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Heat release rate measurements of burning mining vehicles in an underground mine

Rickard Hansen^{a,*}, Haukur Ingason^{a,b}^a Mälardalen University, Box 833, S-721 23 Västerås, Sweden^b SP Technical Research Institute of Sweden, Box 857, 501 15 Borås, Sweden

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ABSTRACT

Heat release rates from two full-scale fire experiments with mining vehicles in an underground mine are presented. The mining vehicles involved were a wheel loader and a drilling rig typical for mining operations. The calculated peak heat release rate of the loader was 15.9 MW and occurred after approximately 11 min from ignition. The calculated peak heat release rate of the drilling rig was 29.4 MW and occurred after approximately 21 min from ignition. The heat release rate was calculated from measured data of gas concentrations of oxygen, carbon monoxide and carbon dioxide, measured gas velocity and measured gas temperatures. The fuel load of the wheel loader consisted mainly of the tyres, the hydraulic oil and the diesel fuel. The fuel load of the drilling rig consisted mainly of the hydraulic oil and the hydraulic hoses. The calculated heat release rate curves were controlled by comparing the summed up energy contents of the participating components with the integrated heat release rate curves.

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1. Introduction

The aim of the full-scale fire experiments presented here was to determine the heat release rate (HRR) for vehicles common in the mining industry. Studies show that vehicles or mobile equipment are the dominating fire object in underground mines [1,2]. The studies show that the better knowledge about fire spread is needed for service vehicles, drilling rigs and loaders. The information from full-scale fire experiments in an underground mine would be most valuable for companies manufacturing underground vehicles as well as mining companies and first responders. The information is also important for the design of evacuation procedures and equipment such as rescue chamber. For example the results can be used in the design process of the fire safety engineering of mines. Information about the fire spread and the HRR of vehicles and mobile equipment is the base in the preventive fire safety work.

There is only one full-scale fire experiment using large vehicle in an underground mine that has been performed and documented earlier [3]. The experiment was carried out in a loader CAT 960, where the fuel load consisted of rubber (2200 kg) and oil (600 l). The aim of the experiment was to investigate the environment that a mobile rescue chamber was exposed to during a fire. During

the experiment the carbon monoxide (CO)-level and temperature inside and outside the rescue chamber were continually measured; the smoke density at the rescue chamber and the airflow in the drift (the term “drift” in this text corresponds to a horizontal passage in an underground mine) was measured; and the experiment was videotaped. Unfortunately no HRR measurements were conducted during the experiment. This information is vital for engineers working with fire safety in underground mines and tunnel construction sites.

Several full-scale fire tests on vehicles or parts of vehicles have been conducted in traffic tunnels, such as the tests involving a heavy goods vehicle (HGV) mock-ups trailer cargo in Runehamar, Norway [4]. The commodity on the trailer mock-up consisted of furniture, polyurethane mattresses, truck tyres etc. The estimated maximum heat release rates were in the interval 66–202 MW [4]. The method of determine the heat release rate using oxygen consumption calorimetry has been applied here [5]. The method uses the possibility to analyse the combustion gases on the downstream side of the air flow. The accuracy of the method has been estimated and will be discussed separately in this paper. In the following a description of the tests and test-setup is given.

2. The mining vehicles

Two full-scale fire tests were carried out, one with a wheel loader and one with a drilling rig. Each of these vehicles has been

* Corresponding author. Tel.: +46 705778759.

E-mail addresses: rickard.hansen@mdh.se (R. Hansen)haukur.ingason@sp.se (H. Ingason)

Notation

A	= cross-sectional area (m^2)
c_{st}	= specific heat capacity of steel (J/kg K)
h_{PT}	= convective heat transfer coefficient of the plate thermometer ($\text{W/m}^2 \text{K}$)
K_{cond}	= conduction correction factor ($\text{W/m}^2 \text{K}$)
M_a	= molecular weight of air
M_{O_2}	= molecular weight of oxygen
N_T	= number of measuring points with thermocouples
Δp	= pressure difference (Pa)
$\dot{Q}$	= heat release rate (HRR) (kW)
q''_{inc}	= incident heat flux (kW/m^2)
T	= gas temperature (K)
T_{avg}	= average temperature in a mine drift (K)
T_h	= temperature at height h (K)
T_i	= temperature at thermocouple i (K)
T_0	= ambient temperature (K)
T_{PT}	= temperature of the plate thermometer (K)

t	= time (s)
u_0	= cold gas velocity (m/s)
u_{avg}	= average longitudinal velocity in a mine drift (m/s)
u_{probe}	= ventilation velocity of bi directional probe (m/s)
$X_{H_2O,0}$	= mole fraction of water in the ambient air
$X_{O_2,avg}$	= average concentration of oxygen
$X_{CO,avg}$	= average concentration of carbon monoxide
$X_{CO_2,avg}$	= average concentration of carbon dioxide
$X_{O_2,0}$	= mole fraction of oxygen in the ambient air
$X_{CO,0}$	= mole fraction of carbon monoxide in the ambient air
$X_{CO_2,0}$	= mole fraction of carbon dioxide in the ambient air
$X_{O_2,h}$	= oxygen concentration at height h
$X_{CO_2,h}$	= carbon dioxide concentration at height h
$X_{CO,h}$	= carbon monoxide concentration at height h
δ	= thickness of steel plate (plate thermometer) (m)
ϵ_{PT}	= surface emissivity of the plate thermometer
ρ_{st}	= density of steel (kg/m^3)
ρ_0	= ambient air density (kg/m^3)
σ	= Stefan–Boltzmann constant, $5.67 \times 10^{-11} \text{ kW/m}^2 \text{K}^4$

in service for several years. In the following a detailed description of each mining vehicle used is given.

2.1. Wheel loader

A wheel loader of type Toro 501 DL was used in the first full-scale fire test. The wheel loader is a diesel driven vehicle commonly used in underground mines. The wheel loader is used for hauling iron ore between the production areas to a vertical shaft (i.e. an ore pass), where the iron ore is unloaded. In Table 1 below some basic information regarding geometry, weight etc of the Toro 501 wheel loader is given (Fig. 1).

Table 1
Basic technical information regarding the Toro 501 DL wheel loader obtained from the manufacturer.

Length	10.3 m
Width	2.81 m
Height	2.85 m
Weight	36,000 kg
Tyre dimensions	26.5 × 25 L55

Fig. 1. The Toro 501 DL wheel loader used in the full-scale fire experiments in Sweden.

