

Estimating Heat Release Rates from Large-scale Tunnel Fires

GEORGE B. GRANT and DOUGAL DRYSDALE

Fire Safety Research Group
Department of Civil and Environmental Engineering
The University of Edinburgh
The King's Buildings
Edinburgh EH9 3JN, Scotland, UK

ABSTRACT

A series of full-scale tunnel fire tests were conducted in Norway under the EUREKA EU499 *firetun* project, a co-operative venture involving participants from several European countries. The Channel Tunnel operators, Eurotunnel, were represented during a test designed to simulate a burning heavy goods vehicle (HGV) being conveyed on a freight shuttle train within the Channel Tunnel. The experimental tunnel was extensively instrumented to enable the progress of the fire to be monitored. In this paper, it is shown how the data on CO and CO₂ production rates were used to calculate the rate of heat release as a function of time and provide an estimate of the maximum heat release rate.

KEYWORDS: tunnel fires, heat release rate, carbon monoxide, carbon dioxide

NOMENCLATURE

D_h	hydraulic diameter (m)
h	Cartesian co-ordinate - height above tunnel ground level (m)
H_{CO}	net heat of combustion of unit mass of CO (kJ.kg ⁻¹)
H_c/k_{CO}	net heat of combustion of fuel/unit mass of CO (kJ.kg ⁻¹)
H_c/k_{CO_2}	net heat of combustion of fuel per unit mass of CO ₂ produced (kJ.kg ⁻¹)
$H_c/k_{CO} - H_{CO}$	net heat of combustion of fuel per unit mass of CO produced (kJ.kg ⁻¹)
\dot{m}_{CO}	mass rate of production of CO (kg.s ⁻¹)
\dot{m}_{CO_2}	mass rate of production of CO ₂ (kg.s ⁻¹)

\dot{m}_x	mass rate of production of species (kg.s ⁻¹)
n	order of polynomial curve fit to velocity profile (-)
P	absolute atmospheric pressure (10 ⁵ Pa)
\dot{Q}	rate of heat release (MW)
r	gas constant per unit mass (J.kg ⁻¹ .K ⁻¹): 188.7 (CO ₂) and 296.8 (CO)
R	pipe radius in pipe flow (m)
t	time (minutes)
T	absolute temperature (K)
U	gas velocity (m.s ⁻¹)
\dot{V}	volumetric flowrate of products (m ³ .s ⁻¹)
w	Cartesian co-ordinate - distance from tunnel wall (m)
ΔP	pressure difference (Pa)

Greek symbols

ρ	gas density (kg.m ⁻³)
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Subscripts

max	maximum value
mean	average value

INTRODUCTION

There has been a recent resurgence of interest in the problem of fires in tunnels, coinciding with the advent of high-profile tunnelling projects such as the Channel Tunnel. It has long been recognised that the provision of a 'well designed' ventilation system is fundamental to the overall fire safety of such long vehicle tunnels. In practice however, reliable quantitative design tools have been unavailable, due to an inadequate understanding of the complex interaction between a fire and the imposed ventilation airflow. Current design practice requires that the ventilation system is capable of achieving 'positive smoke control' in order to prevent upstream smoke propagation in the event of a fire. The established design methodology relies on the extrapolation of crude empirical relationships to estimate a 'critical ventilation velocity', based on the heat output of a design fire. An extensive critique of the current state-of-the-art has been presented by Grant and Jagger [1]; that review traces the development of the conventional, empirical, design tools and describes some new advances in the field, including a series of large-scale tunnel fire experiments performed by the UK Health & Safety Executive. It is also stressed in [1] that such experiments are of little value unless two key parameters are determined accurately; *viz.* the velocity profile upstream of the fire and the heat release rate history of the test fire.

The deficiencies of current design practice have become more widely acknowledged due to the increasing number of major tunnelling projects. Much of the impetus for the new research can be attributed to these projects and considerable funds have been invested in novel

experimental and theoretical studies in an effort to optimise the design of tunnel ventilation systems and thereby to improve public safety. The EUREKA EU499 *firetun* project is a good example of the significant research investment in this area. Nine European nations contributed to the programme of over 20 large scale fire tests performed in a disused mine tunnel at Repparfjord, near Hammerfest in northern Norway [2]. The Channel Tunnel operators Eurotunnel were represented at these tests and initiated an experiment intended to simulate a fire onboard a stationary Eurotunnel HGV (heavy goods vehicle) shuttle train within the Channel Tunnel. The principal objectives of the experiment were to determine how the development of a 'typical' HGV fire would be influenced by the presence of a longitudinal ventilating airflow and to estimate the ultimate heat release rate (\dot{Q}_{\max}) of the fully-developed fire. The latter parameter in particular, is of crucial importance as it determines both the effectiveness of the ventilation and the thermal stresses imposed on the tunnel structure.

