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STUDY OF HEAT RELEASE RATES OF MINING VEHICLES IN UNDERGROUND HARD ROCK MINES

Rickard Hansen

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School of Business, Society and Engineering

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STUDY OF HEAT RELEASE RATES OF MINING
VEHICLES IN UNDERGROUND HARD ROCK MINES

Rickard Hansen

Akademisk avhandling

som för avläggande av teknologie doktorsexamen i energi- och
miljöteknik vid Akademin för ekonomi, samhälle och teknik kommer att
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Akademin för ekonomi, samhälle och teknik

Abstract

A unique study on fire safety in hard rock underground mines with focus on heat release rates of mining vehicles is presented. A literature inventory was conducted with respect to fires in underground hard rock mines, which revealed that the most common fire cause in underground mines was flammable liquid sprayed onto hot surface and the most common fire object was a vehicle. A major concern was the lack of documented fire experiments in mining vehicles and heat release rate curves. It also revealed the limited research carried out on fire safety and fire development on vehicles found in hard rock underground mines.

In order to fill the gap of knowledge lack on heat release rates, fire experiments were carried out on wood cribs and wooden pallets in a model-scale tunnel with longitudinal ventilation where the distance between the fuel items were kept constant as well as varied. Different ignition criteria were applied in the ensuing calculations. It was found that the critical heat flux criterion generally showed very good agreement with the corresponding results of performed fire experiments but tended to have too short ignition times when the distance between the fuel items was increased. The ignition temperature criterion generally performed poorly compared with the measured results, but it was found that the accuracy improved considerably as the distance between the fuel items and the amount of energy accumulated on the fuel surface was increased.

As a final approach, two full-scale fire experiments were carried out in an operative underground mine using a wheel loader and a drilling rig respectively. The resulting heat release rates of the experiments were compared with calculated overall heat release rates applying the different ignition criteria. It was found that the critical heat flux criterion resulted in ignition times very close to the observed ignition times. The ignition temperature criterion resulted in surface temperatures that never achieved the corresponding ignition temperatures. Some difficulties were experienced when calculating the heat release rate curve of the wheel loader, as it was difficult to accurately predict the mechanical failure of a significant part initiating the highly significant fire in the hydraulic oil. Additional heat terms were added to the heat balance, where the added flame radiation term was found to have a large impact on the output results while the heat loss terms were found to have very little effect.

I dedicate this work to late Hemming
Blohmé, my teacher in mathematics and
chemistry at Pauli upper secondary
school in Malmö.

List of Papers

This thesis is based on the following papers and reports, which are referred to in the text by their Roman numerals. Reprints were made with permission from the respective publishers.

Appended:

- I Hansen, R. (2010). Overview of fire and smoke spread in underground mines. *Proceedings from the Fourth International Symposium on Tunnel Safety and Security*, Frankfurt am Main, Germany, March 17–19, 483–494.
(Peer review of Abstract.)
- II Hansen, R., & Ingason, H. (2011). An Engineering tool to calculate heat release rates of multiple objects in underground structures. *Fire Safety Journal*, 46(4):194–203
(Full peer review process.)
- III Hansen, R., & Ingason, H. (2012). Heat Release Rates of Multiple Objects at Varying Distances. *Fire Safety Journal*, 52:1–10.
(Full peer review process.)
- IV Hansen, R., & Ingason, H. (2013). Heat Release Rate Measurements of Burning Mining Vehicles in an Underground Mine. *Fire Safety Journal*, 61:12–25.
(Full peer review process.)
- V Hansen, R. (2012). Methodologies for Calculating the Overall Heat Release rate of a Vehicle in an Underground Structure. *Proceedings from the Fifth International Symposium on Tunnel Safety and Security*, New York, USA, March 14–16, 419–428.
(Peer review of Abstract.)
- VI Hansen, R. (2015). Analysis of Methodologies for Calculating the Heat Release Rates of Mining Vehicle Fires in Underground Mines. *Fire Safety Journal*, 71:194–216.
(Full peer review process.)

Not appended:

- VII Hansen, R. (2009). *Literature survey – fire and smoke spread in underground mines*. Research report SiST 2009:2. Västerås: Mälardalen University.
- VIII Hansen, R. (2010). *Site inventory of operational mines – fire and smoke spread in underground mines*. Work report SiST 2010:1. Västerås: Mälardalen University.
- IX Hansen, R. (2010). *Design fires in underground mines*. Research report SiST 2010:2. Västerås: Mälardalen University.
- X Hansen, R. (2010). *Smoke spread calculations for fires in underground mines*. Work report SiST 2010:7. Västerås: Mälardalen University.
- XI Hansen, R., & Ingason, H. (2010). *Model scale fire experiments in a model tunnel with wooden pallets at varying distances*. Research report SiST 2010:8. Västerås: Mälardalen University.
- XII Hansen, R. (2010). *Final recommendations – GRUVAN project*. Work report SiST 2010:9. Västerås: Mälardalen University.
- XIII Hansen, R., & Ingason, H. (2013). *Full Scale Fire Experiments with Mining Vehicles in an Underground Mine*. Research report SiST 2013:2. Västerås: Mälardalen University.
- XIV Hansen, R. (2013). *Investigation on fire causes and fire behaviour – vehicle fires in underground mines in Sweden 1988–2010*. Work report SiST 2013:3. Västerås: Mälardalen University.
- XV Hansen, R. (2012). Regression Analysis of Wildfire Suppression. *Proceedings from the Third International Conference on Modelling, Monitoring and Management of Forest Fires*, New Forest, UK, May 22–24, 213–224.
(Peer review of Abstract.)
- XVI Hansen, R. (2012). Estimating the amount of water required to extinguish wildfires under different conditions and in various fuel types. *International Journal of Wildland Fires*, 21(5):525–536.
(Full peer review process.)

- XVII Hansen, R. (2015). Statistical expressions on water based wildfire suppression in Sweden, 1996-2011. *International Journal of Safety and Security Engineering* (Accepted).
(Full peer review process.)

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Nomenclature

A = cross-sectional area of the tunnel or mine drift (m^2)

c_p = specific heat of air ($\text{kJ} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$)

$c_{p,fuel}$ = specific heat of the solid fuel ($\text{kJ} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$)

E_{tot} = total energy content (MJ)

$F_{smokelayer}$ = view factor smoke layer to target

F_{flame} = view factor flames to target

F_{fuel} = view factor fuel surface to target

H = tunnel or mine drift height (m)

h = lumped heat loss coefficient ($\text{kW} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$)

h_c = convective heat loss coefficient ($\text{kW} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$)

H_f = vertical distance between the fire source centre and the tunnel/mine drift ceiling (m)

k = thermal conductivity of the solid item ($\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$)

κ_s = time width coefficient

L_f = flame length (m)

L_f^* = dimensionless flame length

\dot{m}_a = massflow ($\text{kg} \cdot \text{s}^{-1}$)

M_a = molecular weight of air ($\text{g} \cdot \text{mol}^{-1}$)

M_{O_2} = molecular weight of oxygen ($\text{g} \cdot \text{mol}^{-1}$)

n_s = retard index of fuel item

N_T = number of measuring points with thermocouples

P = perimeter of the mine drift (m)

\dot{Q} = heat release rate (kW)

\dot{Q}_f^* = dimensionless heat release rate

\dot{q}_{cr}'' = critical heat flux ($\text{kW} \cdot \text{m}^{-2}$)

\dot{q}_{flux}'' = external heat flux ($\text{kW} \cdot \text{m}^{-2}$)
 \dot{Q}_{max} = maximum heat release rate (kW)
 \dot{q}_{net}'' = net heat flux into the solid item ($\text{kW} \cdot \text{m}^{-2}$)
 r_s = amplitude coefficient
 T_a = ambient temperature (K)
 T_{avg} = average gas temperature (K)
 T_f = average temperature at the fire location (K)
 ΔT_f = average excess temperature at the fire location (K)
 T_{flame} = flame temperature (K)
 T_h = temperature at height h (K)
 T_i = temperature at thermocouple i (K)
 $t_{ignition}$ = time to ignition (s)
 $t_{incipient}$ = time point when exiting the incipient phase (s)
 t_{max} = time to maximum heat release rate (s)
 T_s = fuel surface temperature (K)
 u_0 = cold gas velocity ($\text{m} \cdot \text{s}^{-1}$)
 x = location of interest (m)
 $X_{H_2O,0}$ = mole fraction of water in the ambient air
 $X_{O_2,avg}$ = average mole fraction of oxygen
 $X_{CO_2,avg}$ = average mole fraction of carbon dioxide
 $X_{O_2,0}$ = mole fraction of oxygen in the ambient air
 $X_{CO_2,0}$ = mole fraction of carbon dioxide in the ambient air
 $X_{O_2,h}$ = mole fraction of oxygen at height h
 $X_{CO_2,h}$ = mole fraction of carbon dioxide at height h
 \mathcal{E} = emissivity factor
 ρ = density of the solid item ($\text{kg} \cdot \text{m}^{-3}$)
 ρ_a = density of the ambient air ($\text{kg} \cdot \text{m}^{-3}$)

σ = Stefan-Boltzmann constant, $5.67 \cdot 10^{-11} \text{ kW} \cdot \text{m}^{-2} \cdot \text{K}^{-4}$
 τ = intermediate time steps (s)

Overview of the thesis

The core of the research work presented in this thesis was performed and congested between the autumn of 2010 and autumn of 2013 at the School of Sustainable Development of Society and Technology at Mälardalen University, with the exception of the model scale experiments which were conducted at the Fire Technology laboratory of SP Technical Research Institute of Sweden in Borås and the full-scale fire experiments which were conducted in a mine drift at Björka Mineral in Sala, Sweden.

The final part of the research work was to summarise all results in the following thesis. The first chapter includes the background and the reasons for carrying out the research work, methodologies applied during the work as well as a description of the earlier research activities performed in the specific field. In the following chapter an introduction to the fire environment, fire behaviour and smoke spread in underground hard rock mines is given. Most of the knowledge is obtained from Paper I as well as Papers VII, VIII and X, where the latter ones were not appended to this thesis. In chapter four Papers II–VI as well as Paper XIV are summarized and discussed. The final chapter summarises the research work and gives numerous suggestions for further works.

The thesis is based on two proceeding papers (Papers I and V) and four peer reviewed papers (Papers II, III, IV and VI). These papers are supported by extensive information on technical data and literature information compiled by the author in eight reports (Papers VII–XIV). Also enclosed to this thesis work are three papers (Papers XV, XVI and XVII) that are not directly within the scope of the research work presented in this thesis. It is included here in order to establish an example of the variety of the work that has been written during this journey.

Introduction

Fire has been present in the life of miners and influenced their lives since ancient times. Firesetting – i.e. heating up the rock with a fire and then in some cases rapidly cooling the rock by applying water – was used several thousands of years ago for breaking rocks in mines and played a major role in the industry. Today the miners will not regard fires as an important working method but instead as a major risk.

The risks the miners in an underground mine face are numerous and extensive if not properly addressed. In coal mines the risks would include methane gas explosions, dust explosions, self-ignition, equipment fires etc. In rock mines extensive smoke spread from vehicle fires is the major risk for the miners. The smoke spread in an underground hard rock mine poses a great challenge to the mining safety officials and involved rescue organisations. Egress routes could be blocked by smoke during an extensive time period stopping the evacuation of the mining personnel and stopping the rescue units from reaching the miners that are left underground. This can force the mining safety personnel to resort to solutions such as refuge chambers or reversible smoke evacuation. The possible success of a fire and rescue operation is highly dependent on the fire development and the measures taken to mitigate the effects.

The fire safety issues in underground hard rock mines are in many ways very similar to the issues faced in tunnel construction projects. Even though the following chapters describes and discusses the nature of fires in underground mines, fires in mining vehicles and other types of combustible materials, the findings and results of the research work can be applied to tunnels under construction as well.

The most common type of fire in underground hard rock mines is a vehicle fire [1] [2]. Vehicle fires may occasionally result in high heat release rates, extensive smoke spread and in difficult and complex evacuation of the mine. Mining vehicles can be found in large numbers throughout every mine and is not restricted to a certain number of places. The mining vehicles can consist of various types. This can be gigantic front wheel loaders, drilling rigs, service vehicles or buses. The fuel load and construction will vary with type of vehicle. Front wheel loaders being distinguished by the very large tyres, drilling rigs with fully loaded hydraulic oil and hydraulic hoses.

A major concern today is the lack of documented fire experiments in such vehicles or other types of mobile equipment. The documentation of heat

release rates for mining vehicles is a vital knowledge and more or less a necessity when evaluating mine sections. Needless to say there is a great need for better information about heat release rate curves in mining vehicles.

The costs of full scale fire experiments are considerable and can be highly time consuming. Performing full scale fire experiments on a variety of mining vehicles and then using the results for validating the results of theoretical methodologies would result in potential methodologies that could be applied to other mining vehicles without performing costly full scale fire experiments. Alternative experimental methods are small scale tests which are less time consuming and costly. A good scientific methodology is to use theoretical modelling that is verified and validated in both model scale and full scale.

1.1 Aims

This thesis focus on vehicle fires in underground hard rock mines and tunnels during construction.

The aims of the thesis work are to obtain data which can validate theoretical methodologies to calculate the total heat release rate of mining vehicles and tunnelling vehicles. The methodologies should be able to produce total heat release rate curves for representative mining and tunnelling vehicles. The methodologies could be applied on any specific mining or tunnelling vehicle found in a mine or a tunnel, resulting in heat release rate curves that would be used when addressing and evaluating the fire development, smoke spread etc. The specific output extracted from the resulting heat release rate curve could for example be the maximum heat release rate, the time to maximum heat release rate as well as the fire duration. The maximum heat release rate and the time to maximum heat release rate will be vital information at the design of the smoke ventilation system at a specific part of the mine as well as the entire ventilation system. An increasing heat release rate will increase the demands on the ventilation system, possibly requiring higher capacity. The fire duration will be a very important information when designing the egress safety at a specific location with limited amounts of egress routes, as refuge chambers – with a limited supply of air – are commonly used in parts of an underground mine where the miners may find themselves trapped during a fire. Any methodology that could be applied without having to perform full scale experiments would be of practical importance. The application of the methodologies would result in a safer working environment for the personnel in underground hard rock mines and tunnel projects.

1.2 Methodology

A number of different methodologies have been applied during the work on this thesis. It started with literature surveys, site inventories and statistical studies of fires in mines. This work is presented in Paper I, VII, VIII and XIV. After that hand calculations and computer simulations were performed. This work is presented in Paper II, VIII, IX and X. In order to obtain more data, model-scale experiments, cone calorimeter experiments and laboratory experiments were performed in order to support the theories and calculation work. These tests are presented in Paper III and XI. The proposed model for calculating the overall heat release rate of a mining vehicle is described and applied in Papers II, III, V and VI. Finally full-scale experiments in a mine using large mining vehicles were performed. This was the last part of the research work.

