the mechanical ventilation system has been started. For the full transverse ventilation, longitudinal ventilation, and the natural ventilation tests, test results with nominal HRRs of 10, 20, 50, and 100 MW were given. For partial transverse ventilation systems only 50

Table 3.7 Relevant data from the Memorial Test program. The table shows data from tests with mechanical ventilation where the data is taken prior to the start of the mechanical ventilation (that is, during the preburn time) [3]

Test Id.	T_0 (°C)	H (m)	Nominal $\dot{Q}_{max}$ (MW)	T_{max} (°C)	L_f toward north portal (m)	L_f toward south portal (m)
101CR	21	4.4	10	281	–	–
103	19	4.4	20	1053	8	7
217A	13	4.4	50	1169	8	9
239	21	4.4	100	1210	41	17
606A	6	7.9	10	152	–	–
618A	11	7.9	20	378	–	–
624B	10	7.9	50	829	10	7
615B	8	7.9	100	957	27	9

minus (−) sign indicate that there were no horizontal flame lengths, L_f, registred by the thermocouples

and 100 MW (if available) tests are presented. For comparison, data from tests with mechanical ventilation where the data is taken during the preburn time (the period prior to the start of the mechanical ventilation when there was a natural ventilation), is presented in Table 3.7.

Ventilation system effectiveness in managing smoke and temperature movement was tested in advance for the calculated fire sizes (nominal): 10, 20, 50, and 100 MW. The corresponding fuel surface area is 4.5 m^2, 9 m^2, 22.2 m^2 and 44.4 m^2, respectively, meaning an average HRR of 2.25 MW/m^2. The fire source consisted of low-sulfur No 2 fuel oil (diesel fuel with lowered sulfur content) in different pools. 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. 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 condition and to prevent backlayering (critical velocity).

The main findings from the Memorial tests are according to the test report [20]:

- The Memorial Tunnel fire ventilation tests have shown that, longitudinal airflow near a fire is equally important as extraction rate for temperature and smoke management. Therefore, specifying a ventilation rate for temperature and smoke management, solely on its extraction capabilities, is insufficient. Further, any criteria established for emergency ventilation should include the impact of tunnel physical characteristics and tunnel ventilation system.
- 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 back-layering in the Memorial Tunnel was approximately 3 m/s for a 100 MW fire.

- 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. 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.
- 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.
- Oversized exhaust ports (OEP) are a modification to transverse type systems which provides smoke extraction capability in the immediate location of a fire. Significant improvement 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.
- 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.
- 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.

3.3.9 Shimizu No. 3 2001

In year 2001, ten fire tests were conducted in the three-lane No. 3 Shimizu tunnel on the New Toumei expressway in Japan [39]. The tunnel was 1119 m long with a slope of 2 % down from west to east. The cross-sectional area was 115 m^2 and the width and the height was 16.5 m and 8.5 m, respectively. The cross section was shaped as a semicircle. The reason for performing these tests was to investigate the fire behavior in tunnels with large cross section regarding combustion rate, formation of smoke layer, interaction of longitudinal flow on the smoke distribution and behavior of FFFS on the smoke layer, and risk for fire spread. Comparison with the P.W.R.I tests (2-lane tunnel) was one of the main arguments for performing these tests. Numerous studies have been published from these tests focusing on different subjects concerning convective HRR and numerical simulations [40], smoke decent [41], plume fires in large tunnel cross section [42], and bus fire [43].

The fire source consisted of gasoline pools with an area of 1, 4, and 9 m^2. In the 1 m^2 pool fire, no forced ventilation was used. In the 4 m^2 pool fire case, tests were carried out both with and without forced ventilation. The forced ventilation consisted of longitudinal ventilation of 2 and 5 m/s from west to east portal. In the 9 m^2 case, longitudinal ventilation of 2 m/s was used. When no forced ventilation was used the west portal was blocked. One test with three passenger cars and a longitudinal velocity of 5 m/s was carried out as well as a single large bus with a longitudinal flow of 2 m/s. Jet fans installed in the west portal created the longitudinal flow in the tunnel. Measurements were made at a number of points throughout the tunnel. Temperature (91 points) was measured by type K thermocouples, optical smoke density (57 points) was measured by optical penetration type absorption density meters, heat radiation was measured by a radiation meter located on the floor 30 m west of the fire, and longitudinal air velocity was measured by means of a vane anemometer (measurable range 0.3–15 m/s) located 100 m east of the fire [40].

In Table 3.8, a summary of the information obtained from references [39–43] is given. There was no information about the ambient temperature, T_0, but only the temperature differences. There was no information on the discharge time of the FFFS available. There was not enough information available to obtain any horizontal flame length. Most likely there were no horizontal flames along the ceiling in these tests, which can be shown by using free burning flame height equations, see example, [44].

The information obtained from these tests is by no means unique. One exception is the test with the large bus and the fact that these tests were performed in a tunnel with a very large cross section. Since the fires used were relatively small it is difficult to see any dramatic effects of the size of the cross section on temperatures or smoke distribution.