Although it was planned initially to rely on oxygen consumption calorimetry to estimate the rates of heat release during the experiment, it was deemed appropriate to cross-check the results against another method. The Fire Safety Research Group at Edinburgh University was asked by Eurotunnel to furnish initial estimates of heat release rates based on the available data. The correlation of heat release rate with CO and CO₂ production rates offers an alternative approach, first suggested by Tewarson [3]. In the present case, the oxygen consumption measurements were initially incomplete, and the CO/CO₂ method offered a means of completing the record and provided the first estimate of heat release yields from the experiment.

EXPERIMENTAL TUNNEL GEOMETRY

The experimental facility, a 2.5 km long disused mine tunnel, contained a large number of sensors linked to data acquisition equipment, which enabled the development of the fire and its environmental impact to be monitored. The main elements of the experimental arrangement relevant to the present paper are shown in Figure 1. The articulated HGV lorry, loaded with 2 tonnes of furniture, also carried a full tank of diesel fuel; the 'blockage' shown upstream of the lorry was designed to represent the amenity coach (or 'club car') conveyed at the head of an HGV shuttle train [4]. At $t = 0$ (*i.e.* ignition inside the HGV's cab), the ventilation system provided a centre-line upstream velocity of $\sim 7 \text{ m.s}^{-1}$, representing the normal airflow over a moving freight shuttle. At $t = 13.5$ minutes, the fan was stopped, in order to simulate the HGV shuttle train coming to a halt following the discovery of the fire (in accordance with Eurotunnel's operating procedures). The fan was re-activated three minutes later but at a lower speed (producing an air velocity of approximately 2 m.s^{-1} at the location described above) to simulate the operation of the Channel Tunnel's longitudinal 'Supplementary Ventilation System' (SVS). Most data were collected for a total time in excess of one hour from the start of the test, although some data channels suffered irreparable damage after about 20 minutes. A summary of the instrumentation has been given by French [4]; this included comprehensive air temperature and velocity measurements in the 'near-field' local to the HGV. 'Far-field' data were collected from various stations along the tunnel from -100 m (upstream) to +100 m (downstream) of the vehicle; these measurements included gas analysis (CO, CO₂, O₂) and smoke density measurements, in addition to air temperature and velocity data.

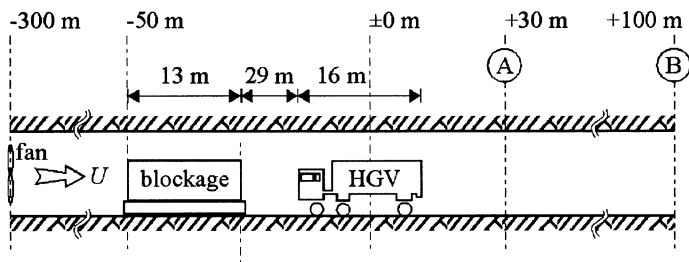


FIGURE 1. Longitudinal schematic cross-section of Repparfjord tunnel (not to scale).

Here, the measurement locations at +30 m downstream and +100 m downstream are of most interest; these are designated as points ‘A’ and ‘B’, respectively in Figure 1 and shown in cross-section, looking downstream, in Figures 2 and 3. The various symbols represent sampling locations for temperature (T), velocity (U), carbon dioxide (CO_2) and carbon monoxide (CO). Since the EUREKA project was a co-operative venture, the instrumentation was supplied by various organisations and the test measurements were recorded using several different data-loggers. This presented a problem since the time step (Δt) and the nominal ‘zero’ point, associated with the start of the test, differed among the instruments even within a given measuring section. Table 1 illustrates the divergence of timing parameters at sections ‘A’ and ‘B’ in Figure 1; the sources of data are designated D (German contractor) and UK (British contractor).