The fuel load of the actual wheel loader consists primarily of the four tyres. The tyre dimension 26.5 × 25 L55 implies a tyre with a section width of 26.5 in. (0.66 m), a rim diameter of 25 in. (0.625 m) and with smooth extra deep tread. In Table 2, an inventory of the combustible components is found. If all the combustible components found in Table 2 would have been consumed in the fire experiment, the total energy released during the experiment would have been 76.2 GJ. These numbers are based on onsite evaluation and inspection before the test. The tyres of the wheel loader were filled with water – instead of air – due to the risk of tyre explosion during normal operation. Each tyre contained 577 l of water (75% of the interior volume of the tyre). Before the fire experiment, the scoop was removed. No other modifications were made on the wheel loader.

2.2. The drilling rig

A drilling rig was used in the second full-scale fire test. The drilling rig was an Atlas Copco Rocket Boomer 322, which is an electrically driven drilling rig commonly used in underground mines. The drilling rig is nonetheless equipped with a diesel powered engine which is used when moving the drilling rig from one site to another. In Table 3 some basic information regarding measurements, weight etc is given (Fig. 2).

The fuel load of the drilling rig consists primarily of the four tyres, the hydraulic oil and the hydraulic hoses. The tyre dimension 13.00 × 20 PR 18 implies a tyre with a section width of 13 in. (0.325 m) and a rim diameter of 20 in. (0.5 m). In Table 4 an inventory of the combustible components is found. The effective heat of combustion of the hydraulic hose was also applied for the water hose. No modifications on the drilling rig were made before the fire experiment. If all the combustible components found in Table 4 would have been consumed in the fire experiment, the total energy released during the experiment would have been 45.8 GJ.

3. The experimental set-up

The site of the full-scale fire experiments was the underground facilities of Björka Mineral AB on the outskirts of Sala, Sweden. The fire experiments were conducted at level 55 (55 m from the top of the mine) which is a non-active part of the mine that is connected

Table 2
Inventory of combustible components found on the Toro 501 DL wheel loader.

Combustible component	Estimated amount prior to test	Effective heat of combustion [MJ/kg]	Estimated energy content [MJ]	Mean heat release rate per unit area [kW/m ²] ^a	Other
Tyres	1560 kg	27 [6]	42,120		Dimensions: overall width 0.7 m; overall diameter 1.8 m
Hydraulic oil in tank	500 l	42.85 [7]	16,283		Type: Shell Tellus VG46
Hydraulic oil in hoses	70 l	42.85 [7]	2,280		Type: Shell Tellus VG46
Hydraulic hoses	170 kg	28.85 ^b	4,905	152 ^c	Material: synthetical rubber; total length: 460 m; average diameter: 21 mm
Diesel	280 l	42.6 [8]	10,138		
Driver seat	10 kg	22.78 ^b	228	158	Material: foamed PVC
Electrical cables	1.5 kg	19.41 ^b	21	190	Total length: 425 m; average diameter: 1.4 mm
Rubber covers	10 kg	27 [6]	270		
Total	–	–	76,245	–	–

^a Obtained from conducted cone calorimeter experiments prior to the full scale test.

^b Measured mean effective heat of combustion obtained from conducted cone calorimeter experiments.

^c The heat release rate at 35 kW/m² was selected as an erroneous value at 50 kW/m² was measured during the cone calorimeter test.

Table 3

Basic technical information regarding the Rocket Boomer 322 drilling rig. This information was obtained from the manufacturer.

Length with boom	12.4 m
Width	2.19 m
Height	2.95 m
Weight	18,400 kg
Tyre dimensions	13.00 × 20 PR 18

Fig. 2. The Rocket Boomer 322 drilling rig used in the full-scale fire experiment in Sala, Sweden. Photo: Andreas Fransson.

to an open pit. The non-active part is connected to an active part that goes down to level 90, see Fig. 3.

The test site – i.e. the mine drift where the experiments took place – was approximately 150 m from the entrance to the mine and 40 m from the exhaust, see Fig. 3. The mine drift used as test site was approximately 100 m long. The difference in height between the entrance of the mine and the exhaust was virtually zero.

The test site had no fans installed in the immediate surroundings. Ventilation resources were therefore needed and a mobile fan of type Tempest model MGV L125, diesel powered, and a diameter of 1.25 m and with a primary air flow rate of 217,000 m³/h was therefore used to direct the flow in one direction. The location of the mobile fan is shown in Fig. 3.

There was only one exhaust on one side of the test site – all other mine drifts were dead ends on that side – allowing for all the smoke to be ventilated out through the single exhaust and thus allowing for heat release rate measurements on this side of the test site.

Before the fire experiments took place it was contemplated to seal the adjacent mine drifts with inflatable partitions in order to more effectively steer the ventilation flow to the exhaust. Performing CFD-simulations – using the FDS software [10] – it was concluded that partitions would not improve the flow of smoke to the exhaust, instead the partitions would increase the turbulence of the smoke. The main airflow became more or less as a bulk flow bypassing the short mine drifts from the fan towards the entrance. Thus the fire experiments were conducted without partitions in the adjacent mine drifts. Tests with the mobile fans prior to the fire tests confirmed this behavior.

The entrance of the mine created a large pressure loss for the fans due to the small exhaust area. The exhaust area can be estimated to be roughly about 12 m². In Fig. 4 a photo of the exhaust area is shown. The entrance opening to the mine was much larger or about 50 m².

In Fig. 5 the test site is shown more in detail, showing the approximate distances and the locations of measuring devices.

In Figs. 6 and 7 the position of the measuring devices at each vehicle is shown. A further description of the positions can also be found in Tables 5 and 6.

An earlier performed investigation on fire causes and fire behaviour with respect to vehicle fires in underground mines in Sweden [11] showed that full-scale fire experiments involving a diesel wheel loader and a drilling rig will have to be ignited using a diesel fire. This could be for example a pool fire underneath or in the engine compartment that is shielded and positioned close to larger amounts of combustibles such as tyres or hydraulic hoses. This would be necessary in order to achieve a fire growth and fire spread that eventually engulfs the entire vehicle. Thus a circular tray was placed underneath the fuel tank of each vehicle and it was located close to at least one tyre. The trays were filled with diesel fuel in order to simulate a pool fire caused by leaking diesel from the tank. The thickness of the fuel is of course exaggerated as it would be much thinner in a real situation. However, due to practical reasons and reasons mentioned earlier about fire spread this was found to be the best ignition method.

The door to the cab was opened and stayed open during the experiment. The two vehicles were not warmed up before the experiment.

Table 4

Inventory of combustible components found on the Rocket Boomer 322 drilling rig.

