Full-scale fire experiments in an underground mine

Rickard Hansen

Malmfältens Brandkonsult, Nyköping, Sweden, 611 67

ABSTRACT

Few full-scale fire experiments have been performed in underground mines, therefore the information needed to validate calculations and estimations in preventive work, risk mitigation as well as incident planning is not readily available. This paper presents two full-scale fire experiments involving a loader and a drilling rig in a mine drift in Sweden. The heat release rate in the fire experiments was determined through oxygen calorimetry, i.e. by measuring the mass flow rate, gas concentrations and temperatures at certain heights at the far end of the mine drift, downstream of the fire source. The resulting heat release rate curve of the loader fire displays a fire that is initially dominated by a sudden increase in heat release rate when the first tire is engulfed by flames and then by the slowly declining heat release rates of the large tires of the vehicle. The calculated peak heat release rate of the loader was 15.9 MW and occurred approximately 11 minutes after ignition. The resulting heat release rate curve of the drilling rig displays a fire with high heat release rates and is relatively short lived – compared with the fire in the loader. Practically all the combustible items were ignited in the early phases of the fire. The calculated peak heat release rate of the drilling rig was 29.4 MW and occurred approximately 21 minutes after ignition. The fuel load of the loader consisted mainly of the tires, 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 heat release rate curves were validated by comparing the summed up energy contents of the participating components with the integrated heat release rate curves.

KEYWORDS: Heat release rate, mining vehicle, full-scale fire experiment, underground mine

1. INTRODUCTION

Collecting information about relevant risks, fire spread in mining vehicles and mobile equipment, and heat release rates for different types of fires is fundamental in preventive work, risk mitigation as well as in incident planning. Few full-scale tests have been performed in underground mines and the information needed to validate calculations and estimations is not readily available. Studies have shown that vehicles and mobile equipment are the dominating source of fire in underground hard rock mines (Hansen, 2009; De Rosa, 2004). The studies have shown that better knowledge about fire behaviour and fire spread is needed for service vehicles, drilling rigs and loaders. Two full-scale fire experiments on mining vehicles were conducted in an underground mine in Sala, Sweden. The full-scale fire experiments involved a loader and a drilling rig and were conducted in order to provide much needed data for future fire safety designs in underground mines.

2. INVOLVED VEHICLES

The loader in question was a Toro 501 DL, a diesel driven loader used for hauling iron ore. Table 1 presents an inventory of the combustible components on the loader. The effective heat of combustion of the hydraulic hoses, low voltage cable and driver seat was taken as the average value using results from cone calorimeter tests. The effective heat of combustion of the tires and rubber covers was set to 27 MJ/kg (Ingason, 2008). The effective heat of combustion of the diesel fuel was set to 42.6 MJ/kg (Totten et al., 2003) and 42.85 MJ/kg for the hydraulic oil (Simonson et al., 1998). When summing the energy contents of the individual components a total energy content of 76,245 MJ was calculated. The loader used in the experiments can be seen in Figure 1.

Table 1: Combustible component inventory – loader.

Component	Estimated amount	Energy content (MJ)
Tyres (rubber material)	~1560 kg	42120
Hydraulic oil	500 liters	16283
Hydraulic oil in hoses	70 liters	2280
Hydraulic hoses (rubber material)	~170 kg	4905
Diesel	280 liters	10138
Driver seat	~10 kg	228
Electrical cables	~1.5 kg	21
Rubber covers	~10 kg	270

*Corresponding author – email : malmfaltensbrandkonsult@bahnhof.se

Figure 1: Loader used in the experiments.

The drilling rig in question was an Atlas Copco Rocket Boomer 322, an electrically driven drilling rig that is also equipped with a diesel powered engine which is used when moving from one site to another. Table 2 presents an inventory of the combustible components. The effective heat of combustion of the hydraulic hose was also applied for the water hose. The effective heat of combustion of the plastic covers (ABS plastic) was set to 30 MJ/kg (Tewarson, 2002). When summing up the energy contents of the individual components a total energy content of 45,758 MJ was calculated.