3.3.10 2nd Benelux Tests 2002

Fourteen large-scale tests were carried out in the Second Benelux Tunnel in the Netherlands in 2002. The tests were designed to assess the tenability conditions for escaping motorists in case tunnel fire and to assess the efficiency of detection system, ventilation system, and FFFS for numerous type of fire sources. These were pool fires, passenger cars, a van, and mock-ups with truckloads. Temperatures, ra-

Table 3.8 Relevant data from test program and data for the No 3. Shimizu Tunnel tests in 2001 [3]

Test no.	Test id.	Fire source (m^2)	u (m/s)	T_0 (°C)	FFFS discharge time from ignition (min)	$\dot{Q}_{max}$ (MW)[a]	ΔT_{max} (°C)
1	1G-0	1	0	NA	NA	2.4	110
2	4G-0	4	0	NA	NA	9.6	577
3	4G-2	4	2	NA	NA	9.6	144
4	4G-5	4	5	NA	NA	9.6	58
5	4G-0	4	0	NA	NA	9.6	NA
6	4G-2	4	2	NA	NA	9.6	NA
7	4G-5	4	5	NA	NA	9.6	NA
8	9G-2	9	2	NA	NA	21.6	300
9		3 passenger cars	5	NA	NA	NA	NA
10		Single large bus	2	NA	NA	30[b]	283

NA not available

[a] Due to the good ventilation condition we assume free burning conditions that is 2.4 MW/m^2 for gasoline (0.055 kg/(m^2 s) 43.7 MJ/kg [36])

[b] This is estimated from the convective HRR of 20 MW derived by Kunikane et al. [43] because a FFFS was activated when the convective HRR was 16.5 MW. We assume that 67 % of the HRR is convective and thereby we can estimate the HRR = 20/0.67 = 30 MW

diation levels, and optical densities in the tunnel were measured, as well as smoke velocities and HRRs.

The tests were carried out in a sink tunnel outside Rotterdam. In Table 3.9 results from these tests are given. The tunnel has a rectangular cross section with a height of 5.1 m and a width of 9.8 m and a length of about 900 m. The tunnel has a maximum slope of 4.4 % and was equipped with longitudinal ventilation. A total of six jet fans were installed at the upstream portal of the tunnel in order to create air velocities up to 6 m/s. The test site was located at 265 m from the downstream portal. The test program included four pool fire tests with ventilation rates between 0 and 6 m/s. The pool fires consisted of a mixture of n-heptane/toluene. The pool fire source consisted of two and four fuel pans, respectively, where each pan measured 1.8 m long and 1 m wide and the fuel level was 0.5 m above the road surface. The total fuel surface was 3.6 m^2 in tests 1 and 2 and 7.2 m^2 in tests 3 and 4.

The effects of ventilation were tested in tests 5–10 using cars and covered truckloads. Passenger cars (tests 5, 6, and 7) and covered truckloads (tests 8, 9, and 10) were tested under different ventilation conditions. Each truckload consisted of 800 kg wooden pallets (total of 36 €-pallets, 4 piles with 9 pallets in each pile), with four tires placed on the top. The fire load was mounted in a mock-up of a truck with a cover of tarpaulin where the rear end was open. The total length of the mock-up was 4.5 m, the width was 2.4 m and the height was 2.5 m. The longitudinal ventilation was varied between 0 and 6 m/s. In tests 12–14, different FFFS were tested for

Table 3.9 Relevant data from the test program for the 2nd Benelux Tunnel tests [3]

Test nr.	Fire source	Type of ventilation	FFFS discharge time from ignition (min)	E_{tot} (GJ)	u (m/s)	T_0 (°C)	$\dot{Q}_{max}$ (MW)	T_{max} (°C)	L_f down-stream (m)	L_f upstream (m)
1	n-heptane/toluene 3.6 m^2	No LTV[a]	No FFFS	NA	~1.5	~13	4.1	218	–	–
2	n-heptane/toluene 3.6 m^2	LTV	″	NA	4	~15	3.5	220	–	-
3a	n-heptane/toluene 7.2 m^2	No LTV	″	NA	1.9	~12	11.5	470	–	–
3b	n-heptane/toluene 7.2 m^2	LTV	″	NA	5	~12	11.5	250	–	–
4	n-heptane/toluene 7.2 m^2	LTV	″	NA	6	~11	11.4	210	–	–
5	Passenger car	No LTV	″	NA	~1.0	10	NA	230	–	–
6	Passenger car	No LTV	″	NA	~1.5	10	4.9	210	–	–
7	Passenger car	LTV	″	NA	6	10	4.8	110	–	–
8	Truck load, 36 wood pallets, four tyres	No LTV	″	~10	~1.5	10	13.2	400	–	–
9	Truck load, 36 wood pallets, four tyres	LTV	″	~10	5.3	10	19.5	290	–	–
10	Truck load, 36 wood pallets, four tyres	LTV	″	~10	5	10	16.2	300	–	–
11	Van	No LTV	FFFS activated at 14 min	NA	~1.0	10	7.4 (at 14 min)	300 (at 14 min)	–	–
12	Truck load—aluminium cover, 36 pallets four tyres	LTV	FFFS activated at 4 min	NA	3	11	6.2 (at 4 min)	270 (at 4 min)	–	–
13	Truck load—aluminium cover, 36 pallets—four tyres	LTV	FFFS activated at 10 min	NA	3	12	13.4 (at 10 min)	~500 (at 10 min)	–	–
14	Truck load—aluminium cover, 72 pallets—six tyres	LTV	FFFS activated at 21 min	19	~2.5	10	26 (at 12 min)	~600	10	–

Minus (−) sign indicate that there were no horizontal flame lengths, L_f, registred by the thermocouples

[a] LTV means longitudinal ventilation

different ventilation rates. In test 11, a van loaded with 800 kg of wooden pallets (36 pallets) and three tires on the top was tested. In tests 12 to 14, a covered truckload was tested with the same fire load as in tests 5–10, using aluminum covering. In test 14 no covering was used and the fire load was doubled to 1600 kg of wooden pallets.

In all the tests, except for the fuel pans, the fire sources were mounted on a weighing platform in order to measure the HRR. The HRR for the pans was obtained from the mass loss rate of the supply fuel tank. The centreline temperatures were measured at five different heights at distance of 10, 20, and 50 m upstream the fire and at 10, 20, 50, and 200 m downstream the fire. The radiation heat flux from the fire was measured with cooled heat flux meters at eye-level at distance of 5, 10, and 20 m from the fire centre. Ventilation velocities were measured at three positions upstream of the fire with hot wire anemometers and at three positions downstream the tunnel using bi-directional probes.