Combustible component	Estimated amount prior to test	Effective heat of combustion [MJ/kg]	Estimated energy content [MJ]	Mean heat release rate per unit area [kW/m ²] ^a	Other
Tyres	155 kg	27 [6]	4,185		Dimensions: overall width 0.35 m; overall diameter 1.2 m Type: Shell Tellus VG46
Hydraulic oil in tank	350 l	42.85 [7]	11,398		Type: Shell Tellus VG46
Hydraulic oil in hoses	150 l	42.85 [7]	4,885		Type: Shell Tellus VG46
Hydraulic hoses	390 kg	28.85 ^b	11,252	152 ^c	Material: synthetical rubber; total length: 1000 m; average diameter: 22 mm Total length: estimated at 100 m; diameter: 35 mm
Water hose (rubber material)	40 kg	28.85 ^b	1,154		
Diesel	100 l	42.6 [8]	3,621		
Driver seat	10 kg	22.78 ^b	228	158	Material: foamed PVC
Electrical cables	450 kg	19.41 ^b	8,735	190	Total length: 700 m; Average diameter: 39 mm
Plastic covers	10 kg	30 [9]	300		
Total	–	–	45,758	–	–

^a Obtained from conducted cone calorimeter experiments prior to the full scale tests.^b Measured mean effective heat of combustion obtained from conducted cone calorimeter experiments.^c The heat release rate at 35 kW/m² was selected as an erroneous value at 50 kW/m² was received. **Fig. 3.** Plan of the level 55 which is today a non-active part mine. The entrance to the mine is indicated on the right hand side of the sketch and the exhaust on the left hand side. **Fig. 4.** A photo of the exhaust area of the mine.

The ignition of the pool fire underneath the tank took place—using pieces of fiber board soaked in diesel.

A video camera was used in each experiment in order to record the ignition of various fuel components, flame spread, fire

development etc. The video footage could for example be used when relating a certain change in the heat release rate to the visual appearance at the scene of the fire.

3.1. Test 1 with a wheel loader

The front of wheel loader was placed 30 m from the measuring station in the mining drift. The fuel tank was emptied to 90 l, the remaining 190 l of diesel fuel was emptied into a circular tray with a diameter of 1.1 m. The fuel surface was even with the top of the rim.

The fan was started 1 min before ignition. The average longitudinal ventilation velocity at the measuring station was close to zero prior to the ignition and the start up of the fan, 0.2 m/s at the time of ignition and 1.6 m/s at the maximum heat release rate (the ventilation velocity was measured approximately 30 m downstream of the fire). A certain delay in the measured ventilation velocity at the measuring station from the mobile fan can be attributed to the distance between the fan and the measuring station. The average ventilation velocity for the initial 12 min of measurements is found in Fig. 8; the measurements were initiated 2 min before ignition.

Approximately 10 min after ignition the backlayering smoke reached the fan and the fan had to be geared down temporarily (was geared up again a few minutes later) and moved approximately

Fig. 5. A plan view of the test site (not to scale).

50 m further away from the fire in order to more easily establish a distinct pressure and flow situation.

3.2. Test 2 with a drilling rig

The front end of the drilling rig was placed about 17 m from the rear end of the remains of the wheel loader from test 1. This means the front end of the drilling rig was now 47 m from the measuring station. Before the test the fuel tank was emptied to 40 l, the remaining 60 l of diesel fuel was emptied into a circular tray with a diameter of 1 m. The free distance between the top of the rim and the fuel surface was 120 mm.

The fan was started approximately 20 min before ignition. The average longitudinal ventilation velocity was 1.3 m/s at ignition and 2.5 m/s at the maximum heat release rate (the ventilation velocity was measured approximately 50 m downstream of the

Fig. 6. The position of the thermocouples and plate thermometers on the wheel loader.

4. Measurement and calculation procedure

The heat release rate in the fire experiments was determined with aid of the oxygen calorimetry concept [5]. This means that the mass flow rate, gas concentrations and temperatures at certain heights at the far end of the mine drift and downstream of the fire source are used to calculate the heat release rate during the test. At the measuring station downstream the fire numerous instruments were mounted over the cross-section. In the first test the measuring station was at a distance of +30 m (plus means downstream of the fire) from the front side of the wheel loader. For the drilling rig this distance was +47 m. The measurements used to determine the heat release rate were thermocouples, pressure probes for determining the velocity and gas instruments to measure the oxygen, carbon monoxide and carbon dioxide content in the hot fire gases. The instrument layout is shown in Fig. 10.

The calculation of the heat release rate applied here is based on method presented by Ingason [12] using many thermocouples distributed over the actual cross-section and only single point for measuring gas concentrations. The environment in a mine drift is generally very harsh for sensitive instruments – with high humidity etc – making this method attractive for HRR measurements in an underground mine. Other advantages with the method are that we can determine very large HRR and we do not need to know the average gas concentration in the applicable cross-section, instead the average value is calculated using temperature and oxygen readings – where only one or two readings may be sufficient – over the cross-section.

The heat release rate – using mass flow rate, gas concentration and temperature data – can be calculated using the following equation assuming that the local gas temperature and the local gas concentration correlate through the average values over the cross-section [12]:

$$\dot{Q} = \frac{13,100 \times \rho_0 \times u_0 \times A \times (M_{O_2}/M_a) \times (1 - X_{H_2O,0})}{(0.1/X_{O_2,0}) + [(1 - X_{O_2,avg}) \times (X_{O_2,avg}/(1 - X_{CO_2,avg})) / (X_{O_2,0} - X_{O_2,avg} \times ((1 - X_{CO_2,0})/(1 - X_{CO_2,avg})))]} \quad (1)$$

center of the fire). The average ventilation velocity for the initial 24 min of measurements is found in Fig. 9; the measurements were initiated 2 min before ignition.

A distinct pressure and flow situation was successfully established during the entire experiment, using the fan position further away from the fire.

The molecular weight of oxygen – M_{O_2} – was set to 32 g/mol. The molecular weight of air – M_a – was set to 28.95 g/mol. The mole fraction of water in the ambient air – $X_{H_2O,0}$ – was set to 0.005. The mole fraction of oxygen in the ambient air – $X_{O_2,0}$ – was set to 0.2095. The mole fraction of carbon dioxide in the ambient air – $X_{CO_2,0}$ – was set to 0.00033.

Fig. 7. The position of the thermocouples and plate thermometers on the drilling rig.

Table 5

Description of the thermocouples and plate thermometers at the wheel loader.