During the computer simulations the following software were used:

- Ventgraph [3] – a so called mine ventilation network simulation program.
- FDS [4] – a computational fluid dynamics program.

1.3 Earlier work

Research regarding fire safety in mines has so far mainly been directed towards coal mines. The risks faced in an underground coal mine are generally different compared with risks faced in an underground hard rock mine. Therefore the need for research in underground hard rock mines is great and especially with respect to the most common type of fire – vehicle fires, both ordinary vehicles as well as heavy vehicles used for mining work. The thesis present the first comprehensive and systematic fire safety research study ever performed on this type of application field.

In Paper I it is pointed out that the only earlier work describing the fire behaviour of a vehicle fire in an underground mine can be found in a report from a full-scale fire experiment conducted in a Swedish mine in the 1980's. In the report by Svenska Gruvföreningen [5], a full-scale fire experiment is described where a loader and a refuge chamber were involved. The loader in question was a CAT 960, where the fuel load mainly consisted of 2200 kg rubber and 600 L of oil. The measured parameters during the experiment were: the CO-level, temperature and smoke density at the refuge chamber as well as the airflow in the drift. One of the findings of the report was that the fire was almost completely burned out after 3–4 h and could then be extinguished relatively easy. Unfortunately the findings of the report are of limited use as no heat release rate measurements were conducted and only a unidirectional flow was measured in the mine drift resulting in an incomplete

flow picture. This test is the ground for the time requirement of 4 h on refuge chambers today.

As there are nearly no data available on heat release rates for mining vehicles, we can only find data on ordinary vehicles. These can be both from road tunnels, underground car parks as well as rail or metro tunnels. In the following, a selection of some of this data is given in order to set the work presented in this thesis in a context of what has been done earlier.

Ingason and Lönnemark [6] presented calculations of heat release rates from four large-scale tests, with a mock-up of a HGV trailer – consisting of a steel rack system loaded with a mixed commodity of wood pallets and polyethylene pallets, wood pallets and polyurethane mattresses, furniture and fixtures with ten truck rubber tyres, and paper cartons and polystyrene cups – in a road tunnel. Initial longitudinal ventilation rates within the tunnel were in the range of 2.8–3.2 m/s. A comparison was made between the results presented and other large-scale tests with HGV trailers in tunnels. Maximum heat release rates in the range of 66–202 MW were measured. The maximum heat release rates were obtained between 7.1 and 18.4 min from ignition in the various tests. As the experiments were conducted in a road tunnel with obvious similarities with a mine drift, the observations, findings and results of the paper can be of use with respect to vehicle fires in underground mines.

Lönnemark et al. [7] presented three full-scale fire tests with a commuter train inside a tunnel. The position and type of initial fire was varied between the tests as well as the fuel load in the carriage. The two tests where the initial fire was positioned inside the carriage evolved into fully developed fires. The maximum heat release rates of the two tests were found to be in the same vicinity, i.e. 76.7 MW and 77.4 MW respectively. The difference in the two tests was found in the time interval to maximum heat release rate, where the maximum occurred after 12.7 min for the case with the original seats and linings and after almost 118 min in the case with modern seats and non-combustible wall and ceiling lining. The difference in the time interval between the two tests could be found in the fire behaviour of the seats, walls and ceiling linings. Same as for the paper by Ingason and Lönnemark [6], the findings and the results of the experiments could be of use when studying vehicle fires in underground mines due to the similarities in the environments.

A number of papers describing conducted full-scale vehicle fire experiments and vehicle component fire experiments are described below. Even though they were not conducted in a mine drift or a tunnel environment and therefore of limited use, they will still give some clues with respect to probable maximum heat release rates and the duration of the fires.

Okamoto et al. [8] describe four full-scale fire experiments where passenger cars from the early 1990's were used. The ignition took place either at the splashguard of the right rear wheel or at the left front seat in the passenger compartment. During the fire experiments the temperature inside the car and

the mass loss rate as well as the heat release rate were measured. The temperature inside the passenger compartment reached a maximum value of 1000 °C during the experiments. The heat release rate curves showed several peaks depending on the burning of the different compartments of the car (engine compartment, passenger compartment and the rear part). The heat release rate peaked at 3 MW when the passenger compartment and the ignition fuel burned at the same time.

Hu et al. [9] presented a study where an improved flame spread model was used to simulate a rail car fire. Data from an earlier performed rail car compartment fire experiment in Sweden was used for validation. The conclusions were that the improved flame spread model was able to reproduce the fire experiment results better than compared with flame spread models using the ignition temperature as the sole ignition criterion.

Mangs and Keski-Rahkonen [10] presented a simple model for describing the fire behaviour of a burning passenger car. Heat release rate curves were obtained from car fire experiments and characterized by superposition of one Boltzmann curve and three symmetrical Gaussian curves. The car fire was described by two fire plumes, one emerging from the car at the centre of the windscreen and the other at the centre of the rear window. Gas temperatures were calculated using Alpert's equations for maximum ceiling jet temperature. The calculated and measured values were found to match each other very well.

Shipp and Spearpoint [11] presented the results from full-scale fire experiments in two passenger cars. Measurements of heat release rate, temperatures and other parameters were given. The fires were well ventilated and allowed to develop fully before extinguishment. Of the two tests the first burned for 17 min with a peak heat release rate of 7.5 MW before being extinguished. The other burned for 57 min with a peak heat release rate of 4.5 MW.

Stroup et al. [12] conducted two fire experiments with a passenger minivan. The heat release rate, the temperatures and gas concentrations inside the passenger compartment were measured during the fire experiments. During the first experiment the windows of the van were closed and the fire self-extinguished due to lack of oxygen within the passenger compartment. During the second experiment the driver and passenger windows were open. The peak heat release rate for the second experiment was measured at 2.4 MW.

Being one of the major components on mining vehicles, tyre fires will have a major impact on the heat release rate of a mining vehicle. A number of tyre fire experiments have been conducted in the past. Hansen [13] presented experiments where a pair of 285/80 R22.5 tyres mounted in tandem were used. The two tyres were ignited by heating up the wheel rims and the maximum heat release rate of approximately 900 kW occurred after approximately 30 min. Ingason and Hammarström [14] presented an experiment

conducted on a front wheel loader tyre with dimension 26.5R25. The ignition of the tyre took place by positioning the tyre in the middle of a diesel pan with loosely compacted gravel. An initial maximum heat release rate of 2.3 MW occurred after approximately 3 min from ignition, contributed to a combination of the diesel pan fire and the burning tyre. A second maximum heat release rate of 3 MW occurred after approximately 70 min and could be explained by an increase in the burning tyre surface. Additional fire experiments have been conducted on un-mounted tyres [15–17] applicable to bulk storage of tyres.

2. Fires in underground hard rock mines

An underground hard rock mine can be distinguished by a number of features. The mine is accessed by a main shaft or a ramp. Using a main shaft you will travel by an elevator and using a ramp you will enter the mine with a vehicle. A ramp may have a spiral configuration or a rectangular shaped configuration when declining downwards and connecting with different parts of the mine [18]. Using the main shaft or the ramp will allow you to reach horizontal working areas, i.e. levels. At a level you will find a number of horizontal openings connected with each other, i.e. drifts. In a mine a number of different types of shafts, levels and drifts can be found depending on the activity. As an example we can have skip shaft (where the ore is hoisted through), ventilation shaft, transportation level, workshop level, media drift and media shaft. An absolutely vital component of an underground mine is the ventilation system. Without a properly designed and functioning ventilation system the work in the mine will be difficult and even impossible. The ventilation system in an underground mine is primarily designed to control the level of gas and dust contaminants, temperature and humidity. A mine ventilation system is generally extensive and complex, where shafts, ramps as well as drifts can be used for transportation. In some areas tubing is used for transporting the air. Intake fans and exhaust fans can be found at strategic positions across the mine, pushing the air in desired directions. In extensive and scattered areas so called booster fans may be used for increasing the power of the air circulations [19]. As can be concluded by the very general description above, the nature of an underground hard rock mine is very complex both with respect to the geometrical features as well as the various activities and hazards found underground.

2.1 Fire hazards, fuel load and fuel distribution

Due to the size of operations and the large number of activities found in an underground hard rock mine the number and types of fire hazards can be considerable. The fuel load in an underground mine can be considerable at specific positions but opposed to industrial facilities above ground the fuel distribution in an underground mine is distinguished by its discontinuity. Islands of flammable or combustible material can be found in a mine but in between the islands one will find long and extensive mine drifts, ramps,

shafts etc containing no flammable or combustible material. The islands of flammable/combustible material will generally be found in workshops, warehouses, office complex etc. In Figure 1 the statistics on fire objects in the Swedish mines for the years 2008–2012 is shown, as can be seen the number of vehicle fires has increased considerably during the last two years which could possibly be attributed to for example the increased mining activities in Sweden in recent years.

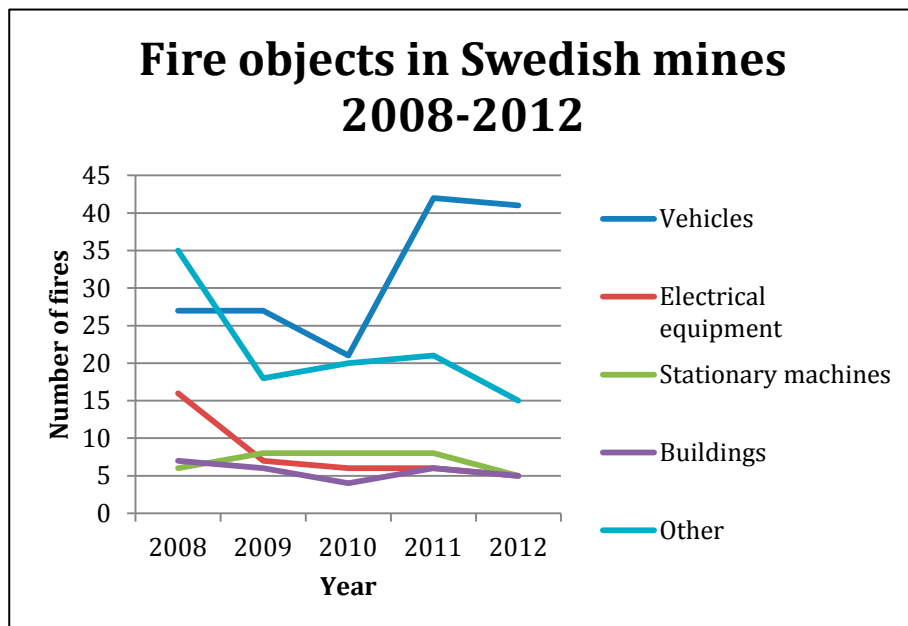


Figure 1. The fire object statistics for the Swedish mines during the time period of 2008–2012 [20]

An underground mine can be distinguished by its maze of drifts, levels, ramps, shafts etc and it is not always possible to install fire barriers in all parts of the mine and the possibility of smoke evacuation may be limited in some areas. Therefore the main risk to people in an underground mine during a fire will be the spread of smoke resulting in poor visibility, smoke inhalation and hampering the egress activities. An example is a vehicle fire – involving a passenger vehicle – in a ramp in the Malmberget mine in northern Sweden in 2008, where the fire and rescue personnel initially had to turn back when attempting to reach the fire due to an extensive smoke spread blocking the path of attack. Meanwhile 8 mining personnel were unable to evacuate and had to use a refuge chamber designed for 6 people. As they were two breathing masks short, they decided that either should nobody use the air supply or else they should share it equally. They shared equally. Due to the critical situation the fire and rescue services decided to load a number

of breathing apparatus units and try to reach the refuge chamber by foot but also to try to evacuate the smoke at the chamber. The latter was successfully done by changing the flow directions of the ventilation in the vicinity of the chamber. After half an hour, the smoke outside the chamber had been evacuated and the mining personnel in the chamber could stop using the air supply. As the situation had turned less critical it was decided to wait and let the fire more or less burn out. Five hours after the detection of the fire yet another attempt was made at extinguishing the fire, but the fire personnel had to turn back as the smoke was too dense. One hour later a third – and successful – attempt was made at extinguishing the fire [21].

Fires in flammable or combustible liquids can be characterized by the rapid fire growth; considerable and rapid smoke production and therefore posing as a considerable risk to the miners. The large number of mobile and stationary equipment requires flammable or combustible liquids such as diesel, hydraulic oil, motor oil, windscreen washer fluid etc. Even though the use of flammable or combustible liquids with lower flash points – such as petrol – is highly restricted or even forbidden, still the hazard of using and storing flammable or combustible liquids in an underground mine is a factor that must be accounted for due to the distribution and amounts of liquid. The flammable or combustible liquids can generally be found – besides on mining vehicles – in workshops, warehouses, fuel stations, ramps etc. As the mining vehicles are either diesel propelled or electricity propelled, fuel stations with diesel are found in large parts of a mine. The typical activities in an underground mine with drilling, loading or crushing will require a large amount of hydraulic oil. Even though combustible hydraulic oil is distinguished by the high flash point, the hazard of the hydraulic oil will still have to be accounted for due to the risk of spray fires when a pressurized distribution line is punctured or ruptured. Besides being found on mining vehicles such as wheel loaders or drilling rigs, hydraulic oil is also found at for example crusher levels, distribution levels and shaft hoisting levels. The amount of flammable/combustible liquid will vary depending on the type of vehicle/machinery. A drilling rig or a wheel loader may contain several hundred liters of hydraulic oil and diesel unless electrically propelled. A fuel station may house several thousand liters of diesel.

Vehicles are generally found in large numbers throughout a mine and are not restricted to a certain number of places underground. As vehicles can be found in most parts of a mine and the likelihood of a vehicle fire must be accounted for, the demand on the fire protection systems – foremost the smoke ventilation system – will in many cases be set with respect to a vehicle fire as the plausible fire scenario. The fire hazards and fire load will vary from vehicle to vehicle depending upon the characteristics, use and dimensions of the vehicle. Common combustible components are: diesel, hydraulic oil, motor oil, windscreen washer fluid, cables, hoses (which can be seen in Figure 2), interior (seats, dashboard etc) and tyres. Containing a large quanti-

ty of diesel, hydraulic oil and tyres with large dimensions, a fully developed fire in a large mining vehicle can in many cases be expected to have a rapid fire development, considerable smoke production and long lasting fire.



Figure 2. Hydraulic hoses on the boom of a drilling rig

Following upon the large number of mining vehicles, tyres and hydraulic hoses are stored at facilities underground. Tyres and hoses can generally be found at workshops or depots of contractors. The tyres found on the larger mining vehicles such as wheel loaders are of considerable size and weight adding several thousand of kilograms to the fuel load of depots, workshops and on the vehicles in question. Fires in tyres and to some extent in larger amounts of hydraulic hoses are often distinguished by the considerable smoke production and the long lasting fires which will increase the demand on the egress safety in the mine.