The effects of longitudinal ventilation (LTV) rate on the fire growth rate and peak HRRs of truck loads is an important knowledge that has been used by researcher world-wide. In test 8 the peak HRR was 13.2 MW (without ventilation), 19.5 MW in test 9 with 5.3 m/s ventilation and 16.2 MW in test 10 with 5 m/s. The tests with the 36 wood pallet fire load shows that, the fire growth rate with ventilation was approximately 4–6 times faster than the fire growth rate without ventilation and the peak HRR 1.5 and 1.2 times higher, respectively. The fire growth rate in the test with 72 pallets (26 MW) was about 1.9 times faster than the 36 wood pallet fire load with no ventilation (test 8).

One of the conclusions from these tests was that the back-layering of smoke was prevented by 3 m/s for all cases. This conclusion complies well with other investigations presented in this chapter. For a small truck fire, deadly conditions due to radiation exposure could be obtained within 10 m from the truck but not at 50 m downwind the fire. The visibility was reduced within few minutes at distances 100–200 m downwind the fire. The escape routes were obscured due to the smoke. An open deluge system reduced the temperature considerably. The risk for fire spread between adjacent vehicles was therefore not deemed to be high. Smoke temperatures downwind did not obtain fatal levels and the steam production was insignificant. Visibility was however reduced such that escape routes would become difficult to observe.

The performance of FFFS was tested in four fire tests with simulated truck loads, tests 11–14. The FFFS was designed with a water discharge density of 12 mm/min. The FFFS reduced gas temperatures significantly and the risk of fire spread was also reduced. The temperature downstream did not attain the lethal tenability and steam production was insignificant. However, the visibilities in these tests were reduced so that escape routes were difficult to detect. Further information about these FFFS tests of the 2nd Benelux tunnel tests are given in Chap. 16.

3.3.11 Runehamar 2003

Large-scale tunnel tests were carried out with HGV-trailer cargos in the Runehamar tunnel in Norway [45]. The tests were carried out by SP Fire Research in Sweden in cooperation with TNO in the Netherlands and SINTEF-NBL in Norway. The tunnel is a two-way-asphalted road tunnel that was taken out of use and is 1600 m long, 6 m high and 9 m wide, with a slope varying between 0.5–1 %. The tunnel was a blasted rock-tunnel with a cross section varying between 47 and 50 m^2. The test section was smaller than the tunnel itself. The area where the fire load was placed was 32 m^2.

In total, four tests were performed with fire in a HGV-trailer mock-up. In Table 3.10, results from these tests are given. The specific commodities used consisted of four different materials, each representing a category of material typically found in the cargo of a HGV-trailer. These commodities were: standardized wood pallets, plastic pallets made of polyethylene (PE), a standardized test commodity consisting of polystyrene cups (PS) in compartmented cardboard cartons and polyurethane mattresses (PUR). In total four tests were performed. In three tests, mixtures of the various cellulosic and plastic materials were used, and in one test a commodity consisting of furniture and fixtures was used. A polyester tarpaulin covered the cargo in each test. The HGV trailer mock-up was 10.45 m long, 2.9 m wide and 4.5 m high with the trailer floor at 1.1 m above the road surface.

In Test 1 the fire load consisted of 11 tonnes of wooden and plastic pallets. At a distance of 15 m from the downstream side (rear end of the trailer-mockup) there was a target consisting of one pallet row of the same test commodity as used in test. In Test 2, the fire load consisted of 6.9 tonnes of wooden pallets and mattresses (include a target at 15 m). In Test 3, the fire load consisted of 8.5 tonnes of furniture on wooden pallets including the target at 15 m. In this test the fire load had 10 tyres (800 kg) positioned around the frame at the locations where they would be on a real HGV trailer. In Test 4 the fire load consisted of 2.8 tonnes of plastic cups in cardboard boxes on wooden pallets (no target used in this test). In each test the amount (mass ratio) of plastic materials was estimated to be about 18–19 %.

In each test, two fans positioned near the tunnel portal were used to generate a longitudinal airflow, this was about 3 m/s (centreline) at the start of each test but reduced to about 2.4−2.5 m/s once the fires became fully involved. At the location of the fire experiments which was approximately 1 km into the tunnel, a 75 m length of the tunnel was lined with fire protective panels, this reduced the cross-sectional area of the tunnel to 32 m^2 in the vicinity of the fire. The tunnel height at the fire location was 4.7 m. The objectives of the test series were to investigate: (a) fire development in HGV cargo loads, (b) the influence of longitudinal ventilation on fire HRR and growth rate, (c) production of toxic gases, (d) fire spread between vehicles, (e) fire-fighting possibilities and (f) temperature development at the tunnel ceiling and along the tunnel.

Peak HRRs in the range of 67–202 MW and peak gas temperatures in the range of 1250–1350 °C were measured using nonhazardous cargoes. Prior to these tests

Table 3.10 Relevant data from the test program for the Runehamar tests [3].