Id #	Specification of instrument (mm)	Position
Tc11	0.5	Tyre; right, rear. Positioned at the rim
Tc12	0.5	Tyre; right, forward. Positioned at the rim
Tc13	0.5	Tyre; left, rear. Positioned at the rim
Tc14	0.5	Tyre; left, forward. Positioned at the rim
Tc15	0.5	On bundle of hydraulic hoses in the rear, left side
Tc16	0.5	On bundle of hydraulic hoses at the waist
Tc17	0.5	Interior of cab, at the ceiling
Tc18	0.5	Interior of cab, on the driver seat
PTC19		Tyre, right, rear. In line with the rear edge of the tyre; facing the vehicle; 0.5 m from the tyre; 0.4 m from the ground to the centre of thermometer
PTC20		Tyre, right, forward. In line with the rear edge of the tyre; facing the rear of the vehicle; 0.5 m from the tyre; 0.44 m from the ground to the centre of thermometer
PTC21		Tyre, left, rear. In line with the rear edge of the tyre; facing the vehicle; 0.43 m from the tyre; 0.4 m from the ground to the centre of thermometer
PTC22		Tyre, left, forward. In line with the rear edge of the tyre; facing the rear of the vehicle; 0.5 m from the tyre; 0.44 m from the ground to the centre of thermometer
Tc23	0.5	In the ceiling above the wheel loader
Tc24	1.5	In the ceiling above the wheel loader

In Eq. (1) it is assumed that 13,100 kJ/kg (E-factor) is released per kg of oxygen consumed and that air mass flow rate of combustion gases equals the ambient air mass flow rate. The integrated HRR over the measuring period was compared to the total energy content of each vehicle given in Tables 2 and 4 minus the remains from the each test. This procedure gives an indication of the accuracy of the HRR calculation method used here.

The observation of a correlation between the local gas temperature and local gas concentrations to the average value for the actual cross-section is based upon the original work of Newman [13], who tested the correlation for different types of fuels in a test gallery representing a duct or a mine drift. Eq. (1) requires that the heat release rate measuring station is positioned outside the reaction zone of the fire and that a uni-directional ventilation flow past the measuring station is secured during the entire experiment. In the case when it is only possible to use one measuring

point for the gas, as in the present case, it is recommended to use more than one temperature measuring point in order to increase the reliability of the output data and the dependence on one single measuring point.

It has been shown by Ingason [12], that it is possible to relate multiple gas temperatures measurements in a single tunnel cross section to the average gas concentrations in a longitudinal tunnel flow, see Eqs. (2)–(4). The average concentration of oxygen and carbon dioxide was calculated using the following equations [12]:

$$X_{O_2,avg} = X_{O_2,0} - \frac{(X_{O_2,0} - X_{O_2,h}) \sum_{i=1}^{N_T} (T_i - T_0)}{(T_h - T_0) N_T} \quad (2)$$

$$X_{CO_2,avg} = X_{CO_2,0} - \frac{(X_{CO_2,0} - X_{CO_2,h}) \sum_{i=1}^{N_T} (T_i - T_0)}{(T_h - T_0) N_T} \quad (3)$$

Table 6
Description of the thermocouples and plate thermometers at the drilling rig.

Id #	Specification of instrument (mm)	Position
Tc11	0.5	Tyre; right, rear. On the upper edge of the tyre
Tc12	0.5	Tyre; right, forward. On the upper edge of the tyre
Tc13	0.5	Tyre; left, rear. On the upper edge of the tyre
Tc14	0.5	Tyre; left, forward. On the upper edge of the tyre
Tc15	0.5	Bundle of hydraulic hoses in the rear, right side
Tc16	0.5	On the rear of the cable reel; left side, rear part
Tc17	0.5	Interior of cab, at the ceiling
Tc18	0.5	Interior of cab, on the driver seat
PTC19		Tyre; right, rear. In line with the rear edge of the tyre; facing the vehicle; 0.5 m from the tyre; 0.4 m from the ground to the centre of thermometer
PTC20		Tyre; right, forward. In line with the rear edge of the tyre; facing the rear of the vehicle; 0.5 m from the tyre; 0.4 m from the ground to the centre of thermometer
PTC21		Tyre; left, rear. In line with the rear edge of the tyre; facing the vehicle; 0.5 m from the tyre; 0.4 m from the ground to the centre of thermometer
PTC22		Tyre; left, forward. In line with the rear edge of the tyre; facing the rear of the vehicle; 0.5 m from the tyre; 0.4 m from the ground to the centre of thermometer
Tc23	0.5	On a bundle of hydraulic hoses; at the lower part of the waist; right hand side
Tc24	1.5	On a bundle of hydraulic hoses; at the upper part of the waist; left hand side
Tc28	0.5	Inside the rear, right wheelhouse; in the rear, upper part of the wheelhouse; attached to hydraulic hoses
Tc29	0.5	Inside the rear, left wheelhouse; in the rear, upper part of the wheelhouse; attached to hydraulic hoses
Tc30	0.5	On bundle of hydraulic hoses; between the forward wheels
Tc31	0.5	On bundle of hydraulic hoses; middle of the boom; right side
Tc32	0.5	On bundle of hydraulic hoses; forward of the boom; right side
Tc33	0.5	On bundle of hydraulic hoses; middle of the boom; left side
Tc34	0.5	On bundle of hydraulic hoses; forward of the boom; left side
Tc35	1.5	In the ceiling above the drilling rig
Tc36	0.5	In the ceiling above the drilling rig

Fig. 8. The average longitudinal ventilation velocity at the measuring station during the initial 12 min of measurements at measuring station +30 m.

In the following calculations the average concentration of carbon monoxide was calculated in an analogous manner:

$$X_{\text{CO,avg}} = X_{\text{CO,0}} - \frac{(X_{\text{CO,0}} - X_{\text{CO,h}}) \sum_{i=1}^{N_T} (T_i - T_0)}{(T_h - T_0) N_T} \quad (4)$$

The mole fraction of carbon monoxide in the ambient air – $X_{\text{CO,0}}$ – was set to 0.00005 as the mole fraction of carbon monoxide was measured approximately at this level in the mine drift before the ignition took place.

The gas temperatures were measured every 10 s by a type K thermocouple of 0.5 mm.

The cold gas velocity in Eq. (1) is calculated using the following equation:

$$u_0 = u_{\text{avg}} \times \left(\frac{T_0}{T_{\text{avg}}} \right) \quad (5)$$

where the average longitudinal velocity and temperature in the mine drift are calculated using the average values of the velocity probes and thermocouples at the heat release rate measuring station (see Fig. 10). An average temperature of the three thermocouples at the same level as the gas analysis was first calculated

Fig. 9. The average longitudinal ventilation velocity during the initial 24 min of measurements at measuring station +47 m.

and then added to the other three temperature readings in order to obtain an average value of the entire cross-section.

Ingason and Lönnemark [4] have used Eqs. (1)–(3) in order to determine the heat release rate in a series of large scale tunnel fire tests.