Table 2: Combustible component inventory - drilling rig.

Component	Estimated amount	Energy content (MJ)
Tyres (rubber material)	~155 kg	4185
Hydraulic oil	350 liters in tank and 150 liters in hoses	16283
Hydraulic hoses (rubber material)	~390 kg	11252
Water hose (rubber material)	~40 kg	1154
Diesel	100 liters	3621
Driver seat	~10 kg	228
Electrical cables	~450 kg	8735
Plastic covers	~10 kg	300

3. DETERMINATION OF THE HEAT RELEASE RATE

The heat release rate in the fire experiments was determined through oxygen calorimetry, i.e. by measuring the mass flow rate, gas concentrations and temperatures at certain heights at the far end of the mine drift – downstream of the fire source - where the fire experiments were conducted. The method relies heavily on installed thermocouples at every measuring point – which are inexpensive, robust and relatively easy to install – in order to reduce the dependence upon expensive and sensitive gas analysis instruments.

Assuming that the local gas temperature and the local gas concentration correlate through the average values over the cross-section (Ingason, 2006), the heat release rate can be calculated using the following expression:

$$\dot{Q} = \frac{13100 \cdot \rho_0 \cdot u_0 \cdot A \cdot \left(\frac{M_{O_2}}{M_a}\right) \cdot \left(1 - X_{H_2O,0}\right)}{\frac{0.1}{X_{O_2,0}} + \frac{1 - X_{O_2,avg} \cdot \left(\frac{X_{O_2,avg}}{1 - X_{CO_2,avg}}\right)}{X_{O_2,0} - \left(X_{O_2,avg} \cdot \left(\frac{1 - X_{CO_2,0}}{1 - X_{CO_2,avg}}\right)\right)}} \quad [kW] \quad (1)$$

Where:

ρ_0 is the ambient air density [kg/m^3]

u_0 is the cold gas velocity in a mine drift [m/s]

A is the cross-sectional area [m^2]

M_{O_2} is the molecular weight of oxygen [g/mol]

M_a is the molecular weight of air [g/mol]

$X_{H_2O,0}$ is the mole fraction of water in the ambient air

$X_{O_2,avg}$ is the average concentration of oxygen

$X_{CO_2,avg}$ is the average concentration of carbon dioxide

$X_{O_2,0}$ is the mole fraction of oxygen in the ambient air

$X_{CO_2,0}$ is the mole fraction of carbon dioxide in the ambient air

The average concentration of oxygen, carbon dioxide and carbon monoxide are calculated using the above mentioned correlation. In equation (1) it is assumed that 13100 kJ/kg is released per kg of oxygen consumed and that the air mass flow rate of combustion gases equals the ambient air mass flow rate. Equation (1) has been used when determining the heat release rate for a number of large scale tunnel fire tests (Ingason and Lönnermark, 2005).

4. THE EXPERIMENTAL SITE

The full-scale fire experiments were conducted in a dolomite mine in Sweden. The fire experiments were conducted at level 55, an inactive part of the mine. Nonetheless, the infrastructure was still in place with power outlets, etc. The preconditions of the potential test site were the following: an active mine with an intact infrastructure, the possibility to

steer the smoke in one direction and through one single exhaust, and accessibility for vehicles. Figure 2 presents a plan of the level.

As there was only one exhaust on one side of the test site, all the smoke was ventilated out through the single exhaust, thus allowing for heat release rate measurements on this side of the test site. The intake of air was from the entrance and the lower regions of the mine.

Approximate dimensions of the mine drifts in the test area were 6 meter in height and 8 meter in width.