Test nr.	Fire source	Target	E_{tot} (GJ)	U (m/s)	T_0 (°C)	$\dot{Q}_{max}$ (MW)	T_{max} (°C)	L_f down-stream (m)
1	360 wood pallets measuring 1200 × 800 × 150 mm, 20 wood pallets measuring 1200 × 1000 × 150 mm and 74 PE plastic pallets measuring 1200 × 800 × 150 mm—122 m^2 polyester tarpaulin	32 wood pallets and 6 PE pallets	242	2.4–3	12	202	1365	93
2	216 wood pallets and 240 PUR mattresses measuring 1200 × 800 × 150 mm—122 m^2 polyester tarpaulin	20 wood pallets and 20 PUR mattresses	141	2.4–3	11	157	1282	85
3	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). 10 large rubber tyres (800 kg)—122 m^2 polyester tarpaulin	Upholstred sofa and arm rest on pallets	131	2.4–3	9.5	119	1281	61
4	600 corrugated paper cartons with interiors (600 mm × 400 mm × 500 mm; L × W × H) and 15 % of total mass of unexpanded polystyrene (PS) cups (18,000 cups) and 40 wood pallets (1200 × 1000 × 150 mm)—10 m^2 polyester tarpaulin	No target	62	2.4–3	11	67	1305	37

this high temperature level had only been observed in tests with liquid fires in tunnels. These tests show that ordinary trailer loads can generate the same level of HRR and ceiling temperatures as a tanker fire. The fire development in all the tests was very fast, despite a relatively small ignition source. The peak HRRs were reached between 8 and 18 min after ignition. The linear fire growth rates were 20.1 MW/min for Test1, 26.3 MW/min for Test 2, 16.4 MW/min for Test 3 and 16.9 MW/min for Test 4.

Calculation of time to incapacitation 458 m from the fire was found to be about 6 min from the time of arrival of the smoke gases using wood and plastic pallets and about 2 min using PUR mattresses. A "pulsing" phenomenon was observed in Test 1 and 2. These tests also indicate that the fire fighters may experience serious problems when trying to fight this type of fire, even with the use of longitudinal ventilation of 2.4–3 m/s.

3.3.12 METRO Tests 2011

Two full scale tests were performed with a commuter train carriages in an abandoned tunnel [46,47]. The tests were a part of the research project METRO, which is an interdisciplinary collaborative research project between universities, research institutes, tunnel infrastructure owners, and fire departments in Sweden [48]. The tests were performed in the Brunsberg tunnel which is a 276 m long tunnel located in western Sweden. The cross section of the tunnel varied but the average ceiling height was 6.9 m and average width at the ground level was 6.4 m. In total the cross section was in average 44 m^2.

Two commuter train carriages used were of the type X1 and had been in operation a long period by the Stockholm Public Transport (SL) who donated the carriages for the tests. The X1 carriage was approximately 24 m long. There was a driver's compartment at one end and the length of the passenger compartment was 21.7 m. The width of the inside of the carriage was 3 m and the height along the centreline was 2.32 m. The height at the wall was 2.06 m. The horizontal part of the ceiling was approximately 1.1 m wide.

The fire was initiated inside the carriages using 1 L of petrol on a corner seat in order to simulate arson. The scenario for these two tests aimed to simulate an arsonist that ignited a seat in a corner. An empty milk container (paper with an inner plastic lining) was filled with 1 L of petrol. The ignition was achieved by placing the small ignition sources at different locations which ignited the spilled petrol from the empty milk container. When pulling a string attached to the milk container, it tumbled over and the petrol flowed out on the seat and floor and ignited by the burning fibre boards. The fire was then allowed to develop and spread to the luggage and other combustible material in the wagon. At the time of ignition the three doors on one side (below referred to as door 1, door 2, and door 3, counted from the front of the train) were open.

The train was in original shape and material (test 2), but the same type of carriage (X1) was used in both tests. The carriage used in the second test (test 3) was refur-

Table 3.11 Relevant data from the test program for the METRO tests

Test nr.	Fire source	E_{tot} (GJ)	u (m/s)	T_0 (°C)	$\dot{Q}_{max}$ (MW)	T_{max} (°C)
2	X1 original	64	2–2.5	10	76.7	1081
3	X1 refurbished	71	2–2.5	10	77.4	1118

bished to be similar to a modern C20 wagon (used in the Stockholm metro). The seats were refitted using X10 seats (relatively similar to C20 seats) and the walls and ceiling were covered by aluminium. The old walls and ceiling materials were retained behind the aluminium lining.

The data acquisition was comprehensive. Gas temperatures at numerous positions, HRR, gas concentrations, and smoke inside the carriage and the tunnel, as well as radiant fluxes, and gas velocities, were measured. The air velocity was measured 50 m upstream of the wagon, 3.45 m from the ground. Inside the carriage, temperature was measured at many positions, both as single thermocouples near the carriage ceiling and in thermocouple trees. Furthermore, CO, CO_2, and O_2 were sampled and analyzed in one position at three heights. The smoke density was also measured with a laser and photo cell system at three heights. In total there were 67 sensors or sampling points inside the carriage. At measuring station 50 m from the fire there were a total of 26 sensors or samplings points (temperature, velocity, optical density, CO, CO_2, O_2).

The necessary air flow was obtained using a mobile fan of type Mobile Ventilation Unit MGV- L125/100FD. The created air velocity in the tunnel was before the ignition 2–2.5 m/s.

The influence of the transitional fire load in mass transport systems carried on by passengers was one of the most important parameters to evaluate. To obtain a good estimation of what passengers in the Stockholm metro and commuter trains carry with them on the trains, a field study was carried out by Mälardalen University [49]. The field study showed that 87% of all passengers in the commuter trains carried bags with them on the train and 82% in the metro. The luggage that was used in the full scale test corresponds to an assumption that approximately 81% of the passengers carried luggage and a loading of one passenger per seat available (98 seats) in the carriage. In total, 79 pieces of luggage were used with an average mass of 4.44 kg. This corresponds to a total transitional (extra) fire load of 351 kg. The different types of bags were filled with clothes and paper (reports and brochures). If an average energy content of 20 MJ/kg is assumed the extra fire load corresponds to 7.2 GJ.

Both tests were initiated inside the carriage and developed to fully flashover fires. The time to flashover was significantly different between the two cases. In the test with the original seats and linings the maximum HRR was 76.7 MW and occurred 12.7 min after ignition. The maximum HRR in the case where more modern seats and aluminium lining were used occurred after 117.9 min and was 77.4 MW. The results from the tests are given in Table 3.11. No flame lengths were reported from the tests.