Even though it is generally attempted to limit the amount of wood being used in underground hard rock mines one can still find wood in some places. In many cases the wood is used in temporary applications or constructions,

such as smaller sheds in draw areas or wooden poles or planks covering corners in production areas and preventing tear on loader cables. In warehouses wooden pallets are often used due to their practicality and low cost. The amount of wooden pallets can be substantial in some warehouses. Otherwise – due to the temporary and ever changing nature of a production area – wood is often found in the production areas.

Conveyor belts can be found in most underground mines, at the loading areas, transport drifts and distribution levels transporting the ore from the production areas to the crusher sites and from the crusher site to the hoisting facilities. Even though self extinguishing conveyor belts are predominantly used in underground mines and thus limiting the fire hazard, a self extinguishing conveyor belt does not entirely rule out a fire and the following smoke production and smoke spread. A fire at a conveyor belt can imply a fire limited in size, but the amount of smoke emitted can still be quite extensive. Transport drifts and distribution levels are often characterized by a large inclination, vastness and their open nature – as wall partitions will have limited effect due to the requirement of an opening for the conveyor belt to function. These factors will contribute to a rapid and extensive smoke and fire spread, increasing the risk for the personnel at the site.

Carrying one of the important media, electrical cables can be found in most parts of an underground hard rock mine and will largely contribute to the overall fire load. In Paper VIII it is pointed out that large amount of cables are for example found at pumping stations, media shafts (the amount of cables can be very high due to the protection of redundancy), crusher level, cable vaults and relay interlocking plants throughout a mine. In mines where trains are used for transporting the ore between different parts, larger amounts of electrical cables can be found at for example track levels.

Due to the rapid changes in an underground mine, where new levels and drifts are constantly planned and constructed and older drifts and levels abandoned in order to keep up the production levels; the removal of old cables, wooden structures and other combustible material is not always prioritized, contributing to an increasing overall fire load and an increase in the fire risk at abandoned parts where the fire protection systems might have been dismantled.

2.2 Fire behaviour

The fire behaviour in a mine drift is highly dependent upon the arrangement and distribution of the adjacent combustible items, the dimensions of the mine drift as well as the ventilation conditions and the access to air.

As the combustible materials in an underground mine can generally be found concentrated at certain positions, the likelihood of the fire spreading from the first item ignited is generally small. The few positions in an under-

ground mine where a continuity in fuel and high fire load can be found are office complexes, warehouses and parking drifts with several vehicles parked at short distances. But nevertheless outside these premises, the distance to the nearest, larger accumulation of combustible items are considerable and thus preventing any fire spread outside the premises. The height of the mine drifts are in many cases in the interval of 5–8 m, in case of a fire the major portion of the hot fire gases will be found in the upper region of the mine drift where the amount of combustible items is highly limited. Therefore any large fuel components found in the lower regions of a mine drift – such as an adjacent mining vehicle – will not necessarily be engulfed in hot fire gases, limiting the effect of the convective spread mechanism. However, if the fire spreads to other, larger, adjacent combustible items, a rapid transition from a localised fire to the combustion of several other items nearby may occur. But catastrophic fires such as in road tunnels, where the fire easily spread from vehicle to vehicle due to the traffic congestions caused by the fire, are highly unlikely in an underground mine as the continuity of combustible objects are lacking.

The drifts, levels and ramps in an underground hard rock mine are characterized by their general openness, lack of barriers, sporadic pockets of combustible materials and large distances barren drifts where the rock will cool off the smoke from the fire. In Paper IX it is concluded that the likelihood of a flashover is highly unlikely in an open mine drift, level or ramp due to the openness, cooling surroundings and the limited amount of combustible material (both in quantity and spatial coverage). A flashover is not entirely unlikely in an underground mine as enclosures – with walls and ceiling – can be found in mine drifts, for example office complexes, workshops, canteens, storage facilities etc.

The surrounding rock close to the fire will after the initial heating process increase the re-radiation mechanism back to the fire and thus influence the combustion process. The rock further downstream of the fire will have more of a cooling effect on the fire smoke and therefore decrease the stratification of the smoke. The effect of the surrounding rock will thus depend on the distance from the fire.

A fire occurring in a mine drift with a distinguished longitudinal ventilation flow will behave differently compared with a fire occurring in a mine drift with only one entry and with limited access to air. A minor fire occurring at the end of a mine drift with limited access to air may eventually self extinguish due to the difficulty in drawing fresh air from outside the fire site. Due to the inerting effects on combustion by the combustion products in the recirculated smoke to the fire, it may finally be extinguished [22].

As opposed to fires in enclosures, the flames and fire plume in a mine drift will be greatly affected by the ventilation flow from the mechanical ventilation system and not just the natural ventilation as in the case of fires in compartments. The effect on the fire behaviour can for example be seen in

the tilting of flames which will lead to faster flame spread and ignition of adjacent fuel items. Besides tilting flames, faster flame spread, the ventilation flow will also lead to a more effective supply of air and oxygen to the fire site, increasing the mixing of oxygen and fuel and thus the combustion efficiency. The air masses available in the mine drifts – with their large dimensions – and the influence of the mechanical ventilation makes ventilation controlled fires less likely compared with for example compartment fires. Obstacles in a mine drift – such as equipment and vehicles – may block the ventilation flow in the mine drift and reduce the influence on the fire plume and the possible tilt of flames. Also the distance to the closest intake fan and intake shaft will influence the amount of air flow available at the site of the fire, where the combustion efficiency may decrease with longer distances due portions of the air flow being directed in other directions. With longer distances and decreasing influence of the mechanical ventilation, the fire will have a larger influence on the ventilation conditions and foremost the ventilation direction and possibly causing a reverse flow of fire gases into the ventilation air stream.

The flame length will play an important part regarding the spread of fire to adjacent combustible items due to the importance of the flame radiation mechanism and the possible tilting of the flame resulting in flame impingement and ignition. A number of flame length correlations are available when generally performing a fire analysis. But the applicability to an underground mine will vary from case to case. When performing an analysis on available expressions in Paper VI the following set of expressions by Ingason and Li [23] were found to match observed non-dimensional flame lengths L_f^* from performed full-scale fire experiments in a mine drift:

$$L_f^* = 4.3 \cdot \dot{Q}_f^* \quad (1)$$

$$L_f^* = \frac{L_f}{H} \quad (2)$$

$$\dot{Q}_f^* = \frac{\dot{Q}}{\rho_a \cdot c_p \cdot T_a \cdot g^{1/2} \cdot A \cdot H_f^{1/2}} \quad (3)$$

where \dot{Q}_f^* is the dimensionless heat release rate, L_f is the flame length (m), H is the mine drift height (m), \dot{Q} is the heat release rate (kW), ρ_a is the density of the ambient air ($\text{kg} \cdot \text{m}^{-3}$), c_p is the specific heat of air ($\text{kJ} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$), T_a is the ambient temperature (K), A is the cross-sectional area of the mine drift (m^2) and H_f is the vertical distance between the fire source centre

and the mine drift ceiling (m). In the expressions the geometry of the mine drift is accounted for. Possible flame tilt due to the longitudinal ventilation will greatly affect the fire spread to adjacent fuel components due to possible flame impingement and increasing view factor. But it was found in the two full-scale experiments that the construction of the vehicles blocked the longitudinal ventilation flow and no significant flame tilt could be observed. The same phenomenon could occur if for example machinery or other vehicles were positioned further upstream of the vehicle fire, blocking or interfering with the longitudinal flow.

The mine drift height will in many cases be considerable and together with a limited fuel load mostly found in the lower regions of a mine drift, ceiling impingement of flames will not be as common as in the case of road or rail tunnel fires. The width and height of a mine drift may vary from mine to mine and also within a mine, depending upon factors such as what types of vehicles that are used, what the specific drift is used for, which mining method that is used etc. When designing a mine drift for example the dimensions of the vehicles being used in the drift will be taken into account as well as providing space for ventilation tubes, electrical cables, water pipes etc. In order to give a general idea on the cross sectional dimensions of a mine drift, typical mine drift dimensions (height and width) found in an underground hard rock mine could for example be 8 x 8 m or 8 x 6 m where traffic in two directions can be found.

The cross-sectional dimensions of the mine drift will affect the fire behaviour in numerous ways. A lower ceiling will result in earlier ignition of adjacent fuel components as the average gas temperature will increase, flames may be deflected at the ceiling and thereby increasing the view factor to fuel components at higher positions. The width of the mine drift will also affect the fire behaviour. A narrower drift will result in earlier ignition of fuel components due to an increase in the average gas temperature and also an increase in the re-radiation to fuel surfaces.

Other than the cross-sectional dimensions, the inclination of the mine drift will also play an important part with respect to ignition of fuel components. Earlier ignition of adjacent fuel components will result if the inclination of the mine drift increases. This is due to an increasing flame tilt and an increasing risk of flame impingement.

In Paper IX it is pointed out that opposed to compartment fires, fully developed fires in mines are also of interest for the life safety aspect because of large smoke spread distances involved and the time requirement on refuge chambers. Fully developed fires will also have an impact on structural components and rupture of pressurized containers, which will affect any rescue operations that are attempted.

2.3 Smoke spread

As described earlier, the ventilation system of an underground hard rock mine will consist of several individual fans and shafts. Adding the three-dimensional aspect to the ventilation system will result in a complex and in many cases a sensitive system. Any outer as well as internal disturbance may result in changed ventilation flow rates and directions. Outer disturbances could for example consist of specific weather conditions such as changes in the wind conditions or temperature changes at the entrances of the mine. Internal disturbances could for example be the present condition of a specific fan which due to malfunctioning could cause imbalance in the ventilation flows. Adding the highly variable and influencing fire parameter will add to the complexities even further.

In Paper X a discussion can be found with respect to the smoke spread in underground mines. Unless a fire occurs within an enclosure such as a bus or offices complex, the smoke from the fire will ascend and spread along the ventilation direction. The smoke spread in a mine drift is largely determined by the occurring smoke stratification, which in turn is depending upon the air velocity in the mine drift, the dimensions of the mine drift, the heat release rate as well as the distance to the fire. With a low or no forced air velocity the smoke stratification is high in the vicinity of the fire while at the other end – at high air velocities – the smoke stratification is low downstream from the fire. With increasing mine drift height and increasing distance to the fire, the vertical temperature gradients will decrease and thus also the smoke stratification. An example of stratification in a mine drift is shown in Figure 3. Regarding the heat release rate of the fire, an increase in the heat release rate will result in an increase in the vertical temperature gradients and an increase in the smoke stratification.

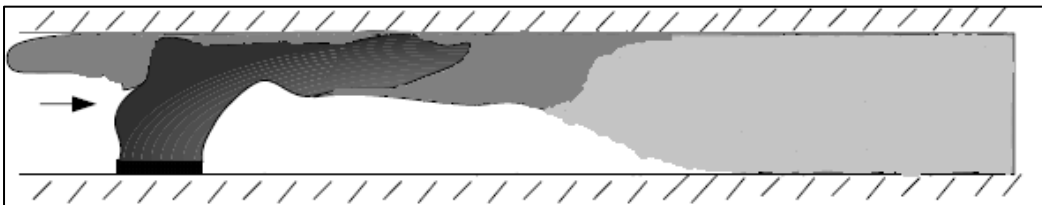


Figure 3. Smoke stratification in a mine drift

The fire itself may also cause phenomenon that may influence the direction of the ventilation flow and the smoke spread. Larger fires with considerable heat release rates may cause two different types of phenomenon, namely the throttle effect and the buoyancy effect respectively [24]. When the air masses pass the fire in a mine drift, the volume of the air masses will increase causing an additional pressure loss known as the throttle effect. The immedi-

ate effects of the throttle effect can be noticed by a blockage in the ventilation flow at the area closest to the fire site. In the case of a fire in a mine drift, ramp etc with an inclination, the heat from the fire will cause an increasing temperature, resulting in a decreasing density of the gas masses downstream of the fire. The decrease in density will enhance the ventilation in rising drifts, ramps etc and cause disturbances and even reversal of the ventilation flow in declining drifts.

Another occurring effect is the so called backlayering, i.e. smoke traveling in the opposite direction with respect to the air ventilation flow. Backlayering usually occurs when the air ventilation velocity is in the low or moderate range, depending on the heat release rate of the fire as well as the geometrical aspects of the mine drift. In the case of backlayering the hot smoke will cool off and descend towards the ground and the smoke concentrations will be diluted along the way. The backlayering phenomenon may hamper and cause problems to rescue personnel if evacuation of refuge chambers is attempted during an ongoing and nearby fire. An example of backlayering in a mine drift is shown in Figure 4.

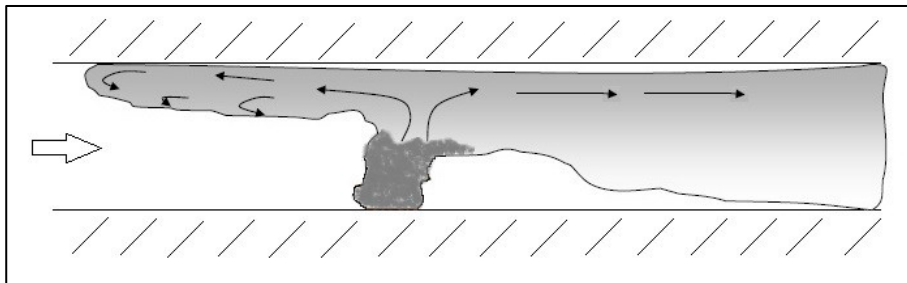


Figure 4. Backlayering in a mine drift

The rough surfaces of a mine drift and ramps, as opposed to the generally smooth surface of a road tunnel, will influence the smoke spread in a mine. The rough surfaces will result in friction losses and additional turbulence to the flow of smoke, which in turn will decrease the stratification of the smoke as well as influencing the possible occurrence of backlayering.

The position of the fire with respect to any ventilation shaft or fan will play an important part with respect to the smoke spread. A fire close to an intake shaft will result in a rapid and extensive smoke spread and increase the risk to the miners. The reasons for this are that the ventilation velocity has not yet been affected by the friction losses and thus remaining at a higher level as well as the fact that an intake shaft will service several areas and thus increase the extension of the smoke spread. A fire close to an exhaust shaft will in many cases result in a limited smoke spread and minor impact

to the miners as the affected area will be limited. A fire occurring in a production area may cause problematic smoke spread as the activities taking place in the area – i.e. blasting operations – will prevent the use of fire barriers. Thus in production areas one will rely heavily on the possibility to steer the ventilation flows in order to mitigate the effects of the smoke spread.