TABLE 1. Data acquisition sources and associated timing parameters

	Data source	Δt (minutes)	Nominal ‘zero’ point (minutes)
<u>Section A</u>			
Temperature	D	1.0	-0.208
CO/CO ₂	D	1.5	+0.73 @ 2 m a.g.l., +0.98 @ 5 m a.g.l.
Velocity	D	0.25	-0.075
<u>Section B</u>			
Temperature	D	1.0	-0.208
CO	UK	0.17	0.0
CO ₂	D	1.5	+0.28 @ 2 m a.g.l., +0.53 @ 4.5 m a.g.l.
Velocity	UK	0.17	0.0

HEAT RELEASE RATE CALCULATION

The oxygen consumption method is commonly used for estimating the heat release rate (HRR) from experimental fires [5]. The attraction lies in its simplicity, since in essence, all that is required is to measure the rate of oxygen consumption in the combustion system. The HRR is then determined by straightforward calculation and the technique has been found to be generally applicable for a wide range of common fuels.

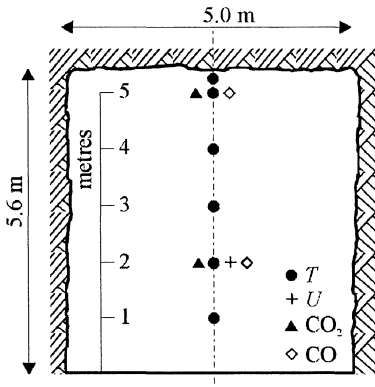


FIGURE 2. Tunnel cross-section at 'A'.

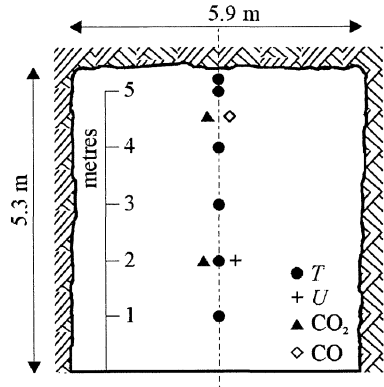


FIGURE 3. Tunnel cross-section at 'B'.

The practical difficulties include achieving adequate mixing of the combustion products and obtaining accurate measurements of the flowrate and oxygen concentration. Adequate mixing of the products is easily achieved in small scale experiments but is more difficult at larger scales where stratification may give rise to spatial concentration gradients. Variations in oxygen concentration are typically between 21% and 18% during small scale testing and a high-precision oxygen analyser is required. Tewarson [3] proposed an alternative method where the HRR is estimated by measuring the rates of production of CO and CO₂. In [3], heat release rates for a wide range of polymeric materials and flammable liquids were deduced from CO and CO₂ production and were found to be approximately equal to the HRR obtained using the oxygen consumption technique. The advantage of the CO/CO₂ method is that the changes in species concentration are quite large and consequently the specifications for the CO and CO₂ analysers are less exacting than for oxygen analysis. The disadvantage of the method is that the correlation between the generation rate of these combustion products and the heat release rate is more dependent on the fuel type than in the oxygen consumption method.

VELOCITY PROFILE AND FLOWRATE DURING THE HGV FIRE TEST

Small scale HRR experiments often employ orifice plates to measure flowrates but these are not practicable for large scale tunnel tests. However, if the flow regime is well defined and the shape of the velocity profile is known, then a record of the time-dependent velocity at a single point, for example at the centre of the tunnel cross section, may be used to deduce the flowrate. Unfortunately, the cross sections of most vehicle tunnels are not well represented by simple geometrical shapes and so the nature of the velocity profile cannot be predicted with confidence; this is particularly true when there are significant blockages in the tunnel and the tunnel is rough-hewn and non-circular (as in the Repparfjord tunnel). During the Repparfjord tests, point velocity histories were inferred from measurements of dynamic pressure obtained using various probes. However, the most complete velocity profiles were obtained by hot-wire anemometry prior to the commencement of the fire tests. Axial velocities were measured at a total of nine points at a location 100 m upstream from the front of the HGV vehicle (*i.e.*

at -100 m) in order to determine the level of turbulence in the tunnel [6]. The width and height of the tunnel at this point were reported as 7.4 m and 5 m respectively, as shown in Figure 4 (looking downstream, towards the HGV position). The location of the measuring section was approximately 17 tunnel ‘hydraulic diameters’ (D_h) downstream of the fan, where,