Table 3.12 Relevant data from the test program for the Carleton University laboratory

Test nr.	Fire source	E_{tot} (GJ)	u (m/s)	T_0 (°C)	$\dot{Q}_{max}$ (MW)
1	Intercity train	50	2.4	10	32
2	Subway coach	23	2.4	10	52.5

3.3.13 Carleton University Laboratory Train Tests 2011

Hadjisophocleous et al. [50] described two large-scale tests to determine the fire development and HRR of intercity railcar and a subway car. Both cars were provided by the Korean Railroad Research Institute. The tests were carried in a test facility at Carleton University located 50 km west of Ottawa. The tunnel is 10 m wide, 5.5 m high and 37.5 m long and is equipped with a mechanical exhaust system that consists of three fans capable of exhausting a total of 132 m^3/s of air. This flow corresponds to a longitudinal flow of 2.4 m/s if one assumes a cross section of 55 m^2. The air flow is introduced into the tunnel through a door which only covered a small portion of the tunnel cross section at the lower part. Due to the short length of the tunnel model, the distribution of the flow in the tunnel model may be very different with the realistic scenarios. The exhaust fan system is designed to draw smoke from the tunnel through a large fan chamber which is equipped with the instrumentation for measuring the HRR using oxygen consumption calorimetry. The method requires measurements of the mass flow rate, CO_2, CO, and O2 concentrations of the exhaust gases.

Table 3.12 gives the relevant test data results. The intercity railcar has a length of 23 m, a width of 3 m, and a height of 3.7 m. The total weight of the railcar is 38 tons. The estimated fire load for the railcar was 50 GJ. The subway car had a length of 19.7 m, a width of 3.15 m and a height of 3.45 m. The estimated fire load of the subway car was about 50 % of the intercity railcar or just over 23 GJ.

In the test with intercity railcar, the fire starts to grow after about 1.7 min from ignition and by 5 min it reaches 10 MW. From there it grows slowly to 15 MW as more windows break. After the breakage of all windows, the HRR reaches the maximum value of 32 MW 18 min after ignition.

In the test of the subway car the fire takes more time to intensify than the intercity railcar fire; however once it starts to grow it does so very quickly. The maximum HRR of 52.5 MW was reached in about 9 min after ignition. In the test it took only 140 s for the fire to grow from 1 MW to 52.5 MW, which is an extremely rapid fire growth rate. According to Hadjisophocleous et. al. [50] this rapid fire growth is a result of the fact that four doors were open from the start of the fire so adequate ventilation was there to sustain such growth. This rapid fire development fits well to the description of a sudden flashover for the entire subway at about the same time frame.

The duration of the subway car fire was shorter than the intercity railcar fire due to the higher HRR and lower fuel load. Ceiling temperatures or flame lengths were not reported from the tests.

3.3.14 Singapore Tests 2011

In 2011, the Efectis Nederland BV on assignment of the Land Transport Authority (LTA) of Singapore carried out six large-scale tests FFFS tests in the TST tunnel facility in Spain [51,52]. One test was carried out with no interaction of the FFFS. This test is of interest to report in this chapter, the FFFS tests are presented in Chap. 16. The test consisted of simulated HGV consisting of 228 pallets with 48 plastic pallets (20 %) and 180 wooden pallets (80 %) were used in all fire tests. An air velocity of approximately 3 m/s was applied. The maximum HRR in this test was obtained after 14 min. The maximum HRR was 150 MW. Prior to this peak value, which probably was obtained after some pallets falling down, it was steady at a level of about 100 MW. The total integrated heat energy was 99.2 GJ.

3.3.15 Runehamar Test 2013

In 2013 SP Fire Research performed five large-scale water spray tests in the Runehamar tunnel on the assignment of the Swedish Transport Administration [53]. One test was also carried without interaction of the FFFS. The other five tests are reported on in Chap. 16. The Runehamar tunnel is situated about 5 km from Åndalsnes in Norway. It is a two-way asphalted road tunnel that was taken out of use in the late 1980 s. It is approximately 1600 m long, 6 m high and 9 m wide with a cross section of about 47 m^2. The fire source comprised of 420 wooden pallets placed in the center of the tunnel, 600 m from the west portal. A target consisting of a pile of 21 wood pallets was positioned 5 m from the rear end of the fuel mock-up. This type of test fuel mock-up is often used to simulate the pay load of a Heavy Goods Vehicle (HGV) trailer. The target is used to evaluate the risk for fire spread. The moisture content in the wood pallets varied between 15–20 %. Each wood pallet weighed about 24 kg and was 0.143 m thick. The total length of the fuel load was just over 8.0 m. The total height of the fuel load was about 3 m. In total, the fuel load weighed just over ten tons. This means that the potential energy content is approximately 180 GJ. The target consists of 21 pallets, giving an additional energy of approximately 9 GJ (in total 189 GJ). The fuel mock-up was shielded with steel sheets both in front, back, and on the top. The fire developed up to 79 MW after 38 min. The velocity in the tunnel was about 3 m/s. The maximum ceiling temperature was 1366 °C.

3.4 Model Scale Fire Tests

In the following a summary of some important model scale tests are given. The level of accuracy on the data is not as extensive as for the large-scale tests.

3.4.1 The TNO Tests

A series of small-scale tests was performed by TNO in an 8 m long, 2 m high, and 2 m wide model tunnel [54]. In these tests very high gas temperatures were measured and the Rijkswaterstaat Tunnel Curve (the RWS Curve) in the Netherlands is based on these tests.

3.4.2 Automatic Water Spray System Tests

A total of 28 tests, including three free-burn tests, were carried out in a 1:15 scale model tunnel [55]. The main aim was to analyze the possibility of using an automatic water spray system instead of a deluge system in a tunnel fire. The fire spread between wood cribs with a free distance of 1.05 m (15.75 m in full scale) was also tested. Further, the effect of ventilation velocities and water flow rates on the activation of nozzles, HRR, fire growth rate, gas temperature, heat radiation, and fire spread was systematically investigated.