3. Vehicle fires and heat release rates in underground hard rock mines

The determination of the heat release rate of mining vehicles would be highly desirable as these fires constitute the most common type of fire occurring in most parts of a mine. In order to determine the heat release rate, the ignition times of the individual fuel items on the vehicle will have to be calculated using an appropriate set of expressions depending on the conditions. Summing up the individual heat release rates of the fuel items will give the overall heat release rate. In this thesis the different sets of expressions for calculating the ignition time are described and discussed, as well as the issue of summing up and depicting the overall heat release rate and the fire behaviour of mining vehicles in a mine drift.

3.1 Mining vehicles and their characteristics

Mining vehicles fulfill a very important role in the operations of a mine, without mining vehicles it would be very difficult to run a mine. Mining vehicles are found in most parts of a mine and are involved in most of the stages of mining: exploration, drilling, blasting, loading (in Figure 5 a wheel loader can be found) and excavation, haulage, service and maintenance. When it comes to loading and excavation – which constitutes the primary mine operation – mining vehicles are an absolute must and play an extremely important role.



Figure 5. A wheel loader commonly used in loading/excavation operations

The environment of an underground mine presents in many ways a unique environment, posing great demands on the mining equipment and mining vehicles as the ambient conditions, wear and tear on tyres, hoses, electronics etc are exceptional due to tough and harsh environment. The demands on the various types of vehicles will depend on the tasks the vehicle will fulfil and the areas where the mining vehicle operates within. Mining vehicles such as loaders are designed to withstand falling rocks in the operator section as their working areas are often found in the production areas. Due to the harsh and tough environment the design of mining vehicles is often distinguished by a compact design and rugged construction.

The fuel load and types of combustible materials will vary depending on the type of vehicle. The types of vehicles found in an underground mine are generally very extensive, everything from smaller pick-ups, buses etc to larger wheel loaders, drilling rigs, trucks etc. A loader can be distinguished by the large tyres and large supply of hydraulic oil, while a drilling rig can be distinguished by the large number of hydraulic hoses and large supply of

hydraulic oil. The electrical cables and hydraulic hoses on mining vehicles will generally form continuity between the other combustible items, providing the means for fire spread. The fire protection in mining vehicles consists of active measures where some vehicles are equipped with an automatic extinguishing system installed in the engine compartment. Another approach is the installment of materials that are fire resistant or non-combustible, reducing the fire load and the risk of fire spread. The use of fire resistant hydraulic fluid, electrical cables and hydraulic hoses are some examples of this approach. In Table 1 an example of a fuel inventory performed on a Toro 501 DL wheel loader is found.

Table 1. Fuel inventory performed on a Toro 501 DL wheel loader

Combustible component	Estimated amount	Effective heat of combustion [MJ/kg]	Estimated energy content [MJ]
Tyres	1560 kg	27	42120
Hydraulic oil in tank	500 L	42.85	16283
Hydraulic oil in hoses	70 L	42.85	2280
Hydraulic hoses	170 kg	28.85	4905
Diesel	280 L	42.6	10138
Driver's seat	10 kg	22.78	228
Electrical cables	1.5 kg	19.41	21
Rubber covers	10 kg	27	270

As pointed out in Paper I the most common fire cause found in underground hard rock mines is flammable liquid on a hot surface, in most cases hydraulic oil sprayed onto equipment hot surfaces [1][2]. This will explain the reason for the installment of automatic extinguishing system in engine compartments and the use of fire resistant hydraulic oil.

In Paper XIV it was found that fires due to electrical faults will generally only comprise the initial object and in some cases one or two adjacent objects and result in a slow and limited fire spread. The specific fire cause was in most cases due to short circuit and the type of item involved was in most cases cables. The electrical cables will in these cases also provide the bridge to adjacent objects. Fires involving the entire vehicle are typically caused by diesel being sprayed on hot engine parts or headlights, often due to a pipe or a hose coming loose and resulting in a rapid fire spread and an extensive fire where the fire spread to adjacent combustible objects such as tires and hoses. The fire hazard of the engine compartment is due to the enclosed type of compartment where a continuous release of a flammable liquid will lead to a rapid increase in temperature. Fires engulfing the entire vehicle most commonly happen to service vehicles and loaders. Taking into account the tough

environment where these vehicles are put to test constantly, it is not surprising that these types of vehicles are most often found in the fire statistics.

3.2 Heat release rates and fire behaviour of mining vehicles

The amount, position and type of combustible parts will vary depending on the type of mining vehicle. Hand in hand with this, the heat release rate and fire behaviour will vary from type to type of vehicle.

Two full-scale fire tests were carried out in an underground mine and are described in detail in Paper IV. One of the purposes of the tests was to measure the heat release rate of typical mining vehicles. The heat release rate was calculated applying the oxygen calorimetry concept [25], which is described in Paper IV. The methodology applied the mass flow rate with a unidirectional flow, gas concentrations and temperatures at certain heights further downstream of the fire source – outside the reaction zone of the fire – in order to calculate the heat release rate. When performing the actual heat release rate calculations a methodology presented by Ingason [26] was applied, using equations (4–6). The methodology consists of using many thermocouples distributed over the actual cross-section and only single point for measuring gas concentrations, which is suitable for mining conditions due to the tough environment and the sensitivity of the measuring equipment. The heat release rate can be calculated using the following equation:

$$\dot{Q} = \frac{13100 \cdot \rho_a \cdot u_0 \cdot A \cdot \left(\frac{M_{O_2}}{M_a} \right) \cdot (1 - X_{H_2O,0})}{\frac{0.1}{X_{O_2,0}} + \frac{1 - X_{O_2,avg} \cdot \left(\frac{X_{O_2,avg}}{1 - X_{CO_2,avg}} \right)}{X_{O_2,0} - \left(X_{O_2,avg} \cdot \left(\frac{1 - X_{CO_2,0}}{1 - X_{CO_2,avg}} \right) \right)}} \quad (4)$$

where u_0 is the cold gas velocity ($\text{m} \cdot \text{s}^{-1}$), M_{O_2} is the molecular weight of oxygen ($\text{g} \cdot \text{mol}^{-1}$), M_a is the molecular weight of air ($\text{g} \cdot \text{mol}^{-1}$), $X_{H_2O,0}$ is the mole fraction of water in the ambient air, $X_{O_2,0}$ 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, $X_{O_2,avg}$ is the average mole fraction of oxygen and $X_{CO_2,avg}$ is the average mole fraction of carbon dioxide. The correlation above between the

local gas temperature and local gas concentrations to the average value for the cross-section in question stems from a work by Newman [27], who tested the correlation for different types of fuels in a test gallery transferable to a duct or a mine drift.

In order to validate the calculated heat release rate, the integrated heat release rate over the measuring period was compared to the total energy content of the consumed fuel items on each vehicle. The comparison in the two tests resulted in close agreement.

The average concentration of oxygen and carbon dioxide was calculated using the following equations:

$$X_{O_2,avg} = X_{O_2,0} - \frac{(X_{O_2,0} - X_{O_2,h}) \sum_{i=1}^{N_T} (T_i - T_a)}{(T_h - T_a) N_T} \quad (5)$$

$$X_{CO_2,avg} = X_{CO_2,0} - \frac{(X_{CO_2,0} - X_{CO_2,h}) \sum_{i=1}^{N_T} (T_i - T_a)}{(T_h - T_a) N_T} \quad (6)$$

where $X_{O_2,h}$ is the mole fraction of oxygen at height h , $X_{CO_2,h}$ is the mole fraction of carbon dioxide at height h , N_T is the number of measuring points with thermocouples, T_i is the temperature at thermocouple i (K) and T_h is the temperature at height h (K). The thermocouples were positioned at a uniform distance of 1.2 m in between them and where the upper thermocouple was positioned 0.8 m below the ceiling. The vehicles in question were a wheel loader and a drilling rig. The wheel loader was a diesel driven vehicle, where the fuel load of the loader consisted primarily of the four tyres. The volume of diesel fuel was 280 L and the total mass of the tyres was 1560 kg. The total energy content of the wheel loader was estimated at 76.2 GJ. The drilling rig was an electrically driven drilling rig but nonetheless equipped with a diesel powered engine for moving the drilling rig. The fuel load of the drilling rig consisted primarily of the four tyres, the hydraulic oil and the hydraulic hoses. The total energy content of the drilling rig was estimated at 45.8 GJ. The resulting heat release rates are found in Figure 6 and 7.

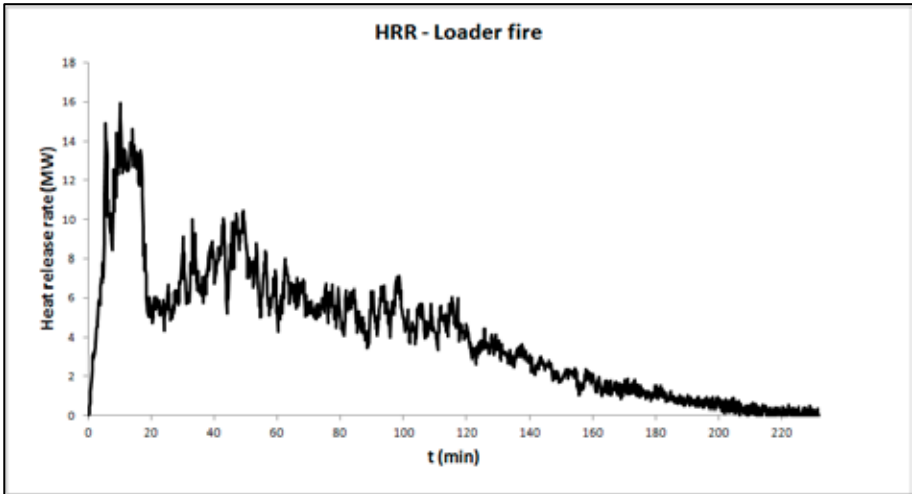


Figure 6. The resulting heat release rate curve of the wheel loader

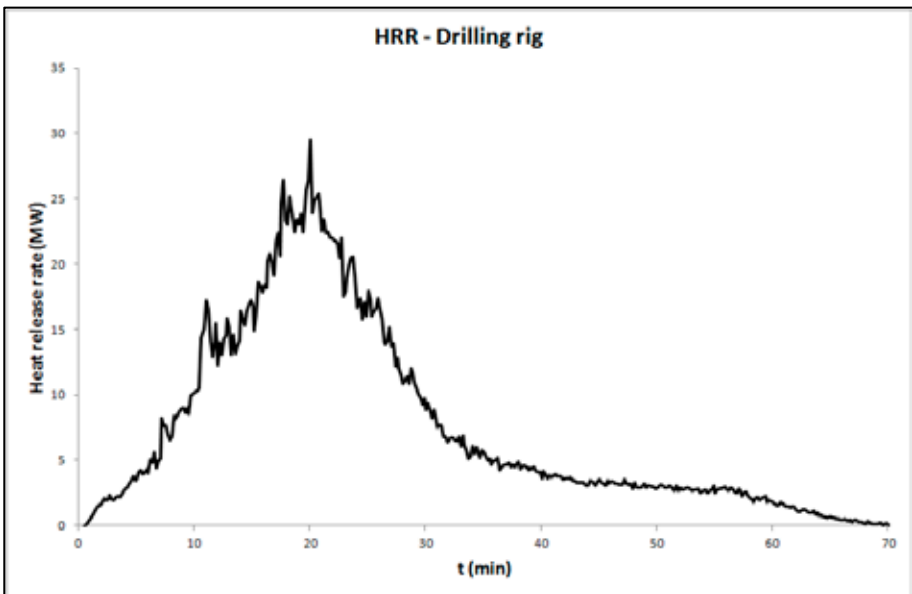


Figure 7. The resulting heat release rate curve of the drilling rig

The heat release rate curve of the wheel loader fire displays a fire that is clearly influenced by the longitudinal ventilation as well as the construction of the vehicle. The longitudinal ventilation was provided through the use of a mobile fan positioned further upstream of the fire. An increase in the longitudinal ventilation flow will increase the flame spread velocity along fuel items not covered by the vehicle construction, increase the mass flow and the

supply of oxygen to the fire and thus secure a high degree in combustion efficiency, increase the impact of tilting flames, increasing the importance of flame radiation and flame impingement which in turn will lead to earlier ignition of adjacent fuel components. The fire is initially characterized by the sudden increase of the pool fire and the flame engulfment of the rear, right tyre attaining a maximum heat release rate at 15.9 MW after approximately 11 min. The pool fire consisted of 190 L of diesel fuel that was emptied into a circular tray with a diameter of 1.1 m. The fuel surface was even with the top of the rim. As observed in Paper VI the rapid flame spread along the surface of the rear, right tyre and the short time interval to the maximum heat release rate could be expected due to the longitudinal ventilation flow pushing the flames from the pool fire along the full side of the tyre. Also the calculated burn off time of the diesel pool fire was more than twice as long as the observed burn off time. A possible explanation listed in Paper VI could be that the pool fire was underneath the vehicle and thus the re-radiation back to the pool surface would be much larger than for a free standing pool fire increasing the heat release rate and decreasing the burn off time. The slow flame spread along the surface of the rear, left tyre and a delayed maximum heat release rate is shown in a slowly declining heat release rates of the vehicles large rear tyres. The slower flame spread could be explained by the distance to the pool fire and that the longitudinal ventilation flow pushed the flames perpendicular to the tyre and thereby decreasing the flame spread along the tyre surface. In Figure 8 the distance between the rear, left tyre and the pool fire is clearly seen as well as the flames from the pool fire engulfing the rear, right tyre.



Figure 8. **The pool fire at the rear of the drilling rig, engulfing the rear, right tyre**

Photo: Andreas Fransson

The mass and bulkiness of the loader most likely affected the fire behaviour, acting as a heat sink and blocking the ventilation flow during the fire. The heat sink effect was most obvious in the middle section where large and heavy metal sections could be found. The heat sink effect together with the blocked ventilation flow reducing the tilting effect on flames, the cables and hoses in the lower sections being partially covered by the construction, the hydraulic hoses being drained on the hydraulic oil, most likely contributed to fire not spreading further than 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).

The fire experiment in the drilling rig resulted in a heat release rate curve with high heat release rates, relatively short in time and where a majority of the combustible items were ignited in the early phases of the fire. The maximum heat release rate was calculated at 29.4 MW and occurred after approximately 21 min. Same as for the wheel loader the tyres played an important part, where a sudden increase in fire growth after approximately 13 min was due to the ignition of the right, forward tyre. The fire spread stopped in the forward part of the boom, which was partially due to the same reasons as for the wheel loader. In Paper IV it was brought forward that in the case of the drilling rig, the drainage of the hydraulic hoses was probably

the main reason why the fire spread ceased as the incident radiation level became too low to propagate the fire in the direction of the ventilation flow.