The heat release rate was measured at the end of the mine drift (see Fig. 4 for the position of the measuring devices) in order to ensure that the measuring station was outside the reaction zone of the fire. The site was also chosen in order to make sure that all the fire gases would directly pass the site without entering other parts of the mine. As can be seen in Fig. 10, the heat release rate was measured using six thermocouples, four velocity probes and one gas analysis (O_2 , CO , CO_2) mounted on pillars positioned downstream of the fire. The dimensions of the mine drift where the heat release rate took place were 6.3 m (height) by 8.5 m (width). The dimensions of the mine drift where the wheel loader and the drilling rig were placed were 6.8 m (height) by 8.7 m (width).

The temperature above each vehicle was measured with thermocouples attached to the ceiling above the vehicle in question.

Fig. 10. The measuring station+30 m and +47 m, respectively, for calculation of the heat release rate using gas concentrations (O_2 , CO_2 , CO), velocity (u) and gas temperatures (T).

The velocity at certain heights in the mine drift was determined by bi-directional probes. A differential pressure transmitter was used in the experiments, model: FCO332-3W (± 50 Pa).

The velocity at each bi-directional probe was determined using the following equation:

$$u_{probe} = \frac{1}{k(Re)} \sqrt{\frac{2 \times \Delta p \times T}{\rho_0 \times T_0}} \quad (6)$$

The diameter of the probes used was 16 mm and the probe length was 32 mm.

The correction coefficient – $k(Re)$ – is found to hold as a constant value of 1.08 for Reynolds number larger than 2000 [14]. In the two conducted fire experiments the Reynolds number was in the range of 1400–2700, implying that the correction coefficient is equal to 1.08 or approximately equal to 1.08.

The oxygen concentration was measured using an M&C PMA10 set for the interval 0–30%. The carbon monoxide and the carbon dioxide were measured using a Rosemount Binos 100 in the case of the wheel loader (CO : 0–10%; CO_2 : 0–30%) and a Siemens Ultramat 22P in the case of the drilling rig (CO : 0–3%; CO_2 : 0–10%). The thermocouples, the differential pressure transmitter, the gas analysers and velocity probes were connected to a 20-channel Solartron 5000 IMP logger. The data was recorded on a laptop computer at a rate of about one scan per 10 s.

The incident radiation heat flux at the tyres of the vehicles was measured using plate thermometers. The incident radiation heat flux was determined using the following equation by Ingason and Wickström [15] developed for the plate thermometer:

$$q''_{inc} = \frac{\epsilon_{PT} \times \sigma \times T_{PT}^4 + (h_{PT} + K_{cond}) \times (T_{PT} - T_0) + \rho_{st} \times c_{st} \times \delta \times \Delta T_{PT} / \Delta t}{\epsilon_{PT}} \quad (7)$$

where the surface emissivity of the plate thermometer – ϵ_{PT} – was set to 0.8, the convective heat transfer coefficient – h_{PT} – was set to $10 \text{ W/m}^2 \text{ K}$ [15], the conduction correction factor – K_{cond} – was set to $22 \text{ W/m}^2 \text{ K}$ [16], the density of steel – ρ_{st} – was set to 8100 kg/m^3 , the specific heat capacity of steel – c_{st} – was set to 460 J/kg K and the thickness of steel plate – δ – was set to 0.0007 m [15].

Fig. 11. The measured oxygen level and the calculated average oxygen level at measuring station +30 m.

5. Results

An inventory of the individual combustible components of the vehicle were obtained, see Tables 2 and 4, and by adding up the individual energy contents it was possible to compare it to the integrated HRR curve yielding the total energy content from the experiments. As a final part of the method, an uncertainty analysis of the HRR measurements was carried out in order to investigate accuracy of the results. The uncertainty analysis is found at the end of this section.

5.1. Test 1 with wheel loader

The heat release rate will be dependent upon the average concentration of the oxygen and carbon dioxide and the cold gas velocity, where the cold gas velocity in return will be dependent upon the average ventilation velocity and average gas temperature.

In Fig. 11 the measured oxygen level at the ceiling level and the calculated average oxygen level for the wheel loader fire is displayed. As can be seen the calculated values follow the fluctuations of the

measured values and the measured oxygen level is generally 0.5–1.0% lower than the calculated level, which could be expected.

A lowest oxygen level was registered at 18.2%. A highest carbon monoxide level was registered at 0.09% and the highest carbon dioxide level at 1.87% occurring at the time of the maximum heat release rate, see Fig. 12 for the variation of the carbon monoxide and carbon dioxide level. Due to the high oxygen level and fairly low highest level of the carbon monoxide, the fire was not ventilation controlled. As can be seen in Fig. 12 the measured CO level curve has a jagged appearance, which is due to that the used scale is closer to the resolution limit. It appears that the CO measurements functioned well for the first 20 min, but after that time interval some kind of disturbance seems to have occurred as the CO value remain fairly constant as opposed to the calculated CO value. Therefore the CO values after 20 min were not used in the ensuing heat release rate calculations. When investigating the error introduced by the lack of CO values it was found that the error was estimated to approximately < 1.0%; i.e. < 1.0% lower than the calculated (as the E-factor will decrease with an incomplete combustion).

The average ventilation velocity before ignition was in the interval 0.02–0.4 m/s, which was in an interval lower than desired. The average ventilation velocity at the time of ignition was measured at 0.3 m/s. The average ventilation velocity between ignition and the time of maximum heat release rate was in the interval 0.3–2.2 m/s, see Fig. 13 for the average velocity at the measuring station from ignition and onwards. See Fig. 8 for the first 12 min into the test. The maximum average ventilation velocity at 2.2 m/s occurred after approximately 7 min which is the time just before the mobile fan was geared down and moved to the position further away from the fire.

Regarding the average gas temperature at the measuring station, the maximum gas temperature, 74 °C, occurs after approximately 11 min, which is the same time as the occurrence of the maximum heat release rate. This latter observation is expected as the average oxygen and carbon dioxide concentration correlates with the average gas temperature at the measuring station. The heat release rate results from these tests are shown in Fig. 15. When observing the appearance of the graphs found in Fig. 15 and the average gas temperature in Fig. 14 the appearance is found to be similar. This behavior is expected for this type of measurements as the velocity and the gas temperature are indicators of the total mass flow rate of air.

Due to the distance between the wheel loader and the measuring station there is a time delay with respect to the heat release rate measurements depending upon the longitudinal ventilation velocity and the distance. Calculating and summing up the progress of the fire gases for each time step with the aid of the calculated average ventilation velocity at the measuring station in the mine drift, the following time delay was received (and the corresponding heat release rate curve and other curves originating from the measuring station was adjusted accordingly): 80 s.

The maximum heat release rate from the experiment was 15.9 MW. The maximum heat release rate was attained approximately 11 min after ignition.