The tunnel itself was 10 m long, 0.6 m wide, and 0.4 m high, as shown in Fig. 2. Average longitudinal velocities of 0.52, 1.03, 1.54, and 2.07 m/s, obtained by adjusting a frequency regulator, were used in the test series. The corresponding large-scale velocities were 2, 4, 6, and 8 m/s, respectively.

The fire load consisted of wood cribs (pine). The weight of a wood crib is about 4.4 kg. The free distance between each horizontal stick was 0.033 m and the total fuel surface area of a wood crib was estimated to be 1.37 m^2. The estimated HRR for the main fuel load was about 200 MW in full scale.

3.4.3 Longitudinal Ventilation Tests

A total of 12 tests were carried out in a 1:23 scale model tunnel with longitudinal ventilation [56]. The fire load was simulated with the aid of wood cribs, corresponding to a scaled-down HGV (Heavy Goods Vehicle) fire load, and the fire spread between two or three wood cribs with a free distance of 0.65 m (about 15 m in full scale) was tested. The tunnel itself was 10 m long, 0.4 m wide, and two heights of 0.3 m and 0.2 m was used respectively. The parameters tested were: the number of wood cribs, type of wood cribs, the longitudinal ventilation rate and the ceiling height. The fire spread between wood cribs, with a free distance corresponding to 15 m in full scale, was also tested. The effects of different ventilation rates on the fire growth rate, fire spread, flame length, gas temperatures, and back-layering, were investigated.

3.4.4 Point Extraction Ventilation Tests

A total of 12 tests were carried out in a 1:23 scale model tunnel with point extraction ventilation [57]. The fire load was simulated using wood cribs. The parameters tested were the longitudinal ventilation rate, the arrangement of the exhaust openings, and the exhaust capacity. Moreover, the fire spread between wood cribs with a free distance of 0.65 m (about 15 m in full scale) was tested. The point extraction ventilation system was tested under different fire conditions together with either forced longitudinal ventilation or natural ventilation. The tunnel itself was 10 m long, 0.4 m wide, and 0.2 m high. The study focuses on smoke control using single and two point extraction systems. Further, the maximum HRR, fire growth rate, maximum excess temperature beneath the ceiling, flame length, and heat flux were analyzed using relationships obtained from theoretical considerations.

3.4.5 Tunnel Cross-Section Tests

A total of 42 tests were performed in model tunnels with longitudinal ventilation to study the effect of the height and width of a tunnel on the mass loss rate, HRR, and gas temperatures [58]. The tunnel was 10 m long with a scale of 1:20. The widths used were 0.3, 0.45, and 0.6 m and the height was varied between 0.25 and 0.4 m. Two different types of fuels were used: pools of heptane and wood cribs. The wood cribs were of three different types. Two were wood cribs with two different porosities and the other one had the laterally placed short pieces of wood replaced by pieces of polyethene. The velocities tested in the model tunnels were in a range of 0.22–1.12 m/s.

3.5 Summary

A dozen of large-scale fire test programs have been carried out to date. The main focus has been on the heat and smoke spread and how different ventilation systems influence these parameters. Nearly half of the test series included FFFS testing. The quality of large-scale tests carried out in the 1960s–1980s varies considerably and in all these tests there is a lack of the key fire hazard parameter; the HRR. In the analysis carried out here new estimated HRRs are given. There is no doubt that the EUREKA EU499 tests and the Memorial tests are the most well-known and well reputed large-scale fire test series to date. They have already been established as the 'large-scale fire tests' and provide a new base for standards and knowledge in tunnel fire safety. The use of oxygen consumption calorimetry has increased the quality in the HRR results and made it possible to measure HRRs from vehicles.

The analysis of liquid fires presented here show that the variation in the results is considerable and it is difficult to assume one value for each type of liquid fuel. Parameters that influence the burning rate for each fuel type are the pan geometry, the fuel depth, the ventilation conditions and the reciprocal tunnel, and the fuel pan geometry. Further, in the case when the tunnel cross-section is large and the width of the tunnel is larger than the width of the fuel pan, as was the case in the Ofenegg tests [9], the influence of the longitudinal ventilation on the burning rate appears to be small.