In Paper VI the tyre fires were treated as surface fires where the maximum heat release rate was calculated applying a maximum heat release rate per exposed surface area of 0.20 MW/m^2 based upon a full scale test with a wheel loader tyre and presented by Ingason [14]. The total outer surface of each drilling rig tyre was calculated to approximately 3.5 m^2 and in the case of the wheel loader the total outer surface was approximately 10.2 m^2 . The total outer surface was calculated using data from tyre manufacturer [28]. An interesting aspect on the mining vehicle tyres is the relatively deep threads on the tyres and their influence on the heat release rate. The threads will act as 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. In Paper VI it was assumed that the longitudinal ventilation velocity would increase the maximum heat release rate with a factor 2 as the tyre treads were relatively deep and therefore adding some porosity characteristics to the tyres, partly based upon the findings in a paper by Lönnermark and Ingason [29]. In Paper VI a sensitivity analysis on the factor 2 was performed and it was found that when the factor was decreased to 1 and increased to 3 the resulting heat release rate curves indicated negligible or small changes. Even though the factor 2 could thus be used in future calculations with confidence, this is an issue that should be looked into further and more thoroughly. Performing experiments on tyre threads typical for the mining industry in order to establish adequate factors and increasing the accuracy of resulting heat release rate curves and decreasing the uncertainties.

The cable fires and the fires in the hydraulic hose – and the hydraulic oil within the hoses – were treated as continuous line fires in Paper VI, where the cables and hoses were uniformly distributed along the sections of the vehicles where cables and hoses could be found. The line fires were assumed to start at the back of each vehicle where the diesel pool fires ignited one cable/hose. The line fires would spread forward towards the front and after one minute doubling the amount of cables/hoses on fire, after two minutes doubling yet again the amount of cables/hoses on fire etc. The maximum heat release rate of the cable/hose fire will be attained at the time when the maximum amounts of cable/hose lengths are involved in the fire. The time of maximum heat release rate is calculated through the flame spread velocity, the fire duration of each segment of cable/hose as well as an assumption on the spread rate from one cable/hose to the next, adjacent cable/hose. The maximum heat release rate is calculated by multiplying the maximum amount of cable/hose length involved with the average heat release rate per unit area cable/hose. Obviously the described approach contains a number of assumptions that will have to be investigated further. In Paper VI a sensitivity analysis was performed on the fire duration value for a hose segment –

based upon the results from cone calorimeter experiments – and the assumption that the number of cables/hoses on fire would double every minute. It was found that if decreasing or increasing the fire duration with two minutes in the case of the drilling rig, the resulting heat release rate curve would decrease or increase with 3 MW. This difference cannot be ignored and therefore the fire duration of cable and hose segments should be determined through experiments specifically designed to establish the fire duration time. A sensitivity analysis on the increase of cables/hoses on fire every minute – increasing the number to three cables/hoses every minute – showed only minor changes to the resulting heat release rate curve. Still the assumption will have to be looked into further – investigating the behaviour of cable or hose bundles on fire – as it does not refer to any performed experiments or actual fires. In Figure 2 and Figure 9 an illustration of the uniform distribution of the hoses and cables can be found.



Figure 9. The uniform distribution of hoses and cables found at the vertical hinge of the drilling rig

Another issue encountered in Paper V and VI was the lack of available flame spread data for the hydraulic hose. The issue was solved by visually observing the flame spread progress using a videotaped sequence from the drilling rig experiment. This lack of data will have to be looked into further and possibly conduct flame spread experiments with and without hydraulic oil. The

latter aspect would be valuable in order to look into the influence on flame spread along the hose when the hydraulic oil has drained off. In Paper VI the uncertainty was examined further where the flame spread velocity was set to 5 mm/s and 9 mm/s in the case of the drilling rig. It was found that assuming a flame spread velocity of 5 mm/s will underestimate the maximum heat release rate by approximately 3 MW and assuming a flame spread velocity of 9 mm/s will overestimate the maximum heat release rate by approximately 3 MW and position the maximum heat release rate at an earlier stage than the one calculated from the experimental data. The differences cannot be ignored and thus the value of 7 mm/s should be used with precaution and preferably flame spread experiments should be performed in order to increase the accuracy and decrease the uncertainty.

3.3 Ignition of fuel components in a mine drift

When determining the heat release rate of a larger object or when evaluating the corresponding fire behaviour, the determination of the ignition times of the individual fuel items on the object plays a crucial role. A delayed ignition time of an individual fuel item will in turn imply the delayed ignition of adjacent fuel items and will therefore have a distinguished influence on the overall heat release rate of the object. Much effort should therefore be spent on establishing credible ignition times. This is especially the case when it comes to fuel items that dominate a vehicle type, such as the hydraulic hoses and hydraulic oil on drilling rigs.

There are a number of different methodologies available for determining the ignition time of an item, one question that arises is whether they are applicable to underground mines or not. As discussed in Paper II a fire in an underground mine can for example be distinguished by a transient heat flux over time from fires in tyres, hoses etc and the influence of the longitudinal ventilation in the mine drift. The methodology of for example Tewarson [30] where the ignition time, t_{ignition} , is calculated using a constant external heat flux will therefore be of limited use at a vehicle fire in a mine drift. Yet another question is what type of ignition criterion should be applied: critical heat flux, ignition temperature or mass loss rate? Taking into account the difficulty in establishing a mass loss rate for an individual item during a validating full-scale fire experiment, the focus should be on a critical heat flux or ignition temperature as ignition criterion.

Applying the critical heat flux criterion, the following expression – listed and discussed in Paper II, III, V and VI – could be used for calculating the external heat flux and setting it equal to the tabulated critical heat flux \dot{q}_{cr}'' of the specific fuel component at the time of ignition [31]:

$$\dot{q}_{flux}'' = h_c(T_{avg} - T_s) + F_{smokelayer} \cdot \varepsilon \cdot \sigma(T_{avg}^4 - T_s^4) \quad (7)$$

where \dot{q}_{flux}'' is the external heat flux ($\text{kW} \cdot \text{m}^{-2}$), h_c is the convective heat loss coefficient ($\text{kW} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$), T_{avg} is the average gas temperature (K), T_s is the fuel surface temperature (K), $F_{smokelayer}$ is the view factor for the smoke layer to the fuel item in question, ε is the emissivity factor and σ is the Stefan-Boltzmann constant. The expression was extracted from an earlier paper by Ingason [31].

In Paper VI it is pointed out that the average gas temperature in equation (7) will result in an approximate value when estimating the external heat flux. In the case of the two mining vehicles all fuel components could be found at mid-height (i.e. the cab) or in the lower region (i.e. tyres, hoses, cables etc.). A position at mid-height of the mine drift will justify the use of the average gas temperature of the mine drift. Regarding the fuel components found in the lower region, a fire gas temperature applicable for the lowest part of the mine drift where the entire mine drift height is accounted for would be inappropriately low in this case. The fire gases from the pool fires etc will rise, encounter the bottom of the vehicle and then follow the direction of the ventilation flow along the bottom. Thus higher fire gas temperatures found at the ceiling of the mine drift will also be present at the bottom of the vehicle, justifying the application of an average gas temperature in this case as well.

By calculating the heat flux numerically – using small time steps – the transient condition is fulfilled. The longitudinal ventilation factor is accounted for - through the mass flow - when the average gas temperature, T_{avg} (K), is calculated [31]:

$$\frac{\Delta T_{avg}(x)}{\Delta T_f} = e^{\left(\frac{-hPx}{\dot{m}_a c_p}\right)} \quad (8)$$

$$\Delta T_f = (T_f - T_a) \quad (9)$$

where ΔT_f is the average excess temperature at the fire location (K), h is the lumped heat loss coefficient ($\text{kW} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$), P is the perimeter of the mine drift (m) and x is the location of interest (m). The average temperature at the fire, T_f (K), is calculated applying [31]:

$$T_f = T_a + \frac{2}{3} \frac{\dot{Q}}{\dot{m}_a c_p} \quad (10)$$

where \dot{m}_a is the massflow of air ($\text{kg}\cdot\text{s}^{-1}$). In equation (10) it is assumed that 2/3 of the total heat release rate consists of convective energy. The assumption is based upon the findings and analysis of earlier performed full-scale fire experiments in a copper mine [32]. In Table 2 a number of key fuel components of the two full-scale fire experiments and the critical heat flux value of the component can be found.

Table 2. Key fuel component parameters and their critical heat flux value

Component	Maximum heat release rate [kW] [Paper VI]	Time to maximum heat release rate [s] [Paper VI]	Total energy content [MJ] [Paper IV]	Flame spread velocity [mm/s] [Paper VI]	Critical heat flux [kW/m ²]
Drilling rig					
Diesel pool	1100	150	2173	-	-
Left, rear tyre	1400	2160	1046	-	17.1 [33]
Right, rear tyre	1400	540	1046	-	17.1 [33]
Front tyre	1400	900	1046	-	17.1 [33]
Electrical cables	4620	1080	7487	2	4.0 [Paper VI]
Hydraulic hoses and hydraulic oil in hoses	12636	960	9682	7	6.2 [Paper VI]
Cab	1106	300	528	-	1.3 [Paper VI]
Hydraulic oil pool	9200	900	7979	-	-
Wheel loader					
Diesel pool	1300	170	6880	-	-
Left, rear tyre	4100	6600	10530	-	17.1 [33]
Right, rear tyre	4100	240	10530	-	17.1 [33]
Electrical cables	58	960	11	2	4.0 [Paper VI]
Hydraulic hoses and hydraulic oil in hoses	7313	900	3593	7	6.2 [Paper VI]
Cab	1106	300	498	-	1.3

					[Paper VI]
Hydraulic oil pool	7500	900	16283	-	-

The critical heat flux criterion will only account for the external heat flux at a specific moment, it will not account for the heat progressively accumulated at the surface of adjacent items. Applying instead the ignition temperature criterion, the following expression for a thermally thick item could be used for calculating the surface temperature [34]:

$$T_s(t) = T_a + \frac{1}{\sqrt{\pi \cdot k \cdot \rho \cdot c_{p,fuel}}} \int_0^t \frac{\dot{q}_{net}''(\tau)}{\sqrt{t - \tau}} d\tau \quad (11)$$

where k is the thermal conductivity of the solid ($\text{W} \cdot \text{m}^{-1} \cdot \text{K}^{-1}$), ρ is the density of the solid ($\text{kg} \cdot \text{m}^{-3}$), $c_{p,fuel}$ is the specific heat of the solid fuel ($\text{kJ} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$), \dot{q}_{net}'' is the net heat flux into the solid ($\text{kW} \cdot \text{m}^{-2}$) and τ are the intermediate time steps towards t ($0 \leq \tau \leq t$). The net heat flux is defined as the difference between the incident heat flux and the heat losses from the fuel surface. The net heat flux can be calculated by applying equation (7) and adding a flame radiation term as well as a convection and a radiation heat loss term. Equation (11) is applied and discussed in Paper II, III and VI. The longitudinal ventilation is accounted for through the net heat flux into the item, which in turn depends on the external heat flux. The transient heat flux is accounted for by calculating the surface temperature numerically applying small increments in time. Ignition is assumed to occur when the calculated surface temperature equals the tabulated ignition temperature value for the material in question.

During the course of this thesis work it was soon realized that there was a need for tests where the theoretical approaches could be verified. Therefore, small scale experiments were carried out in a model tunnel – seen in Figure 10 – where the distance between the combustible objects were non-uniform. Also, data from earlier fire experiments with uniform distance between the fuel items was used during the verification. In the small-scale fire experiments the two ignition criteria were evaluated using wood cribs and piles of pallets in two different sets of experiments and model scale tunnels where the longitudinal distance between the fuel items were uniform (Paper II) as well as non-uniform (Paper III). The experiments and analysis of the data are described in Paper II and III.



Figure 10. The model scale tunnel used during the small scale experiments

It was found in Paper II that for the critical heat flux criterion the calculated result matched exceptionally well with the measured result having a uniform distance between the piles of wood components. See Figure 11 for a comparison between resulting heat release rate curves of three individual wood cribs.

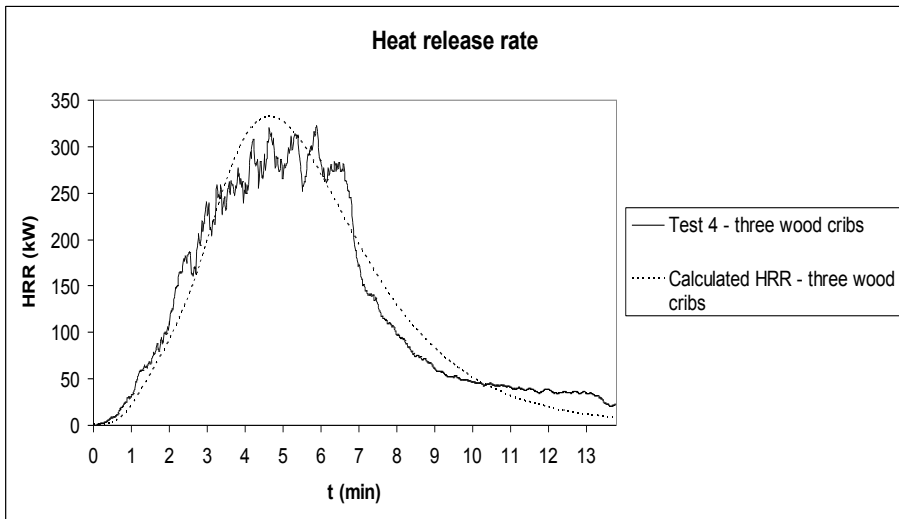


Figure 11. The calculated heat release rate (HRR) using the critical heat flux as ignition criteria versus the measured heat release rate value

A question that might arise here is whether the match is actually due to short distances (i.e. 0.65 m in the conducted experiments) between the piles, resulting in a rapid ignition of adjacent piles where the amount of heat accumulated in the wood crib was relatively low. What would instead happen if the distance between the piles was increased?

In subsequent small-scale tests of Paper III where the distance was non-uniform and increased, it was found that for shorter distances the calculated values matched the measured values well but for longer distances the calculated values tended to have too rapid ignition times compared with the measured values. See Figure 12 for the measured and calculated heat release rate of one of the tests.

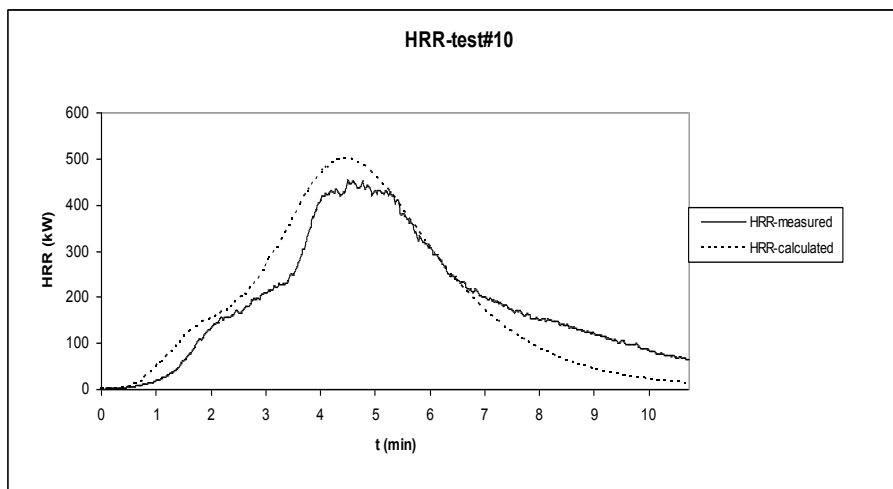


Figure 12. The measured heat release rate versus the calculated heat release rate for a case with a distance of 0.7 m between the first and second pile; 0.8 m between the second and third pile; 1.1 m between the third and fourth pile.