When examining the remains after the experiment it was found that only the rear tyres had participated in the fire and the front tyres were remained intact. Furthermore, the hydraulic hoses from the waist and forward and in some parts of the section behind the rear tyres also remained intact. The interior of the cab had participated fully in the fire and the combustible material being consumed.

The energy content of the combustible materials consumed in the fire was determined by integrating the measured heat release

Fig. 12. The measured carbon monoxide and carbon dioxide level and the calculated average carbon monoxide and carbon dioxide level at measuring station +47 m.

Fig. 14. The average gas temperature at the measuring station in the case of the wheel loader fire at measuring station +30 m.

Fig. 13. The average ventilation velocity during the entire tests at measuring station +30 m.

Fig. 15. The calculated heat release rate of the wheel loader.

rate curve. The total integrated energy content using the measured heat release rate was 57 GJ. When summing up the energy contents of the materials participating in the fire and found in Table 2, an energy content of 50.5 GJ was obtained (if everything would have burned the total was estimated to be 76.2 GJ). Be aware that only 280 l of diesel, the cab (driver seat and rubber covers), the hydraulic oil in the tank, the two rear tyres, estimated 50% of the hydraulic hoses, the hydraulic oil in the hoses and the electrical cables were assumed to have participated in the fire. The estimated energy content using an inventory was thus approximately 13% larger than the calculated energy content where the measured heat release rate curve was integrated. This difference is most likely due to the uncertainties when primarily estimating the amount of combustibles available and to some extent the amount of combustibles consumed in the fire Fig. 16.

5.2. Test 2 with drilling rig

In Fig. 17 the measured oxygen level at the ceiling level and the calculated average oxygen level for the drilling rig fire is displayed. Same as for the case of the wheel loader fire it can be seen that the calculated values follow the fluctuations of the measured values and that the measured oxygen level is generally about 1.0% lower than the calculated level.

Fig. 16. The wheel loader after the fire experiment. Photo: Andreas Fransson.

Fig. 17. The measured oxygen level and the calculated average oxygen level at measuring station +47 m.

A minimum oxygen level was registered at 17.2%. A highest carbon dioxide level at 2.37% occurred at the time of the maximum heat release rate. See Fig. 18 for the measured values of carbon dioxide. Unfortunately a measuring error occurred with respect to the carbon monoxide measurements and no graph can therefore be displayed. The error due to the lack of carbon monoxide values was estimated to approximately < 1.5%; i.e. < 1.5% lower than the calculated (as the E-factor will decrease with an incomplete combustion).

The average ventilation velocity before ignition was in the interval 1.2–1.4 m/s. The average ventilation velocity at the time of ignition was measured at 1.3 m/s. The average ventilation velocity between ignition and the time of maximum heat release rate was in the interval 1.1–2.6 m/s, the maximum value occurring at the time of the maximum heat release rate (Fig. 19).

The maximum average gas temperature at the measuring station, 93 °C, occurs after approximately 21 min, which is the same time as the occurrence of the maximum heat release rate. The heat release rate results from these tests are shown in Fig. 21.

When comparing the average gas temperature in Fig. 20 and the heat release rate curve in Fig. 21 it can be seen that the average gas temperature at the measuring station correlates well with the measured heat release rate.

The time delay with respect to the heat release rate measurements was found to be 80 s and the corresponding heat release rate curve was adjusted accordingly.

Fig. 18. The measured carbon dioxide level and calculated average carbon dioxide level at measuring station +47 m.

Fig. 19. The average ventilation velocity during the entire test at the measuring station (+47 m).

Fig. 20. The average gas temperature at the measuring station in the case of the drilling rig fire at measuring station +47 m.

Fig. 21. The calculated heat release rate of the drilling rig.

The maximum heat release rate from the experiment was 29.4 MW. The maximum heat release rate was attained after 21 min.

When examining the remains after the drilling rig experiment it was found that a portion of the hydraulic oil did not participate in the fire as apparently a hydraulic hose had busted and hydraulic oil being released. The hydraulic hoses approximately 2 m in front of the cab and forward, some amount of hydraulic oil as mentioned above, the water hose and the low voltage cable on the cable reel had not participated in the fire.

Using the measured heat release rate curve the energy content of the combustible materials consumed in the fire was calculated at 30.9 GJ. It was estimated that 600 m of hydraulic hoses, 70% of the hydraulic oil, the tyres, 600 m of electrical cables (thus excluding the 100 m found on the cable reel and assuming that the remaining cables would be fully consumed as practically no cables are found on the boom), the cab and 60 l of diesel had participated in the fire. When summing up the energy contents of the materials participating in the fire and found in Table 5, the summation results in an energy content of 32.5 GJ. The difference between the estimated energy content using an inventory and the calculated energy content – integrating the resulting heat release rate curve – was about 5%. This is a slight difference and is most likely due to the same uncertainties as in the case of the wheel loader, i.e. when primarily estimating the amount of combustibles available and to some extent the amount of combustibles consumed in the fire.

5.3. Uncertainty analysis of the heat release rate measurements

An uncertainty analysis was performed for the HRR measurements of the two experiments. The results show that the combined expanded relative standard uncertainty with a 95% confidence

interval was 17.6%. The volume flow measurements had the largest impact on the results (8.2%), followed by the E-factor (2.5%) (i.e. the factor 13,100 kJ/kg) and the oxygen measurements (2.2%). When comparing with the corresponding uncertainty analysis performed for the full-scale fire experiments at Runehamar [4] it was found that the combined expanded relative standard uncertainty was at 14.9% and that the contribution of the volume flow measurements was 6.7%. Thus the uncertainty of the full-scale fire experiments performed in the mine drift in Sala was higher than for the corresponding tests performed at Runehamar and the contribution of the volume flow measurements had the largest impact on this result. When studying the volume flow measurements it was found that the cross sectional area of the mine drift had the largest impact on the outcome, which was due to the very rough and uneven surface of the mine drift. In laboratory experiments – i.e. room corner experiments – the uncertainty varied between 7.1% and 13.5% [17].

Regarding the issue of having only one measuring point with respect to the O_2 -measurements; it was found during the analysis that the O_2 -measurements correlated well with the temperature measurements in the corresponding segments for both experiments. Also, earlier experiments where the same method has been applied have shown that the output results matched the actual results well [4].

6. Discussion

In the following a discussion on the fire development for each of the tests is presented. This detailed discussion is based on observations and analysis of the measurements obtained in the tests. Based on these discussions some final conclusions on the fire development for these two types of vehicles will be presented.