The mine drift where the experiments took place was approximately 100 meters long, approximately 150 meters from the entrance to the mine and 40 meters from the exhaust. There were practically no differences in height between the entrance of the mine and the exhaust.
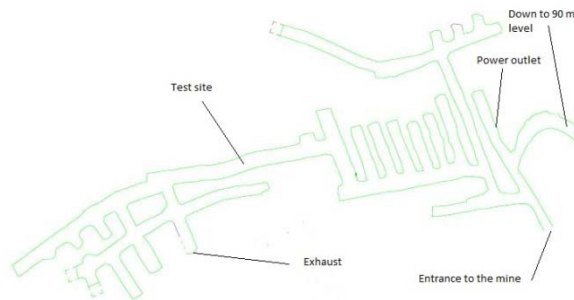

Figure 2: Experimental area.

5. EXPERIMENTAL SET UP

At the end of the mine drift – where all the fire gases would pass - the data needed for calculating the heat release rate was collected at a measuring station (see Figure 3 for the experimental set up in the mine drift). The data was measured using six thermocouples, four velocity probes and one gas monitor (measuring O_2, CO and CO_2) positioned at different heights. The temperature above each vehicle was measured with a thermocouple attached to the ceiling. A video camera was placed in the mine drift aimed at the side the each vehicle in order to record the fire behavior and the time of ignition of the combustible items.

On each vehicle a number of thermocouples were placed on the combustible components, i.e. the tires, hoses, cables and the interior of the cab. Four plate thermometers were placed at the ground at each tire during the tests in order to measure the heat flux at the locations.
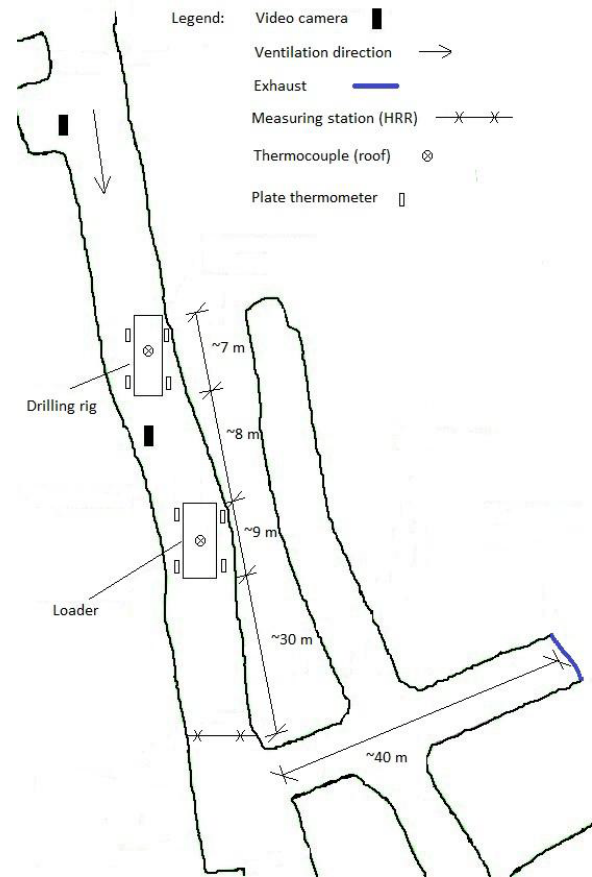

Figure 3: Experimental set up.

The existing ventilation flow in the area was found to be insufficient to ventilate all the smoke in one predetermined direction - in order to obtain adequate heat release rate measurements. Additional ventilation resources were therefore needed and a mobile fan with a capacity of 217,000 m^3/h was used during the experiments.

Regarding fire initiation, a circular tray was placed underneath the fuel tank of each vehicle and it was located close to at least one tire. The trays were filled with diesel fuel in order to simulate a pool fire caused by leaking diesel from the tank.

6. EXPERIMENTAL RESULTS

6.1 Loader Experiment

After the completion of the loader experiment it was found that the front tires had not been consumed in the fire and were therefore intact. Also, the hydraulic hoses from the vertical hinge (the vehicle is split into a front and a rear half which are connected by a vertical hinge approximately at the middle of the vehicle) and forward and in some parts of the rear section behind the rear tires also remained intact.