$$D_h = \frac{4 \times \text{Area}}{\text{Perimeter}} \tag{1}$$

The velocity profile within a tunnel varies constantly with distance downstream and theoretically becomes ‘fully developed’ only at an infinite distance from the flow inlet (*i.e.* the fan location in this case). In practice, however, the flow regime is deemed to be fully developed when the velocity on the axis of the tunnel is within 1% of its ultimate value. For smooth-walled tunnels an entry length of around 50 diameters is sufficient to give this condition, but for rougher tunnels (such as Repparfjord) the required distance will be reduced [7].

The mean velocity data from the turbulence study were plotted to give a centreline vertical velocity distribution and a horizontal velocity distribution at 2m above the tunnel ground level at the -100 m location (Figure 4). Table 2 summarises the data used. In addition to the velocity data quoted in Table 2, zero velocity values were adopted at the tunnel walls, inferred from the conventional ‘no-slip’ condition at solid boundaries. Figure 5 shows plots of these data with 4th and 5th order polynomial approximations to the velocity profile in the vertical (upper) and horizontal (lower) planes. These polynomial equations have been integrated in order to obtain estimates of the mean velocity over the tunnel cross section. Table 3 presents the results of these calculations.

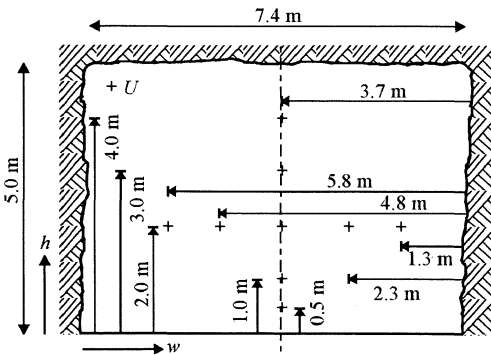


FIGURE 4. Tunnel section at -100 m

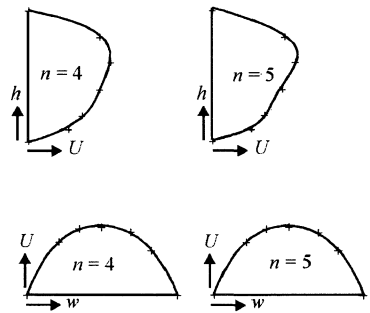


FIGURE 5. Interpolated velocity profiles

TABLE 2. Mean velocities from hot wire anemometry data

Probe location	w (m)	h (m)	U_{mean} (m.s^{-1})
1	3.70	0.50	3.766
2	3.70	1.00	4.714
3	3.70	2.00	6.412
4	3.70	3.00	7.627
5	3.70	4.00	6.452
6	1.30	2.00	4.187
7	2.30	2.00	5.924
8	5.80	2.00	4.988
9	1.80	2.00	6.245

TABLE 3. Mean velocities derived by polynomial velocity distributions

Plane of velocity profile	Order of polynomial fit	U_{mean} (m.s^{-1})	Ratio $U_{\text{mean}}/U_{\text{max}}$
Vertical	4	5.46	0.715
Vertical	5	5.39	0.707
Horizontal	4	4.65	0.727
Horizontal	5	4.66	0.728

An attempt was made to use these data to check the continuity of mass flow between the measuring stations at -100 m and +100 m before ignition, since point velocity data were being logged at times just before ignition. The calculation proved ambiguous, and three reasons are proposed for the discrepancy:

- (i) The selection of a single mean velocity value based on the above velocity profiles is not justified given the marked variation in form between the horizontal and vertical distributions, in particular the strong asymmetry evident in the vertical case (Figure 5) supports this view;
- (ii) The instantaneous velocities measured in the tunnel during the preliminary turbulence study and during the HGV fire test may have been subject to large-amplitude fluctuations in axial velocity. This is probable if the measuring station was relatively close to the fan inlet. Unless the point velocity data can be relied upon to be fairly steady in nature then it is not possible to correlate mass inflow and outflow over such a large distance in the tunnel using simplistic methods;
- (iii) The tunnel area was not accurately known and the original data indicate that the internal dimensions varied quite markedly along the tunnel length. Therefore, even if the mean velocity can be approximated, an additional source of error is introduced in the calculated flowrate if the tunnel area is questionable.