6.1. Test 1 with wheel loader

After about 2 min after ignition the right, rear tyre was ignited, and after approximately 8 min after ignition the left, rear tyre was ignited. Approximately 10 min after ignition the backlayering became too large and the mobile fan had to be moved further back, closer to the entrance to the mine (see Fig. 3 for the location). Eighteen minutes after ignition there was a sudden increase in the intensity, possibly a hydraulic hose bursting. Thirty-five minutes after ignition the right, rear tyre burst. Thirty-seven minutes after ignition rocks started to fall from the ceiling. Four hours and 20 min after ignition the mobile fan was shifted into a lower gear, a few minutes later it was shifted back again. The measurements were stopped 5 h and 23 min after ignition and the extinguishment of the remaining fire took place. The fire turned out to be very difficult to entirely extinguish due to the glowing fires in the remaining parts of the tyres. Glowing fires producing a lot of smoke and occasionally flaming fires actually occurred a week after the fire experiment. The glowing fires were difficult to extinguish as the entire vehicle was pressing down and resting on the glowing remains of the tyres. In a real fire situation the problem would have been easy to solve as towing the vehicle a short distance would have uncovered the glowing fire and made extinguishment easy. But due to a pressed timetable – as the drilling rig would be positioned right behind the wheel loader and measuring devices set up with only a couple of days to spare – it was decided that towing would not take place but instead the glowing fires were held down with occasional doses of dry powder.

After approximately 80 min from ignition the thermocouple at the right, forward tyre (see Fig. 6 and Table 5 for position of the thermocouple Tc12) registered temperatures about 630 °C, but

ignition did not occur. Unfortunately the plate thermometer at the tyre stopped functioning after approximately 40 min from ignition and thus the incident heat flux at the tyre could not be determined, but during the first 40 min the incident heat flux at the right, forward tyre never exceeded 13.7 kW/m^2 and would thus explain why ignition of the tyre in question did not occur during this time interval if assuming a critical heat flux of 17.1 kW/m^2 [18] for natural rubber. See Figs. 22 and 23 for the measurements at the thermocouple at the right, forward tyre and the four plate thermometers.

The sudden increase from ambient temperature up towards 630°C after about 80 min and as the right, rear tyre was fully engulfed in flames much earlier than this point of time, the increase in temperature must be contributed to the fire in hydraulic hoses and electrical cables close to the thermocouple above the right, forward tyre. This conclusion is further enforced by the fact that the thermocouple was shielded from the flames of the rear tyre by the construction of the vehicle and the sudden decrease in temperature after a fairly short time interval due to the fact that the fire in the hydraulic hoses and electrical cables did not spread beyond the waist of the vehicle.

Unfortunately the thermocouple (Tc24) above the wheel loader (see Fig. 5) stopped working after approximately 37 min. When comparing the temperature curve found in Fig. 22 with the heat release rate curve found in Fig. 15 for the first 20 min it can be seen that the appearance of the two curves matches well with each other. The maximum value occurred in both cases after approximately 12 min. This observation further strengthens the validity in the heat release rates measured.

The other thermocouple above the wheel loader (Tc23) stopped functioning after less than 20 min from ignition.

When studying the temperature at the left, rear tyre (Tc13) it can be seen that the temperature increased rapidly after approximately

130 min, most likely this was due to that the left, rear tyre was initially and at an early stage ignited at the inner surface facing the pool fire, the flames then slowly spread across the tyre and finally reaching the opposite side facing the thermocouple.

The temperature in the cab (Tc17) rapidly reached temperatures around 800°C after approximately 15 min after ignition and was by then engulfed in flames, the temperature then gradually decreased and reached 300°C after approximately 40 min. The interior of the cab was thus rapidly consumed in the fire.

The initial rapid increase in the incident heat flux at the right rear tyre (PTC19) was contributed to the incident heat flux from the pool fire and then gradually the flames reaching the outer surface facing the plate thermometer directly. As can be seen the incident heat flux at the left forward tyre (PTC22) never exceeded 10 kW/m^2 and thus explaining that ignition of this tyre did not take place. The incident heat flux at the left rear tyre (PTC21) was initially at lower values but started to increase after about 80 min and reaching a maximum after about 140 min, this is due to that the tyre was initially ignited at the inner surface facing the pool fire and then slowly and eventually the flames reached the surface facing the plate thermometer.

The resulting heat release rate curve of the wheel loader displayed a fire that was dominated by initially the sudden increase of the pool fire and when the first tyre was engulfed by flames and then by the slowly declining heat release rates of the large tyres of the vehicle. Still, the stop of fire spread from the waist and forward clearly shortened the duration of the fire considerably.

The initial sharp rise and high heat release rate for the first 20 min of the fire can be explained mainly due to the pool fire and the fire in the rear, right tyre. The sharp drop after about 20 min was due to the pool fire burning off. The burn off time of the diesel pool fire at the wheel loader fire experiment was calculated to about 43 min (assuming a regression rate of 0.066 kg/s m^2 (deep pool)). Assuming a maximum heat release rate per unit area of 1.33 MW/m^2 [19] for thick fuel bed, the maximum heat release rate of the diesel pool fire was calculated to be 1.26 MW . When studying the heat release rate curve in Fig. 15, the decrease in heat release rate was about 8 MW which was much larger than the calculated 1.26 MW of the pool fire. The difference can be explained by the fact that the diesel tank of the wheel loader was not equipped with a magnetic valve – as in the case of the drilling rig – which suggest that the fuel hoses in the proximity of the fuel tank could have been burned off during the early stages, draining the tank and thereby increasing the size of the pool fire and consequently the heat release rate of the diesel pool fire. Also the pool fire was underneath the wheel loader and thus the re-radiation back to the pool surface would be much larger than for a free standing pool fire and thus the heat release rate would be larger. This observation is further enforced by the fact that the calculated burn off time of the diesel pool fire was more than twice as long as the observed burn off time. But the differences will have to be investigated further in order to fully explain them.

The slow increase in heat release from about 20 min to about 50 min was due to the slow flame spread along the surface of the rear, left tyre. The sudden – and temporary – decrease in the ventilation velocities and heat release rate approximately 10 min after ignition can be related to the change of position of the mobile fan, where the fan was geared down temporarily during the transport. A maximum backlayering of approximately 50 m was visually observed during the experiment. The corresponding average longitudinal ventilation rate was 1.6 m/s .

6.2. Test 2 with drilling rig

Approximately 2 min after ignition both rear tyres were ignited and the fire spread further to hydraulic hoses in the rear, upper

Fig. 22. The temperature at the right, forward tyre (Tc12), above the loader (Tc24), left rear tyre (Tc13) and the interior of the cab (ceiling) (Tc17).

Fig. 23. The incident heat flux at the four plate thermometers.

part. After about 12 min after ignition the right, forward tyre was ignited. At about the same time a sudden increase in intensity occurred, most likely due to that the right, rear tyre burst. After 26 min there was a second sudden increase in intensity, due to that the right front tyre burst. Two hours and 25 min after ignition the measurements were stopped and the remaining fire was extinguished.