References

1. NFPA 502 (2004) Standard for Road Tunnels, Bridges, and other Limited Access Highways. 2004 edn. National Fire Protection Association
2. Fire and Smoke Control in Road Tunnels (1999), PIARC
3. Ingason H (2006) Fire Testing in Road and Railway Tunnels. In: Apted V (ed) Flammability testing of materials used in construction, transport and mining. Woodhead Publishing, pp 231–274
4. Grant GB, Jagger SF, Lea CJ (1998) Fires in tunnels. Phil Trans R Soc Lond 356:2873–2906
5. Haerter A Fire Tests in the Ofenegg-Tunnel in 1965. In: Ivarson E (ed) International Conference on Fires in Tunnels, SP REPORT 1994:54, Borås, Sweden, 10–11 October 1994. SP Sweden National Testing and Research Institute, pp 195–214
6. Feizlmayr A Research in Austria on tunnel fire, Paper J2, BHRA. In: 2nd Int Symp on Aerodynamics and Ventilation of Vehicle Tunnels, Cambrigde, UK, 1976. pp 19–40
7. Pucher K Fire Tests in the Zwenberg Tunnel (Austria). In: Ivarson E (ed) International Conference on Fires in Tunnels, Borås, Sweden, 1994. SP Swedish National Testing and Research Institute, pp 187–194
8. ILF (1976) Brandversuche in einem Tunnel. Ingenieurgemeinschaft Lässer-Feizlmayr; Bundesministerium f. Bauten u. Technik, Strassenforschung
9. Schlussbericht der Versuche im Ofenegg Tunnel von 17.5 - 31.5 1965 (1965). Kommission für Sicherheitsmassnahmen in Strassentunneln
10. State of the Road Tunnel Equipment in Japan – Ventilation, Lighting, Safety Equipment (1993). Public Works Research Institute, Japan
11. Huggett C (1980) Estimation of Rate of Heat Release by Means of Oxygen Consumption Measurements. Fire and Materials 4 (2):61–65
12. Parker WJ (1984) Calculations of the Heat Release Rate by Oxygen Consumption for Various Applications. Journal of Fire Sciences 2 (September/October):380–395
13. Tewarson A (1982) Experimental Evaluation of Flammability Parameters of Polymeric Materials. In: Lewin M, Atlas SM, Pearce EM (eds) Flame Retardant Polymeric Materials. Plenum Press, New York, pp 97–153
14. Keski-Rahkonen O Tunnel Fire Tests in Finland. In: Proceedings of the International Conference on Fires in Tunnels, Borås, 10–11 October 1994, 1994. Swedish National Testing and Research Institute, pp 222−237
15. Fires in Transport Tunnels: Report on Full-Scale Tests (1995). edited by Studiensgesellschaft Stahlanwendung e. V., Düsseldorf, Germany
16. Mikkola E (2004) Email correspondance to the author at 10 of September
17. Ingason H Heat Release Rate Measurements in Tunnel Fires. In: Ivarson E (ed) International Conference on Fires in Tunnels, Borås, Sweden, October 10–11, 1994 1994. SP Swedish National Testing and Research Institute, pp 86–103

18. Grant GB, Drysdale D Estimating Heat Release Rates from Large-scale Tunnel Fires. In: Fire Safety Science – Proceedings of the Fifth International Symposium, Melbourne, 1995, pp 1213–1224
19. Steinert C Smoke and Heat Production in Tunnel Fires. In: The International Conference on Fires in Tunnels, Borås, Sweden, 10–11 October 1994. SP Swedish National Testing and Research Institute, pp 123–137
20. Memorial Tunnel Fire Ventilation Test Program – Test Report (1995). Massachusetts Highway Department and Federal Highway Administration
21. Takekuni K Disaster Prevention of Road Tunnel and Characteristics of the Evacuation Environment during Fires in Large-scale Tunnels in Japan. In: 4th Joint Workshop COB/JTA 2Joint Meeting JTA/Cob Open Work Shop 2001 in Netherlands, 2001. pp 35–43
22. Lemaire A, van de Leur PHE, Kenyon YM (2002) Safety Proef: TNO Metingen Beneluxtunnel – Meetrapport. TNO
23. Ingason H, Lönnermark A Large-scale Fire Tests in the Runehamar tunnel – Heat Release Rate (HRR). In: Ingason H (ed) International Symposium on Catastrophic Tunnel Fires (CTF), Borås, Sweden, 20–21 November 2003. SP Swedish National Testing and Research Institute, pp SP Report 2004:2005, p. 2081–2092
24. Lönnermark A, Ingason H Large-scale Fire Tests in the Runehamar Tunnel – Gas Temperature and Radiation. In: Ingason H (ed) International Symposium on Catastrophic Tunnel Fires (CTF), Borås, Sweden, 20–21 November 2003. SP Swedish National Testing and Research Institute, pp SP Report 2004:2005, p. 2093–2103
25. Apte VB, Green AR, Kent JH Pool Fire Plume Flow in a Large-Scale Wind Tunnel. In: Cox G, Langford B (eds) Proceedings of the Third International Symposium on Fire Safety Science, Edinburgh, Scotland, 8–12 July 1991. Elsevier Applied Science, pp 425–434
26. Bettis RJ, Jagger SF, Lea CJ, Jones IP, Lennon S, Guilbert PW The Use of Physical and Mathematical Modelling to Assess the Hazards of Tunnel Fires. In: Cockram I (ed) 8th International Symposium on Aerodynamics and Ventilation of Vehicle Tunnels, Liverpool, 1994. Mech Eng Public Lim, pp 439–469
27. Thomas PH (1970) Movement of Smoke in Horizontal Corridors against an Air Flow. Inst. Fire Engrs Q
28. Ingason H, Nireus K, Werling P (1997) Fire Tests in a Blasted Rock Tunnel. FOA, Sweden
29. Ingason H, Persson B Prediction of Optical Density using CFD. In: Curtat M (ed) Fire Safety Science – Proceedings of the 6th International Symposium, Poitiers, 1999. pp 817–828
30. Perard M, Brousse B Full size tests beforeopening two French tunnels. In: Cockram I (ed) 8th Int Symp on Areodynamics and Ventilation of Vehicle Tunnels, Liverpool, UK, 1994. pp. 383–408
31. Casale E, Brousse B, Weatherill A, Marlier E Full Scale Fire Tests Performed in the Mont Blanc Tunnel – Evaluation of the Efficiency of the Fully Automatic Ventilation Responses. In: Fourth International Conference on Fires in Tunnels, Basel, Switzerland, 2–4 December 2002. pp 313–325
32. Beard AN, Carvel RO (2012) Handbook of tunnel fire safety – Second Edition. ICE Publishing
33. Brousse B, Voeltzel A, Botlan YL, Ruffin E (2002) Mont Blanc tunnel ventilation and fire tests. Tunnel Management International Vol. 5, Nr 1:13–22
34. Rew C, Deaves D Fire spread and flame length in ventilated tunnels – a model used in Channel tunnel assessments. In: Proceedings of the International Conference on Tunnel Fires and Escape from Tunnels, Lyon, France, 5–7 May 1999. Independent Technical Conferences Ltd, pp 397–406
35. Heselden A Studies of fire and smoke behavior relevant to tunnels. In: 2nd Int Symp on Aerodynamics and Ventilation of Vehicle Tunnels, Cambridge, UK, 23–25 March 1976. Paper J1, BHRA Fluid Engineering, pp J1–1– J1–18
36. Babrauskas V (1995) Burning rates. In: DiNenno PJ, Beyler CL, Custer RLP et al. (eds) In SFPE Handbook of Fire Protection Engineering, vol 2nd Edition. The Natioanl Fire Protection Association, USA, pp 3.1–3.15