Finally, in view of the uncertainties inherent in the data, it was decided that a more simplified approach to calculating the flowrate was justifiable, and the following assumptions were made:

- (i) The velocity probe located at 2 m above ground level at section 'B' (Figure 1) was accurate, and remained unaffected by soot or other contaminants during the test;
- (ii) The tunnel cross section at 'B' was ~ 5.3 m high by ~ 5.9 m wide (scaled from the drawings in [9]), giving an area of 31.3 m²;
- (iii) The velocity distribution at +100 m could be approximated by the fully developed pipe-flow velocity profile described in [8].

The velocity profile for fully developed pipe-flow is [8],

$$U = U_{\max} \left(1 - \frac{r}{R} \right)^{1/7} \quad (2)$$

which leads to,

$$U_{\text{mean}}/U_{\max} = 0.817 \quad (3)$$

which is somewhat higher than the ratios presented in Table 3. From equations (2) and (3), for a velocity probe at 2 m above ground level in a tunnel of height 5.3 m and area 31.27 m² the volumetric flowrate is approximated by,

$$\dot{V} = 31.3U_{\text{mean}} \quad (4)$$

(m³.s⁻¹) which has been used in the calculation of heat release rate at section 'B'.

ESTIMATION OF HEAT RELEASE RATE BASED ON CO AND CO₂ PRODUCTION AT SECTION 'B' (+100 m DOWNSTREAM)

Tewarson's [3] expression relating the rate of heat release to the production of CO and CO₂ is;

$$\dot{Q} = \dot{m}_{\text{CO}_2} \left(\frac{H_c}{k_{\text{CO}_2}} \right) + \dot{m}_{\text{CO}} \left(\frac{H_c}{k_{\text{CO}}} - H_{\text{CO}} \right) \quad (5)$$

and is used to estimate the HRR history based on the experimental data in [9]. The flow of combustion products at section 'B' was assumed to be well mixed, based on a comparison of the German CO₂ concentrations measured at 2 m height and 4.5 m height [9]. An exact comparison of the instantaneous concentrations was not possible since the analyser readings were always out of phase by at least 15 seconds (Table 1); however the readings were in fair agreement at comparable sample times. A degree of stratification was evident however, since the upper probe recorded +5% greater concentrations than the lower probe at 5 minutes into the test. This divergence increased to +8% at 30 minutes and was later reversed at 35 minutes with CO₂ concentrations remaining higher in the lower half of the tunnel until near-equilibrium values were established at 78 minutes. The 'background' levels of CO₂ concentration were assumed to be 0.037% ($t = 0.28$ min) and 0.041% ($t = 0.53$ min) for the lower and upper

probes respectively, so that the amount of CO₂ produced by the fire was calculated by the increase above these base values. It is acknowledged that there may be some general increase in CO₂ due to the fire even at this early stage but this has been ignored, and this is not expected to introduce a significant error, particularly once the fire is well developed.

For the CO production, it was assumed that the single sample point UK data [9] was representative of the increase in CO concentration over the whole tunnel cross section. Since the UK and German data were not in-phase, the data were filtered to produce a 'best set', closely associated with some well defined time intervals after ignition. The UK time base was selected as the standard, and this defined the representative CO, velocity and temperature measurements at section 'B'. Carbon dioxide concentrations were extracted from either the upper or lower probe (German) data, to ensure a sample time close to that of the CO probe. This procedure resulted in only 18 values of heat release rate being estimated for the period from ignition to 20.13 minutes; at this point some of the instruments failed at section 'B' making further calculation impossible.

The mass rate of production of each of the two gas species through section 'B' was obtained from the expression,

$$\dot{m}_x = \frac{PV \times (\% \text{ concentration by volume})}{rT \times 100} \quad (6)$$

in units of kg.s⁻¹. For the present calculation, mean values for H_c/k_{CO_2} and $(H_c/k_{CO} - H_{CO})$ of 12.5 kJ.kg⁻¹ and 7.02 kJ.kg⁻¹ have been assumed, these being average values for a representative 'mix' of fuels [10]. The results of the HRR calculation are shown in Figure 6, together with a graph of the time-dependent CO/CO₂ ratio. It is seen that the fire remains below ~ 2 MW for the first seven minutes of the test but a rapid growth to over 11 MW is observed at about 11 minutes from ignition, and a further jump to ~ 28 MW is indicated at 12.3 minutes. The maximum fire size estimated by this calculation is ~ 121 MW at 18.13 minutes after ignition. It should also be noted that the HRR data in the interval from 13.5 to 16.5 minutes are unreliable since the fan was inactive during this period, thus interrupting the downstream advection of the combustion products.