When applying the ignition temperature criterion to the small-scale experiments with uniform and short distance between the wood cribs, it was found in Paper II that the calculated heat release rate contained too long ignition times compared with the measured results. In Figure 13 the result for one of the experiments can be found.

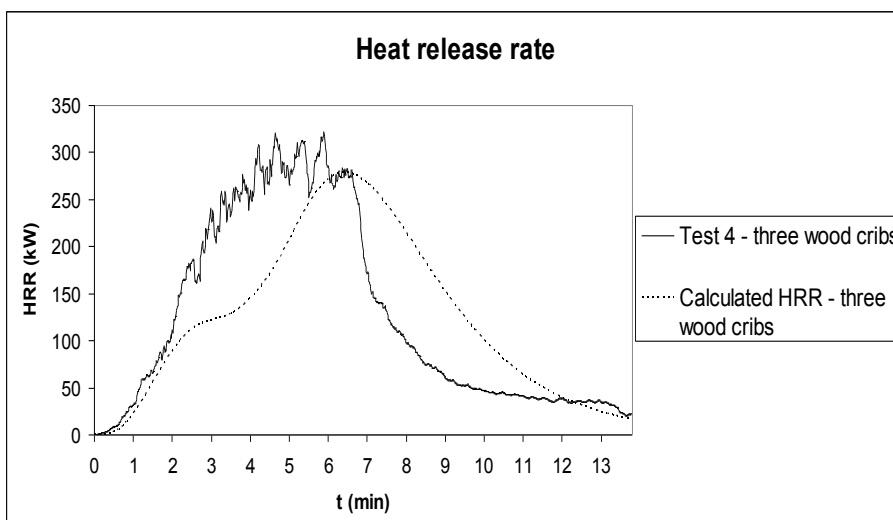


Figure 13. The calculated heat release rate versus the measured heat release rate value using the ignition temperature criterion

A possible explanation for the delayed calculated ignition time presented in Paper II could be that the ignition criterion responds too slowly in the case of a rapid fire growth and short distances resulting in a rapid increase in fire gas temperature. When applying the ignition temperature criterion to the small-scale experiments with non-uniform and increased distance between the fuel items, it was found in Paper III that the large longitudinal ventilation velocity prevented any higher surface temperatures in the calculations. But as the variation of the distances consisted in shorter distances between the initial piles – in order to achieve a "critical mass" sufficient to ignite the adjacent piles – and longer distances between the last piles, a mixed ignition criterion was tested where the critical heat flux was applied to the ignition of the first piles and the ignition temperature criterion was applied to the last piles. It was found that the ignition criterion poorly determined the time of ignition when the distance between the pallet piles was small, but the accuracy improved considerably as the distance increased and where the amount of heat accumulated in the pile was higher. A distance between the individual piles of more than 1 m was found to be representative of a long distance when studying the experimental results in Paper III.

A possible way to improve the results is to modify equation (7) as the equation is essential for both ignition criteria. Equation (7) does not fully account for the energy balance at the fuel surface but only includes the convective heat transfer from the fire gases to the fuel surfaces and the radiative heat transfer from the fire gases to the fuel surfaces. Adding a flame radiation term – as the flame radiation will play an important part with increasing flame length – and a convection loss and a radiation loss term would result in the following relationship:

$$\begin{aligned} \dot{q}_{flux}'' = & h_c(T_{avg} - T_s) + F_{smokelayer} \cdot \varepsilon \cdot \sigma(T_{avg}^4 - T_s^4) + F_{flame} \cdot \varepsilon \cdot \sigma(T_{flame}^4 - T_s^4) \\ & - h_c(T_s - T_a) - F_{fuel} \cdot \varepsilon \cdot \sigma(T_s^4 - T_a^4) \end{aligned} \quad (12)$$

where F_{flame} is the view factor for the flames to the fuel item in question, F_{fuel} is the view factor for the fuel surface to the surroundings and T_{flame} is the flame temperature (K). Adding the proposed terms would result in an expression where the energy balance is more comprehensively accounted for than in equation (7). Obviously the temperature of the smoke layer will vary depending on the vertical as well as the horizontal distance from the fire. A difficulty when applying equation (12) consists of trying to obtain an appropriate flame temperature for the fuel type in question as the flame temperature will vary from material to material. In the ensuing calculations an average solid flame temperature was applied in all cases as no appropriate material specific flame temperatures were found in the literature.

Equation (12) was evaluated together with equations (7) and (11) against two full-scale fire experiments conducted on mining vehicles in an underground mine. Thus for the critical heat flux criterion both an earlier proposed expression (equation (7)) and a new expression (equation (12)) was validated against the experimental results. Paper IV and VI give a full coverage on this improvement. The study was conducted in order to further validate the two ignition criteria against full-scale fire experiments. The findings of Paper VI were that the ignition temperature criterion could be ruled out as the surface temperatures of all fuel components never attained the corresponding ignition temperatures. This conclusion is in line with Papers II and III. Also the concept of using the distance between the fuel components in order to determine the appropriate ignition criterion was also ruled out in Paper VI, as the critical heat flux criterion was found to be the only applicable criterion of the two. It was found that applying equation (7) for the critical heat flux criterion was not suitable in the case of the two mining vehicles as the expression does not include a flame radiation term. The flame radiation was found to play a crucial part with respect to spread mechanisms. Finally it was found that equation (12) would come very close to the observed ignition times, except in the case of the left, rear tyre of the drilling rig where it would predict a much higher ignition time than the one observed. The surface heat loss terms found in equation (12) were found to have no effect on the output results and could therefore be neglected in the calculations. See Figure 14 for the resulting heat release rate curve from the full-scale experiment versus the calculated heat release rate applying equation (12) and a critical heat flux criterion in the case of the drilling rig.

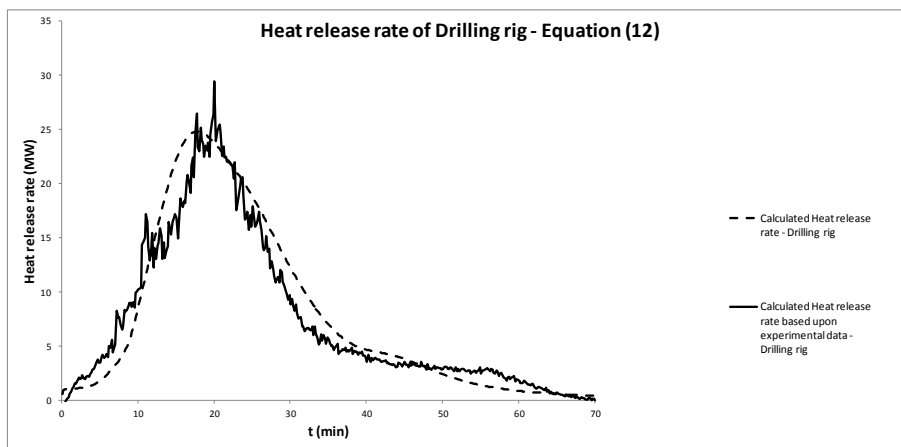


Figure 14. The resulting heat release rate of the drilling rig versus the calculated heat release rate using equation (12) and a critical heat flux criterion.

Thus when looking into the potentially improved capability of equation (12) to predict the ignition time, it was found that the addition of a flame radiation term proved to be of outmost importance and largely effected the resulting ignition times. But the addition of the loss terms was shown to have no effect and could therefore be neglected in equation (12). The reason for the small influence on the result was due to that the surface temperatures never attained any higher temperatures comparable with for example the temperature of the smoke layer.

In order to demonstrate the calculation procedure when calculating the ignition time of a certain fuel component the calculation of the ignition time of the drilling rig's front tyres is described here as an example. The procedure is basically the same for other fuel components, the difference lay in the involved heat transfer mechanisms. The critical heat flux criterion is used as the ignition criterion and equation (12) (but excluding the heat loss terms) is applied when calculating the heat flux level at the front tyres. Initially, the nearby fires and the applicable heat transfer mechanisms that will contribute to the ignition of the fuel component will have to be analyzed and selected. In the case of the front tyres, the contributing fires were the fires in the rear tyres and the diesel pool fire. As the front tyres will be exposed to the flow of fire gases from all three fires, the summed up T_{avg} of all three fires are calculated using equations (8-10). T_{avg} is then used in the convective heat transfer term in equation (12). As the flames of the three fires will be visible at the front tyres, the radiative heat transfer from the flames will have to be accounted for in equation (12). The flame heights of the three fires are calculated using equations (1-3). The view factors of the three fires are calculated using the flame height values and the flame widths (in this specific case the flame widths were set equal to the diameter of the pool tray and the tyre diameters). The calculated view factors are applied in equation (12) for the flame radiation where a flame temperature of 870 °C is assumed. Finally the front tyres will also be exposed to a radiative heat transfer from the smoke layer underneath the vehicle. The radiative heat transfer from the smoke layer is calculated using the earlier calculated T_{avg} in equation (12). The view factor of the smoke layer is calculated where the smoke layer is regarded as a rectangle perpendicular to the front tyres. The radiative (from flames and smoke layer) and convective heat transfer of the three fires are finally summed up into a total heat flux at the front tyres and compared with the critical heat flux value of the fuel component (in the case of the front tyres it was 17.1 kW/m²). Ignition is assumed to occur when the calculated heat flux value exceeds the critical heat flux value of the component.

As concluded in Paper VI one of the difficulties generally encountered when calculating the ignition times of the fuel items were the difficulty in predicting the failure of a mechanical part which would initiate a fire in an item. Also when the construction of the mining vehicle may cause phenome-

non, which could possibly require further refinements to the methodologies. The latter case was highlighted with respect to the ignition of the forward tyres due to the mass flow underneath each vehicle. In Paper V only the mass flow underneath the vehicle in question was accounted for when calculating the ignition time of the various tyres. But in Paper VI it was found that this approach was not satisfactory as the resulting temperatures were found to be unstable, oscillating between very low temperatures and unrealistically high temperatures. Thus in Paper VI the mass flow of the entire cross section of the mine drift was applied in the calculations. These are issues that should be looked into further.

Yet another issue that has arisen during the course of the work is the influence on ignition time that the roughness and structure of the fuel surfaces will have. Considering the generally rough surfaces encountered in an underground mine due to the tough environment, the threads on the vehicle tyres is an issue that needs to be looked into further.

In Papers II and III the view factor was set to unity, while in Papers V and VI the view factors of the smoke layer and radiating flames were instead calculated for the different cases. Setting the view factor to unity contributed to the too rapid ignition times calculated in Paper III. If setting the view factor to unity in the case of the two full-scale fire experiments it was found that all fuel components – except for the cabs – were ignited nearly instantaneously. As the flame radiation will play a very important part in the calculations of the ignition times of the various fuel components it is essential that the view factors are calculated and not assumed to be unity.

In Paper VI a discussion is included on the use of critical heat flux values for the various fuel components. The values used are table values or calculated values based upon performed cone calorimeter experiments and should be regarded as values at the lower end of the scale or minimum values. Thus applying the table values during the initial 10 min could be problematic as the ignition time of a fuel component will vary depending on the incident heat flux and ignition taking part during the initial minutes will require a higher heat flux value than the table value. But it was found that the ignition times of the left, rear tyres, front tyres and the cabs was close to or exceeding 10 min, for the other fuel components the calculated incident heat flux became several times higher than the critical heat flux only a few seconds after exceeding the critical heat flux. Applying a tabulated critical heat flux value in these cases was thus found to be applicable. Some examples of critical heat flux values could for example be 6.2 kW/m^2 for the hydraulic hose and 4.0 kW/m^2 for the electrical cable, both values were calculated values from performed cone calorimeter experiments and can be found in Paper VI.

The model scale experiments in Papers II and III involved discrete fuel objects positioned at certain intervals and with no contact between the objects. In Paper VI a discussion can be found on how can this be related to and transferred to the fire spread between the individual fuel components of

the two full-scale experiments. In brief the vehicles consists mostly of fuel components that are all positioned at different distances between them and with no direct physical contact between them. The only fuel components that may link with other fuel components are the electrical cables and hydraulic hoses, but they were not in direct contact with any of the other major fuel components and were therefore also treated as discrete fuel components. In Paper VI a discussion on the applicability to transversal fire spread - perpendicular to the longitudinal ventilation flow found both in the small-scale experiments and the full-scale experiments - can also be found. One case was found where the fire spread was perpendicular to the ventilation direction: the left, rear tyre. It was found that the calculated ignition time of the wheel loader would come very close to the observed ignition time, but in the case of the drilling rig it would predict a much higher ignition time than the one observed. The reasons for the difference in ignition time are unclear and a need exists to further investigate the applicability of the sets of expressions to fuel components found perpendicular to the flow of fire gases.

When calculating the ignition times of the various fuel components, the direction and amplitude of the ventilation in the mine drift will have a significant and complex impact on the result. The ventilation will be included in the mass flow in the mine drift and thus also included in the calculations of the average gas temperature. An increasing ventilation velocity will lower the average gas temperature in the near vicinity of the fire but on the other hand increase the average gas temperature at longer distances. Flames exposed to the ventilation flow may tilt and lean towards adjacent fuel components. This will shorten the time to ignition as the view factor will increase and flame impingement may occur as well. The flame tilt issue was not addressed in Paper VI as the vehicle construction was found to effectively shield the flames from the ventilation flow. The flow direction of fire gases and direction of tilted flames may affect the possible heat transfer mechanisms. The ventilation flow may for example push the fire gases away from an adjacent fuel component, thus excluding the convective heat transfer term and increasing the time to ignition. This issue was addressed in Paper VI when for example calculating the ignition times of the various tyres. The amplitude of the ventilation velocity will affect the porosity characteristics of the tyre threads, the heat release rate of the tyre and thus also the ignition times of fuel components close to the tyre. A decreasing ventilation velocity will decrease the maximum heat release rate and increase the ignition time of surrounding items, an increasing ventilation velocity will increase the maximum heat release rate up to a certain point where the fire in the tyre threads turns into a fuel controlled fire. Any unshielded fuel surfaces will result in an increasing flame spread velocity due to an increasing ventilation velocity; the increase in flame spread velocity will increase the maximum heat release rate of the fuel component and lead to shorter ignition times of surrounding fuel components.