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Other parts had participated fully in the fire. The resulting heat release rate curve can be seen in Figure 4. The maximum heat release rate from the experiment was 15.9 MW. The maximum heat release rate was reached approximately 11 minutes after ignition. The resulting heat release rate curve displayed a fire that was dominated by a 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 vertical hinge and forward clearly shortened the duration of the fire considerably.
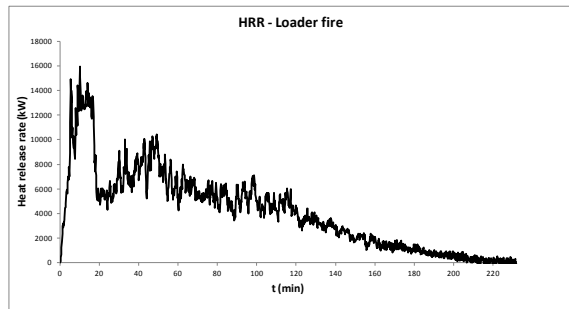

Figure 4: The resulting heat release rate of the loader.

The maximum average gas temperature at the measuring station (74°C) occured after approximately 11 minutes, 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 average gas temperature measurements can be seen in Figure 5.
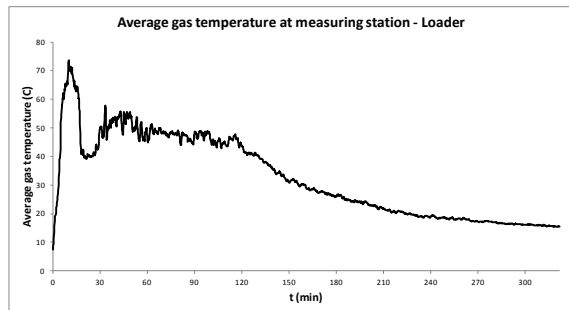

Figure 5: The average gas temperature at the measuring station - loader experiment.

Using the heat release rate curve the energy content of the combustible materials consumed in the fire was calculated at 57 GJ. When summing the energy contents of the materials participating in the fire the summation results in an energy content of

50.5 GJ. The difference is most likely due to the uncertainties when estimating the amount of combustibles available and the amount of combustibles consumed in the fire.

6.2. Drill Experiment

After the completion of the drilling rig experiment it was found that a small portion of the hydraulic oil did not participate in the fire. Except for the hydraulic hoses approximately two meters 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 heat release rate curve from the experiment can be seen in Figure 6. The maximum heat release rate from the experiment was 29.4 MW and was attained after 21 minutes. 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 loader. Practically all the combustible items were ignited in the early phases of the fire.
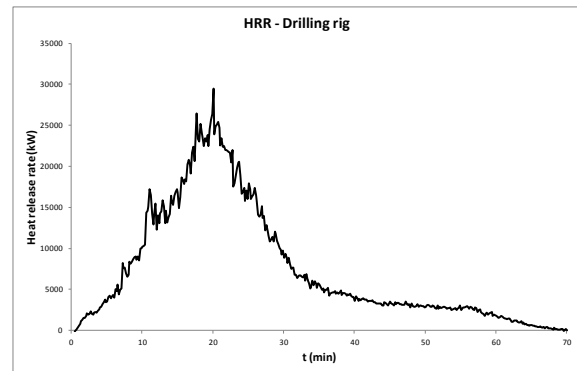

Figure 6: The resulting heat release rate of the drilling rig.