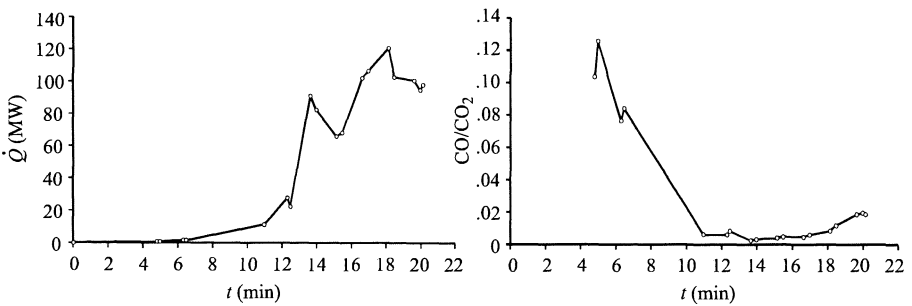


FIGURE 6. Heat release rate and CO/CO₂ ratio at +100 m

ESTIMATION OF HEAT RELEASE RATE BASED ON CO AND CO₂ PRODUCTION AT SECTION 'A' (+30 m DOWNSTREAM)

Since the data at location 'A' (+30 m downstream) were available for the entire test duration (~ 90 minutes), the HRR calculation was repeated for this section. In this case, although all the data were of German origin, the problem of out-of-phase data persisted and a similar filtering operation was necessary. Figure 2 shows the locations of the relevant instrumentation and it can be seen that both CO and CO₂ concentrations were recorded at heights above ground level of 2 m and 5 m. Reduced CO and CO₂ concentrations were again obtained by subtracting the background concentration value for each analyser (recorded at the first positive time step). Again some degree of stratification was evident from the data, although this remained low (~ ±3%) throughout the test. This observation is perhaps counter-intuitive, since it might be anticipated that enhanced smoke stratification would occur at downstream locations closer to the fire. However, it is suspected that the buoyancy forces were suppressed in the near downstream region by the turbulence generated by the fire itself coupled with the general expansion of the flow leaving the annulus surrounding the HGV. The velocity of the gas stream was inferred from the pressure difference data reported in [9], using the equation;

$$\Delta P = \frac{1}{2}\rho U^2 \quad (7)$$

where U is the local air velocity.

For the calculation of ρ , it was assumed that the downstream gas composition was identical to air at atmospheric pressure. The tunnel cross section at 'A' was scaled from [9] giving a height of 5.6 m and width of 5.0 m (Figure 2); the corresponding area is 28 m². Adopting the same velocity profile as in the previous calculation, with velocity data at 2 m above ground level, the volumetric flowrate at 'A' (m³.s⁻¹) was approximated by the expression,

$$\dot{V} = 28 \times U_{\text{mean}} \quad (8)$$

for the calculation of heat release rate over the first 55.13 minutes of the test, based on the instrumentation at +30 m.

The mass flow rates of the gas species were calculated as before and Tewarson's [3] expression (5) was again used to estimate the rate of heat release throughout the test, using the quoted mean values of H_c/k_{CO_2} and $(H_c/k_{\text{CO}} - H_{\text{CO}})$. The results of the heat release rate calculation are shown in Figure 7, with the accompanying CO/CO₂ behaviour. These calculations confirm that the fire remains below approximately 2 MW for the first seven minutes of the test with a rapid growth to 13.5 MW at around 9.75 minutes from ignition, and a further jump to 24 MW indicated at 10.00 minutes. The fire reaches 27 MW at 11.52 minutes after ignition, and the maximum fire size estimated by this calculation is around 128 MW at 18.78 minutes after ignition. The data for this calculation are available at more frequent time intervals than at Section 'B', providing an increased temporal resolution of the fire growth history. However, the interruption of the forced ventilation airflow between approximately 13.5 and 16.5 minutes again requires that the estimates of heat release rate in this interval be ignored.