Most of the calculated ignition times of the various fuel components in Paper VI were found to occur within the initial minutes of the fire. What would the result be if simply assuming instantaneous ignition for all fuel components? In Paper VI the calculated heat release rate curves of the two full-scale fire experiments are presented where instantaneous ignition of all fuel components were assumed. The results for the two cases can be seen in Figure 15 and 16.

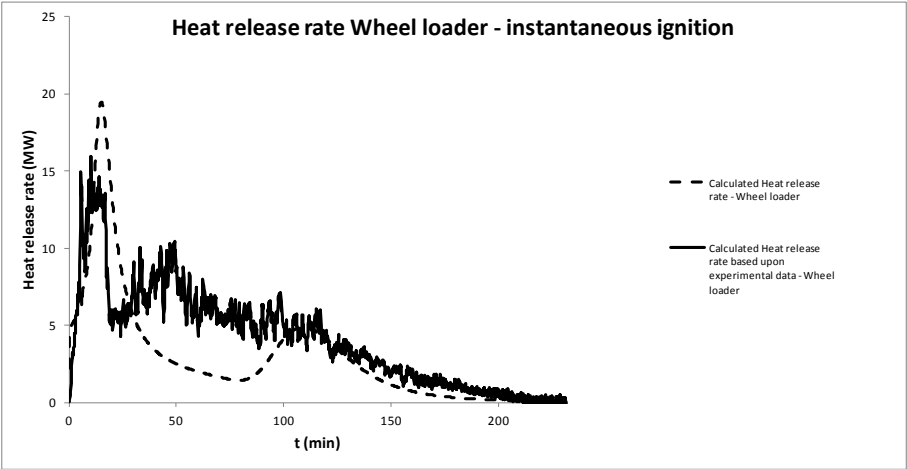


Figure 15. The heat release rate of the wheel loader, assuming instantaneous ignition.

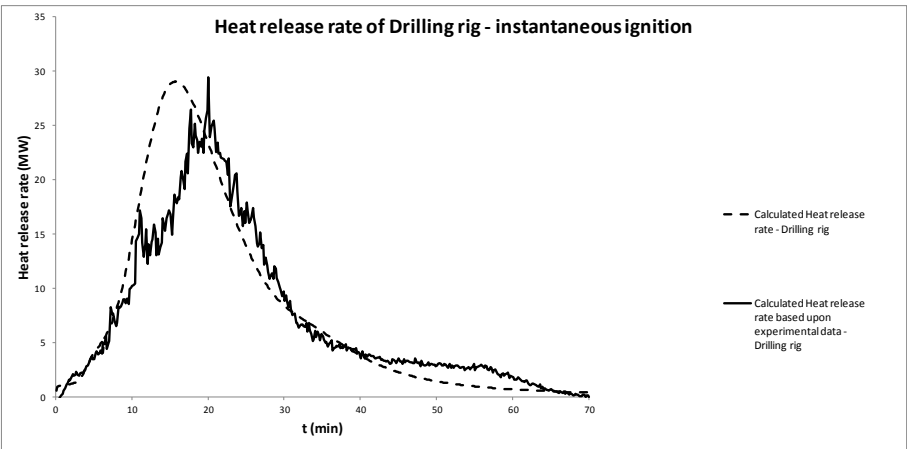


Figure 16. The heat release rate of the drilling rig, assuming instantaneous ignition.

As can be seen in Figure 15, assuming instantaneous ignition in the case of the wheel loader would overestimate the maximum heat release rate by approximately 5 MW. If the distances between the individual fuel components would have increased, the resulting error in the heat release rate curve would have increased as well. In Figure 16 it can be seen that for the drilling rig the maximum heat release rate would also be overestimated by approximately 5 MW and the time to maximum heat release rate would be calculated to occur at an earlier point of time than the actual. The latter difference would increase in size if the initial fire would have been smaller in size, a slower fire growth rate would have occurred or if the distance to adjacent fuel components would have increased.

A number of assumptions were made in Paper VI and consequently a number of sensitivity analyses were performed in order to follow up the impact of the assumptions on the time of ignition and the appearance of the resulting heat release rate curves. Among the analyzed parameters, two were found to have a large impact on the ignition times: the flame temperature and the critical heat flux of the tyres. In Paper VI the flame temperature was assumed to be 870 °C, which is a measured value from a rack storage experiment. If instead decreasing/increasing the flame temperature by 100 °C, it was found that the resulting ignition times differed considerably in some cases (resulting in a difference of 100–120 s compared with the earlier results). The same result was received when analyzing the critical heat flux of the tyres, which was a tabular value applicable to natural rubber. These two results are not surprising as the flame radiation will play an important part in the incident heat flux calculations and the critical heat flux value plays a very important part at the end of the calculations, determining whether ignition would occur or not. The impact of these two parameters underlines the importance to obtain experimental or table values that are clearly valid and applicable to the fuel/s in question as the applied values in Paper VI are not fully applicable and should be used with precaution.

As mentioned before the critical heat flux values extracted from cone calorimeter experiments or from tables will be values found at the lower end of the scale and will be of questionable value with respect to fuel components that are ignited at an early stage. Also, the heat flux will vary with time during the fire and not stay constant. A more rigid approach where both a transient heat flux and the time aspect of the ignition are accounted for could possibly be the use of the following expression [33]:

$$B = t^{0.05} \cdot 0.5 \cdot \int_0^t \frac{\dot{q}_{flux}''(t) - \dot{q}_{cr}''}{\sqrt{t - \tau}} d\tau \quad (13)$$

Ignition is assumed to occur when $B \geq B_{ig}$, where B_{ig} is the inverse of the slope received from the cone calorimeter experiments of the specific fuel

component following Janssen's procedure [33]. The straight line - from which the slope is obtained - is plotted using a number of ignition times at varying heat fluxes, where $t_{\text{ignition}}^{-0.55}$ will be the y-axis and \dot{q}_{flux}'' will be the x-axis. The B_{ig} value can be found as a table value. One should be aware that applying equation (13) will result in longer ignition times as the loss term \dot{q}_{cr}'' is assumed to be constant throughout the sequence, but prior to ignition the loss term will actually be lower due to lower surface temperatures [33].

Finally it must be emphasized that the heat release rate curve from earlier experiments cannot be used directly for other cases without further analysis of the specific geometry of the mine drift, flow conditions, vehicle construction etc. Also the calculation of the ignition time of the individual fuel components will consider the specific conditions of the fire in question, for example the dimensions of the mine drift, ventilation, existing barriers, inclination etc. An extensive discussion on this topic can be found in Paper VI.

3.4 Depicting the heat release rates of mining vehicles

In Paper II, III, V and VI a single exponential function for each fuel item was used in order to represent the heat release rate. The advantages of the exponential function are the fact that a single function successfully can depict the entire fire sequence and not having to rely on several separate functions for different time intervals. The appearance of the exponential function also depicts the different phases of a fire – i.e growth phase, decay phase etc. – in a realistic and smooth way. Even the incipient phase – the time from ignition until the fire growth rate starts to be significant – is realistically depicted with the function. The exponential function was proposed by Ingason [35] based upon the work by Numajiri and Furukawa [36]. The exponential function in its original condition is only valid for fuel controlled conditions, but after some modifications it could also be applied to longer and constant sequences of heat release rates such as in the case of ventilation controlled fires or pool fires.

The depiction of the overall heat release rate of an object involves the summation of the individual heat release rates. Applying this approach requires that the heat release rate curves of the individual fuel items are known beforehand through experiments or reconstructed successfully using data from conducted fire experiments or earlier actual fires. The overall heat release rate of an object is described with the following set of equations [35]:

$$\dot{Q} = \sum_{s=1}^p \dot{Q}_{\text{max},s} \cdot n_s \cdot r_s \cdot (1 - e^{-k_s \cdot t})^{n_s-1} \cdot e^{-k_s \cdot t} \quad (14)$$

$$r_s = \left(1 - \frac{1}{n_s}\right)^{1-n_s} \quad (15)$$

$$k_s = \frac{\dot{Q}_{\max,s}}{E_{\text{tot},s}} \cdot r_s \quad (16)$$

$$t_{\max,s} = \frac{\ln(n_s)}{k_s} \quad (17)$$

where $\dot{Q}_{\max,s}$ is the maximum heat release rate (kW), n_s is the retard index of the fuel item, r_s is the amplitude coefficient, k_s is the time width coefficient, $E_{\text{tot},s}$ is the total energy content (MJ) and $t_{\max,s}$ is the time to maximum heat release rate (s). The design of the individual heat release rate curve may follow different approaches. One method would be to apply the starting time of the initial fire to all fuel components, named the t_0 -method in the ensuing discussion. Initially the maximum heat release rate, time to maximum heat release rate and total energy content are extracted from conducted fire experiments. Based upon these values, the retard index, amplitude coefficient and time width coefficient can be calculated. The next step involves selecting a new retard index that will match the time of ignition, i.e. the point of time when the fire is estimated to start to develop. The retard index is varied until the desired starting point is received. In order to be able to find a suitable retard index a criterion will have to be established that defines when the fire exits the incipient phase, a discussion on this topic can be found in Paper II and further ahead in this chapter. The retard index will have a clear influence on when the fire growth will start to pick up and exit the incipient phase. When selecting a new retard index, the time to maximum heat release rate will change as well which could possibly reflect its dependence on the time of ignition. In order to illustrate the above described methodology, the heat release rate curve of a single wood crib found in Figure 17 is used. The maximum heat release rate is estimated at approximately 180 kW and the total energy content is summed up to 67.6 MJ.

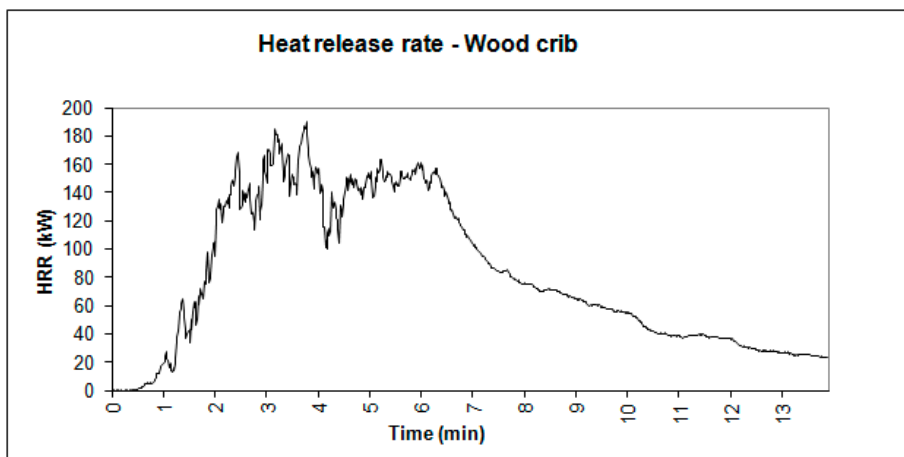


Figure 17. The heat release rate of a single wood crib

Selecting a new and suitable retard index value, the resulting calculated heat release rate curve is found in Figure 18. The suitable retard index n_s was found to be 5.5 and the time to maximum heat release rate to 4 min.

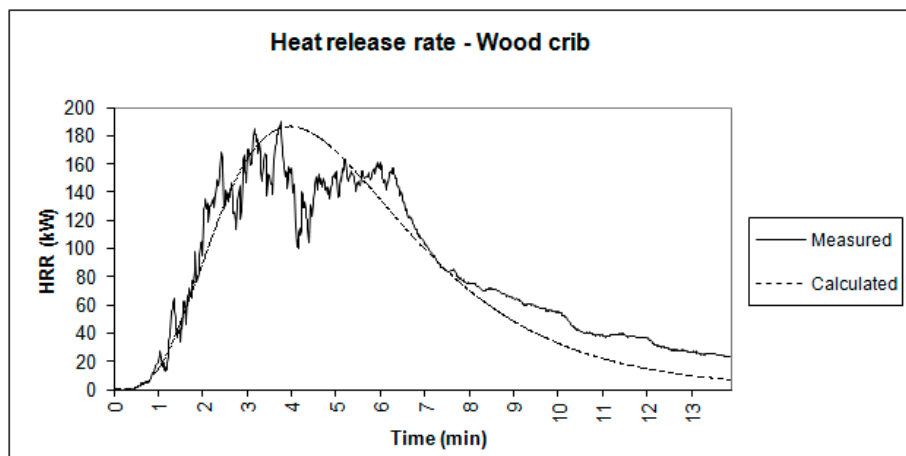


Figure 18. The measured and calculated heat release rate of a wood crib

The other method would be to set the time variable of the exponential function to zero at the time of ignition of the fuel item in question, being the starting point of the specific fire. The method is named the t_{ign} -method in the ensuing discussion. For fuel items ignited after the initial fire, the time given in the exponential function would be the ignition time of the fuel component subtracted from the time variable: $t - t_{ignition}$. Each fuel item would

thus be considered as inert until ignition took place. The retard index will be determined numerically using equation (15–17) and the following three parameters: the maximum heat release rate, total energy content and the time to attain maximum heat release rate. The input parameters can be extracted from earlier performed fire experiments but also from visual observations, video footage, fuel inventories etc from actual fires. The time to maximum heat release rate for a specific fuel component may vary from fire to fire depending on the conditions and will therefore have to be adjusted accordingly. When applying the t_{ign} -method in Paper VI an analysis was performed with respect to the time to maximum heat release rate of the individual tyres, where conditions of the various tyres were compared with earlier tyre fire experiments as well as with measurements taken during the full-scale experiments in order to obtain realistic time components. In order to clarify the t_{ign} -method an example on the calculation procedure could be as follow: in an earlier fire experiment with a wheel loader tyre the total energy content was calculated to 10500 MJ (which was obtained by multiplying the weight of the tyre with its heat of combustion value), the time to maximum heat release rate was observed to be 240 s and the maximum heat release rate was calculated at 4.1 MW. Rearranging equation (17):

$$k_s = \frac{\ln(n_s)}{t_{\max,s}} \quad (18)$$

Thus the right hand side of equation (16) can be set equal to the right hand side of equation (18):

$$\frac{\dot{Q}_{\max}}{E_{tot,s}} \cdot r_s = \frac{\ln(n_s)}{t_{\max,s}} \quad (19)$$

Rearranging equation (19):

$$r_s = \frac{\ln(n_s) \cdot E_{tot,s}}{t_{\max,s} \cdot \dot{Q}_{\max}} \quad (20)$$

Setting the right hand side of equation (20) equal to the right hand side of equation (15):

$$\frac{\ln(n_s) \cdot E_{tot,s}}{t_{\max,s} \cdot \dot{Q}_{\max}} = \left(1 - \frac{1}{n_s}\right)^{1-n_s} \quad (21)$$

Solving for n_s will result in a value of 1.13. The value of k_s is then calculated to 0.00051 applying equation (18). The value of r_s is calculated to 1.31 applying either equation (15) or equation (20).