The maximum average gas temperature at the measuring station - 93°C - occurs after approximately 21 minutes, which is the same time as the occurrence of the maximum heat release rate (see Figure 7 for the average gas temperature at the measuring station). When comparing the average gas temperature in Figure 7 and the heat release rate curve in Figure 6 it can be seen that the average gas temperature at the measuring station correlates well with the measured heat release rate.
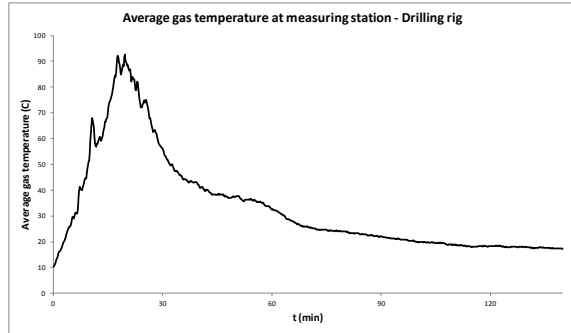
Figure 7: The average gas temperature at the measuring station - drilling rig experiment.

The energy content of the combustible materials consumed in the fire was calculated at 30.9 GJ. When summing up the energy contents of the materials participating in the fire the summation results in an energy content of 32.5 GJ. The difference is most likely due to the same uncertainties as in the case of the loader.

7. DISCUSSION

The initial sharp rise and high heat release rate for the first 20 minutes of the loader fire can be explained mainly due to the pool fire and the fire in the rear, right tire. The sharp drop after about 20 minutes was due to the pool fire burning off. The burn off time of the diesel pool fire at the loader experiment was calculated to be about 43 minutes (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 (Lönnermark et al., 2008) for a 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 Figure 4, 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 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. The differences will have to be investigated further in order to be fully explained.

The slow increase in heat release from about 20 minutes to about 50 minutes was due to the slow flame spread along the surface of the rear, left tire. The sudden – and temporary - decrease in the ventilation velocities and heat release rate approximately 10 minutes after ignition can be related to the change of position of the mobile fan, where the fan was geared down temporarily during the transport. The change of position was due to extensive backlayering reaching and passing the initial position of the fan.

The plate thermometers positioned at the forward tires did not record incident heat fluxes exceeding 14 kW/m^2 (unfortunately the plate thermometer at the right, forward tire stopped functioning approximately 40 minutes after ignition) and were therefore in line with the fact that ignition of the forward tires did not take place - if assuming and applying a critical heat flux of 17.1 kW/m² (Babrauskas, 2003) for natural rubber.

Approximately two minutes after ignition both rear tires of the drilling rig were ignited and the fire spread further to hydraulic hoses in the rear, upper part. About 12 minutes after ignition the right, forward tire was ignited. At about the same time a sudden increase in intensity occurred, most likely due to the bursting of the right, rear tire. After 26 minutes there was a second sudden increase in intensity, due to the bursting of the right, front tire.

The temperature at the forward part of the drilling rig boom – where the hydraulic hose did not ignite and burn – exceeded 930°C approximately 25 minutes after ignition, when studying the temperature recordings of the thermocouple at the boom. 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.

8. CONCLUSIONS

Two full scale fire experiments involving a loader and a drilling rig were carried out in an operative underground mine in Sweden, in order to produce total heat release rate curves for representative mining vehicles.

It was found in the loader experiment that the front part of the vehicle with front tires never ignited. The maximum measured heat fluxes at the front tires were found to never exceed the critical heat flux of natural rubber and was thus in line with the fact that ignition did not occur.

The maximum heat release rate from the experiment was 15.9 MW and it was reached approximately 11 minutes after ignition.

The resulting heat release rate curve of the loader fire displayed a fire that is dominated initially by the sudden increase in heat release rate when the first tire is engulfed by flames and then by the slowly declining heat release rates of the large tires of the vehicle. Still, the stop of fire spread from the vertical hinge and forward clearly shortened the duration of the fire considerably.

Regarding the drilling rig fire experiment it was found that except for the hydraulic hoses approximately two meters in front of the cab and forward, some amount of hydraulic oil, and a major part of the low voltage cable on the cable reel, the entire vehicle had participated in the fire.

The maximum heat release rate from the drilling rig experiment was 29.4 MW and it was attained after 21 minutes.

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

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