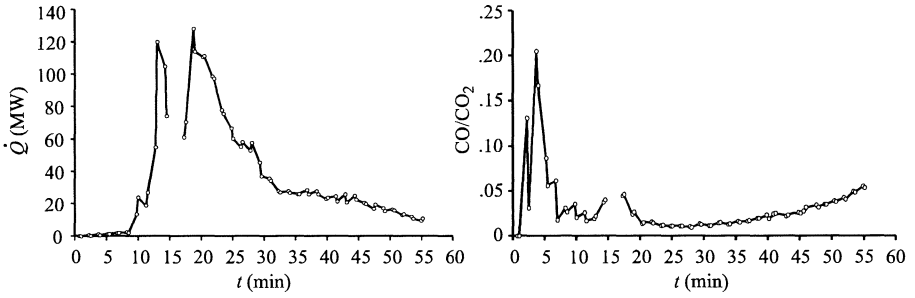


FIGURE 7. Heat release rate and CO/CO₂ ratio at +30 m

DISCUSSION

Some estimates of the heat release rate history for a burning HGV in a longitudinally-ventilated tunnel have been made from an incomplete data set. The results seem reasonable, given the nature of the fuel load. Two caveats apply however; firstly, the time resolution of the data is poor, consequently there are ill-defined periods of fire development. Secondly the fan was inactive between approximately $t = 13.5$ minutes and $t = 16.5$ minutes and so the estimates of HRR in this interval should be ignored since the calculation method adopted requires a well-mixed unidirectional flow downstream of the fire. The accuracy of the HRR estimates is dependent upon the accuracy of the various input data, and there are several possible sources of error, including: calibration of instrumentation, variations in tunnel area and in the shape of the velocity profile. It should also be noted that the calculation method is semi-empirical and Tewarson [3] obtained combustion parameters for a range of common fuels; average values for a ‘mixed fuel load’ have been adopted here. The implications of this assumption are now briefly considered, and Table 4 presents \dot{Q}_{max} estimates based on the combustion parameters for three different simple fuels [3], using the method outlined above.

TABLE 4. Maximum HRR for Repparfjord data assuming three simple fuels

Fuel Type	H_c/k_{CO_2} (kJ.kg ⁻¹)	$H_c/k_{CO} - H_{CO}$ (kJ.kg ⁻¹)	\dot{Q}_{max} +100 m (MW) (at $t = 18.78$ min)	\dot{Q}_{max} +30 m (MW) (at $t = 18.13$ min)
Wood cribs	9.22	4.34	89.2	94.4
PVC	11.55	8.09	112	119
Kerosene	14.33	12.38	139	148

The heat release rate values derived in Table 4 would apply if the entire fuel load of the HGV were composed of the relevant single fuel. Theoretically, if the breakdown of the HGV fuel load is known, together with the sequence of burning, then the calculation could be modified to reflect the changes in fuel character during the fire. Such sophistication is probably not justified however and the adoption of mean values for the combustion parameters is reasonable in this case given the other uncertainties in the data. If the HRR values in Table 4

are compared with the 'mixed fuel' results, the greatest divergence occurs with the wood crib assumption; the maximum HRR in this case is 26% lower than the mixed fuel fire. The HRR associated with the PVC fire is about 7% lower, while the kerosene assumption leads to a fire with a maximum HRR 15% higher than the mixed fuel case. Assuming a mixed fuel load, the estimated maximum HRR is between 120 to 128 MW. Considering the above, and allowing a reasonable margin for various errors, a conservative estimate for the maximum HRR would be between 100 to 150 MW. The time-dependent CO/CO₂ ratios shown in Figures 6 and 7 are similar, with initially fairly high values (> 0.1) while the fire is less than ~ 10 MW. This is characteristic of a ventilation-controlled compartment fire, before external flaming has developed sufficiently to 'burn off' the excess CO, and is consistent with the reported observations of fire development [9]. At later stages the CO/CO₂ ratio is seen to decay to ~ 0.01 or less, characteristic of a well-ventilated fire, again consistent with observations.

The interpretation of 'third party' experimental data in this manner is a severe test of any calculation procedure and particularly where many imponderables exist (tunnel dimensions, roughness, data synchronisation, datum zeros on instruments etc.) It is therefore gratifying that such plausible estimates for the heat release rates emerged from the computation.

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