The temperature at the forward part of the boom – where the hydraulic hose did not ignite and burn – exceeded 930 °C after approximately 25 min from ignition (see Fig. 7 and Table 6 for the position of thermocouple Tc34). It is unclear why the hydraulic hoses did not ignite and burn. It could possibly and partially be explained by the hydraulic hoses already being drained of all hydraulic oil and thus decreasing the heat release rate and the fire spread when initially ignited. The incident radiation level was simply too low to propagate the fire in the direction of the ventilation flow. The temperature measurements at the forward part of the boom can be seen in Fig. 24. As can be seen the temperature in the forward part of the boom reached temperatures above 730 °C at an early stage of the fire, which could be contributed to the strong longitudinal ventilation flow of the mobile fan as the thermocouple was positioned at a low position, i.e. on the loosely hung bundle of hydraulic hoses on the boom. The sudden increase in temperature could be explained by that the longitudinal ventilation velocity at that stage reached a velocity that bend the plume sufficiently to be able to reach the thermocouple.

The maximum temperature above the drilling rig (Tc35) at 459 °C occurred after approximately 21 min (the same time as the maximum heat release rate). Furthermore, the appearance of the curve in Fig. 21 and the temperature above the drilling rig in Fig. 24 were similar and thus all these observations strengthened the reliability of the heat release rate in Fig. 21.

Thermocouple Tc36 showed identical results with Tc35.

The temperature in the cab (Tc17) increased to about 800 °C in less than 10 min from ignition; the cab was thus ignited at an early stage of the fire. The temperature started to decrease from the higher temperatures of 800–1000 °C after 25 min from ignition. Same as for the case of the wheel loader, the fire in the cab was rapid in fire growth and the interior was quickly consumed in the fire.

At the waist of the drilling rig the temperature (Tc23) reached temperatures around 800 °C after 6 min. The hydraulic hoses in the waist were most likely in flames at this time.

Fig. 25 shows the incident heat flux at the plate thermometers and as can be seen the plate thermometer at the left, forward tyre (PTC22) stopped functioning after approximately 9 min. The plate thermometer at the right rear tyre (PTC19) initially showed the highest values as this plate thermometer was placed closest to the

Fig. 25. The incident heat flux at the four plate thermometers.

pool fire. The plate thermometer at the right forward tyre (PTC20) showed a sudden increase after approximately 12 min which coincided with the ignition of the tyre. The plate thermometer at the left rear tyre (PTC21) showed a sudden peak after approximately 12 min which was due to the sudden increase in intensity due to the rupture of the opposite tyre. After that the incident heat flux slowly increased as the flames eventually reached the side facing the plate thermometer.

The resulting heat release rate curve of the drilling rig displayed a fire with high heat release rates and relatively short lived – compared with the fire in the wheel loader. Practically all the combustible items were ignited in the early phases of the fire.

A sudden increase in fire growth can be seen in Fig. 21 after approximately 13 min, this was due to the ignition of the right, forward tyre.

A maximum backlayering of approximately 70 m was visually observed during the experiment. The corresponding average longitudinal ventilation rate was 2.6 m/s.

With respect to the longitudinal ventilation and backlayering, the differences in the two experiments demonstrated the importance of establishing a distinct pressure in the mine drift which will take time due to the extensive and complex geometry. This stresses the importance of not changing the ventilation too fast but awaiting change before alternating the ventilation.

The longitudinal ventilation will also affect the heat release rate of the tyres due to the threads of the tyre, containing voids with separate and protected atmospheres. An increasing longitudinal ventilation velocity will increase the air supply into the voids and thus increase the heat release rate.

7. Conclusions

Two full scale fire experiments were carried out in an operative underground mine in Sweden. The fire experiments were carried out using a wheel loader and a drilling rig. The measured parameters during the full scale fire experiments were: the heat release rate, the temperatures and the incident radiation heat fluxes at certain points, the ventilation velocities in the mine drift; and the oxygen, carbon monoxide and carbon dioxide levels.

The results of the full-scale fire experiments show that in the experiment involving the wheel loader that the front part of the vehicle with front tyres etc. never ignited. The maximum heat release rate from the experiment was 15.9 MW and it was attained approximately 11 min after ignition. A portion of the heat release rate could possibly be attributed to a higher heat release rate due to a higher evaporation of the pool fire due to a higher degree of

Fig. 24. The temperature at the forward part of the boom (Tc34), above the drilling rig (Tc35), interior of the cab (ceiling) (Tc17) and the lower part of the waist (Tc23).

re-radiation and a possible leakage of the diesel tank, but the issue will have to be investigated further.

The maximum backlayering distance of the wheel loader fire was approximately 50 m. The resulting heat release rate curve of the wheel loader fire displays a fire that is dominated by initially the sudden increase of the pool fire and when the first tyre is engulfed by flames and then by the slowly declining heat release rates of the large tyres of the vehicle. Still, the stop of fire spread from the waist and forward clearly shortened the duration of the fire considerably.

It was found in the experiment with the drilling rig that except for the hydraulic hoses approximately 2 m in front of the cab and forward, some amount of hydraulic oil as mentioned above and a major part of the low voltage cable on the cable reel, the entire vehicle had participated in the fire and the combustible material had been consumed. The maximum heat release rate from the experiment was 29.4 MW and it was attained after 21 min. The maximum backlayering distance of the drilling rig fire was about 70 m. The resulting heat release rate curve of the drilling rig displays a fire with high heat release rates and relatively short lived—compared with the fire in the wheel loader. Practically all the combustible items were ignited in the early phases of the fire.

The differences between the estimated energy content using inventories and the calculated energy contents – integrating the resulting heat release rate curves – were relatively small or very slight. The difference is most likely due to the uncertainties when estimating the amount of combustibles available and to some extent the amount of combustibles consumed in the fire.

When calculating the heat release rate in the two cases, the applied method included some uncertainties. An uncertainty analysis showed that the combined expanded relative standard uncertainty with a 95% confidence interval was 17.6%. It turned out that the volume flow measurements had the largest impact on the results (8.2%), followed by the E-factor (2.5%) and the oxygen measurements (2.2%).

The fires in both cases were fuel controlled throughout the entire sequence, due to the high minimum oxygen level and low maximum level of the carbon monoxide.

The differences in the two experiments – with respect to longitudinal ventilation and backlayering – demonstrated the importance of establishing a distinct pressure in the mine drift which will take time due to the extensive and complex geometry. This stresses the importance of not changing the ventilation too fast in an underground mine but awaiting change before alternating the ventilation.

Further validation work should take place with respect to validating the experimental data with output data from theoretical models and the output data from the cone calorimeter experiments and the TPS experiments.

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