37. Heselden A, Hinkley PL (1970) Smoke travel in shopping malls. Experiments in cooperation with Glasgow Fire Brigade. Parts 1 and 2. Fire Research Station
38. Ekkehard R Propagation and Development of Temperatures from Test with Railway and Road Vehicles. In: International Conference on Fires in Tunnels, Borås 10–11 of October, 1994. Swedish National Testing and Research Institute, pp 51–62
39. Shimoda A Evaluation of Evacuation Environment during Fires in Large-Scale Tunnels. In: 5th Joint Workshop COB/JTA, Japan, 2002. pp 117–125
40. Kunikane Y, Kawabata N, Takekuni K, Shimoda A Heat Release Rate Induced by Gasoline Pool Fire in a Large-Cross-Section Tunnel. In: 4th Int. Conf. Tunnel Fires, Basel, Switzerland, 2–4 December 2002. Tunnel Management International, pp 387–396
41. Kawabata N, Kunikane, Y., Yamamoto, N., Takekuni, K., and Shimoda, A. Numerical Simulation of Smoke Descent in a Tunnel Fire Accident. In: 4th Int. Conf. Tunnel Fires, Basel, Switzerland, 2002. pp 357–366
42. Kunikane Y, Kawabata N, Okubo K, Shimoda A Behaviour of Fire Plume in a Large Cross Sectional Tunnel. In: 11th Int. Symp. on AVVT, Luzern, Switzerland, 2003. pp 78–93
43. Kunikane Y, Kawabata N, Ishikawa T, Takekuni K, Shimoda A Thermal Fumes and Smoke Induced by Bus Fire Accident in Large Cross Sectional Tunnel. In: The fifth JSME-KSME Fluids Engineering Conference, Nagoya, Japan, 17–21 November 2002
44. Heskestad G (2002) Fire Plumes, Flame Height, and Air Entrainment. In: DiNenno PJ (ed) The SFPE Handbook of Fire Protection Engineering. Third edition edn. National Fire Protection Association, Quincy, Massachusetts, USA, pp 2–1–2–17
45. Ingason H, Lönnermark A, Li YZ (2011) Runehamar Tunnel Fire Tests. SP Technical Research Institute, SP Report 2011:55, Borås, Sweden
46. Lönnermark A, Lindström J, Li YZ, Claesson A, Kumm M, Ingason H (2012) Full-scale fire tests with a commuter train in a tunnel. SP Report 2012:05. SP Technical Research Institute of Sweden, Borås, Sweden
47. Lönnermark A, Lindström J, Li YZ, Ingason H, Kumm M Large-scale Commuter Train Tests – Results from the METRO Project. In: Proceedings from the Fifth International Symposium on Tunnel Safety and Security (ISTSS 2012), New York, USA, 14–16 March 2012. SP Technical Research Institute of Sweden, pp 447–456
48. Ingason H, Kumm M, Nilsson D, Lönnermark A, Claesson A, Li YZ, Fridolf K, Åkerstedt R, Nyman H, Dittmer T, Forsén R, Janzon B, Meyer G, Bryntse A, Carlberg T, Newlove-Eriksson L, Palm A (2012) The METRO project – Final Report 2010:08. Mälardalen University, Västerås
49. Kumm M (2010) Carried Fire Load in Mass Transport Systems – a study of occurrence, allocation and fire behavior of bags and luggage in metro and commuter trains in Stockholm. Mälardalen University, Västerås, Sweden
50. Hadjisophocleous G, Lee DH, Park WH Full-scale Experiments for Heat Release Rate Measurements of Railcar Fires. In: International Symposium on Tunnel Safety and Security (ISTSS), New York, 2012. SP Technical Research Institute of Sweden, pp 457–466
51. Cheong MK, Cheong WO, Leong KW, Lemaire AD, LM N (2013) Heat Release Rates of Heavy Goods Vehicle Fire in Tunnels with Fire Suppression System. Fire Technology. doi:10.1007/s10694-013-0367-0
52. Cheong MK, Cheong WO, Leong KW, Lemaire AD, Noordijk LM, Tarada F Heat release rates of heavy goods vehicle fires in tunnels. In: In: 15th International Symposium on Aerodynamics, Ventilation & Fire in Tunnels, Barcelona, Spain, 2013. BHR Group, pp 779–788
53. Ingason H, Appel G, Li YZ, Lundström U, Becker C Large-scale fire tests with a Fixed Fire Fighting System (FFFS). In: ISTSS 6th International Symposium on Tunnel Safety and Security, Marseille, 2014
54. Rapport betreffende de beproeving van het gedrag van twee isolatiematerialen ter bescherming van tunnels tegen brand (1980). Instituut TNO voor Bouwmaterialen en Bouwconstructies, Delft, The Netherlands

55. Li YZ, Ingason H (2013) Model scale tunnel fire tests with automatic sprinkler. Fire Safety Journal 61:298–313
56. Ingason H, Li YZ (2010) Model scale tunnel fire tests with longitudinal ventilation. Fire Safety Journal 45:371–384
57. Ingason H, Li YZ (2011) Model scale tunnel fire tests with point extraction ventilation. Journal of Fire Protection Engineering 21 (1):5–36
58. Lönnermark A, Ingason H (2007) The Effect of Cross-sectional Area and Air Velocity on the Conditions in a Tunnel during a Fire. SP Report 2007:05. SP Technical Research Institute of Sweden, Borås, Sweden