In Paper II and III the t_0 -method was used - even though least squares fit was applied in these papers when finding suitable retard index values, which is not a necessity - and in Paper V and VI the t_{ign} -method was applied. In Paper II, III, V and VI the exponential function was found to generally visualize the individual as well as the overall heat release rate in a very realistic and satisfactorily manner. If comparing the two methods for the same case (see Figure 19) it can be seen that the resulting heat release rate curve of the t_{ign} -method clearly matches the heat release rate curve based upon experimental data better than the t_0 -method. When looking into the individual t_{max} values of the two methods it was found that the t_0 -method generally resulted in lower values than the t_{ign} -method. Which can also be seen in Figure 19 where the resulting heat release rate curve of the t_0 -method has an earlier maximum heat release rate than the other two curves. The conclusion here is that it is better to try to establish a suitable t_{max} based upon an analysis where fire experiments or actual fires are accounted for rather than relying on a mathematical expression that does not involve any physics.

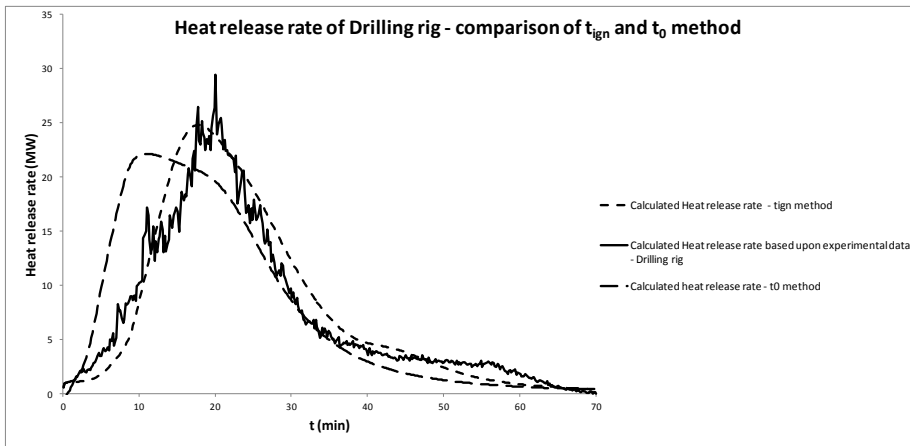


Figure 19. A comparison between the t_0 -method and the t_{ign} -method.

If continuing the discussion on the t_0 -method. The retard index applied in the t_0 -method is highly interesting with respect to the ignition of the fuel item, as the index will decide when the heat release rate will start to develop and the incipient phase is exited. In Paper II the issue when the fire exits the

incipient phase is discussed and analyzed. A criterion based upon the change of heat release rate over time was suggested, namely:

$$\frac{\Delta \dot{Q}}{\Delta t} \geq 0.2 \text{ kW/s}$$

Thus the incipient phase is assumed to end when the increase of heat release rate starts to be significant. A sensitivity analysis was performed which indicated that criterion was not very sensitive to changes and would only result in minor changes in the corresponding retard index values. The issue should be worthwhile looking further into, analyzing potential criteria.

If applying the criterion above for the point of time when the incipient phase is exited, the point of time could be calculated by determining the derivative of equation (14) applying the product rule and the chain rule. Resulting in the following expression for a single fuel item:

$$\frac{d\dot{Q}}{dt} = \dot{Q}_{\max} \cdot n \cdot r \cdot \left(-k \cdot e^{-k \cdot t} \cdot (1 - e^{-k \cdot t})^{n-1} + (n-1) \cdot k \cdot e^{-2 \cdot k \cdot t} \cdot (1 - e^{-k \cdot t})^{n-2} \right) \quad (22)$$

Approximating equation (22) with the earlier described criterion will result in the following relationship:

$$0.2 \approx \dot{Q}_{\max} \cdot n \cdot r \cdot \left(-k \cdot e^{-k \cdot t_{\text{incipient}}} \cdot (1 - e^{-k \cdot t_{\text{incipient}}})^{n-1} + (n-1) \cdot k \cdot e^{-2 \cdot k \cdot t_{\text{incipient}}} \cdot (1 - e^{-k \cdot t_{\text{incipient}}})^{n-2} \right) \quad (23)$$

Solving for $t_{\text{incipient}}$ will give us the point of time when the incipient phase is exited for the fuel item in question. Obviously the left hand side of equation (23) can be replaced by any other criterion deemed to be appropriate.

Furthermore in Paper II the retard index value was investigated against the number of adjacent fuel items, keeping the distance between the fuel items constant. It was found that for uniform distances between the fuel items the difference in the retard index – i.e. dn – could be determined having a uniform value and therefore the retard index increases linearly with each fuel item ($n_1 = 5.2$; $n_2 = 12.2$; $n_3 = 19.2$). But opposed to the linear increase in the retard index, the corresponding difference in the ignition time will instead decrease non-linearly. Figure 20 displays this difference in the retard index and ignition time schematically.

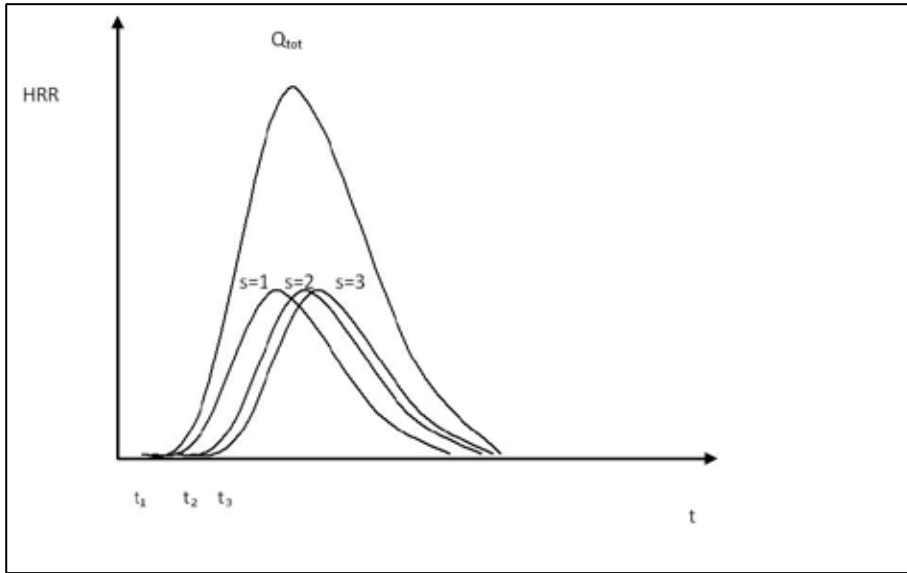


Figure 20. The summation of individual heat release rate curves adding to a total heat release rate curve

In Paper III – where the distance between the fuel items were non-uniform – any similar consistency could not be found in dn . Even though the distance between the second and third fuel item increased compared with the distance between the first and second fuel item, the dn value decreased. Continuing the work from Paper III and comparing the difference in the dn value between the first and second fuel item, the second and third fuel item and the third and fourth fuel item respectively, the dn value increased which was expected as the distance increased as well. In Figure 21 the difference in the retard index as a function of the corresponding distance between the fuel items is found. This divergence in the dn value will have to be analyzed further. In figure 22 a schematic drawing of the individual pallet piles with their respectively retard index n and horizontal distance x to the adjacent pile is shown.

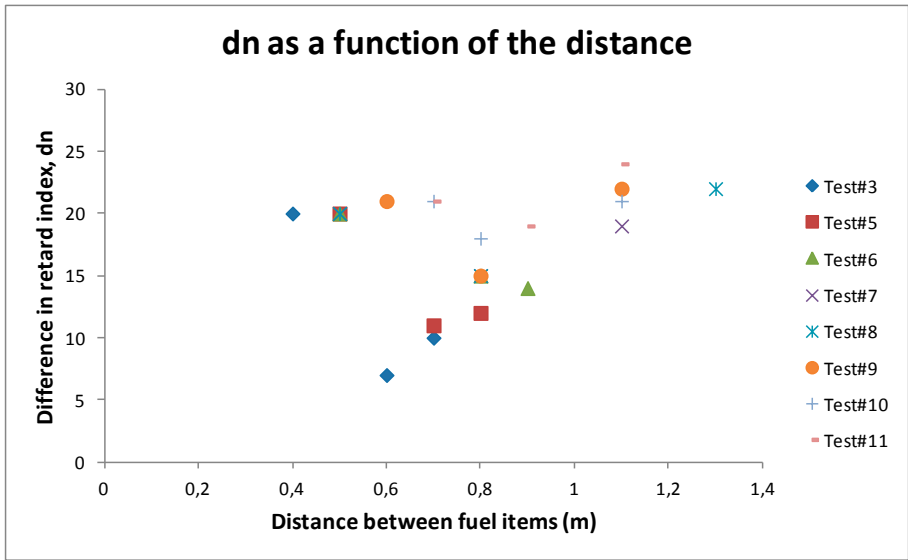


Figure 21. The difference in the retard index as a function of the horizontal distance between the fuel items for the non-uniform test series

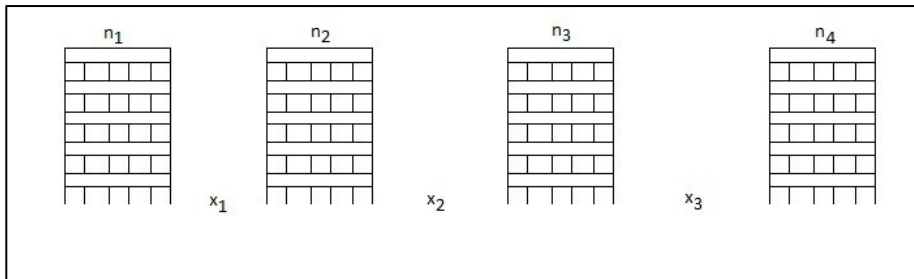


Figure 22. Drawing of the individual wooden pallet piles, their retard index and horizontal distance to adjacent pile

4. Summary and conclusions

In *Paper I* it was found that the most common fire cause in underground mines was flammable liquid sprayed onto hot surface and the most common fire object was a vehicle. Furthermore a major concern was the lack of documented fire experiments in vehicles and therefore the need for corresponding heat release rate curves is great.

In *Paper II* theoretical calculations of the heat release rate of several fuel items at uniform distances in a mine drift/tunnel were carried out and compared with the results from corresponding fire experiments on wood cribs in a model-scale tunnel with longitudinal ventilation. The most important findings were that the critical heat flux criterion exhibited very good agreement with the corresponding results of performed fire experiments and the ignition temperature criterion did not agree very well with the corresponding results of performed fire experiments. But a major concern was the influence of an increasing and varying distance between the fuel items. Would the delayed ignition and increasing amount of energy accumulated in the fuel surface result in the same conclusions on the different criteria?

The issue on an increased and non-uniform distance between the fuel items was further investigated in *Paper III*, comparing the calculated heat release rates with the performed fire experiments on piles of wooden pallets in a model-scale tunnel. The findings were that critical heat flux criterion exhibited very good agreement with the performed fire experiments, but tended to have too short ignition times in the case of longer distances between the fuel items. On the other hand the ignition temperature criterion did not agree very well with the results of the performed fire experiments, but it was found that the accuracy improved considerably as the distance between the fuel items was increased and thereby increasing the applicability of the criterion. The apparent next step would be to validate the different criteria and sets of expressions against full-scale fire experiments in mining vehicles.

Following the small-scale experiments, two full-scale fire experiments were carried out in an operative underground mine in Sweden and are described in *Paper IV*. The fire experiments were carried out on a wheel loader and a drilling rig respectively. A number of different parameters were measured such as the heat release rate, the temperatures and the incident radiation heat flux at a number of positions on each vehicle. The maximum heat release rate from the wheel loader experiment was 15.9 MW and it was attained approximately 11 min after ignition. The fire in the wheel loader was

distinguished by the initially dominating and rapidly increasing pool fire, rapidly spreading to and engulfing the first tyre and then by the slowly declining fires of the large tyres of the vehicle. In the case of the drilling rig the maximum heat release rate from the experiment was 29.4 MW and it was attained after 21 min. The fire in the drilling rig revealed a fire with high heat release rates and a relatively short lived fire – compared with the fire in the wheel loader. Practically all the combustible items were ignited in the early phases of the fire and most of the combustible materials were consumed in the fire as opposed to the fire in the wheel loader where the front part of the vehicle never participated in the fire. The full-scale fire experiments laid a good foundation for the validation studies found in Paper V and VI.

The critical heat flux criterion was validated against the results of the drilling rig fire experiment in *Paper V*. The calculated heat release rate curve of the drilling rig was found to match the calculated heat release rate curve based upon experimental data very well. It was found during the work that the crucial part in the calculations was to determine the correct ignition time and the appearance of the heat release rate of the hydraulic hoses and hydraulic oil as the fires in the hydraulic hoses and the hydraulic oil clearly dominated the appearance of the heat release rate curve. Additional findings of the paper were that an uncertainty in the calculations was the lack of flame spread data for the hydraulic hoses which are found on most types of the larger mining vehicles. Also the need for additional work on the influence of the vehicle construction was identified – i.e. the mechanical failure of a vehicle component, the influence on flow conditions in the mine drift etc.

The criteria and sets of expressions were further validated and analyzed against the full-scale fire experiments in *Paper VI*, applying output data from conducted cone calorimeter experiments and TPS experiments. During the analysis it was found that the critical heat flux criterion, applying equation (12) resulted in ignition times very close to the observed ignition times except in the case of the left, rear tyre of the drilling rig where a much higher ignition time was predicted than the one observed. Additional heat loss terms and heat gain terms were added to the heat balance, the added flame radiation term was found to have a large impact on the resulting ignition times while the heat loss terms were found to have none or very little effect on the output results. The ignition temperature criterion was ruled out as the surface temperature of the fuel components never attained their tabulated ignition temperatures. The best match in the case of the drilling rig was found when applying equation (12) and the critical heat flux criterion. The corresponding match in the case of the wheel loader was harder to achieve as it was found difficult in this case to accurately predicting the mechanical failure of the suction hose which would initiate the highly significant hydraulic oil pool fire.

The findings of the work will be a good foundation for future studies regarding the calculation of the overall heat release rate of mining vehicles as well as the ignition of fuel items in a mine drift. The work has shown the possibility to calculate the overall heat release rate of a mining vehicle in a mine drift based upon the heat release rates of the individual fuel items of the vehicle, not having to rely solely on expensive and time consuming full-scale fire experiments. The work has also shown that the critical heat flux criterion was applicable to the two full-scale experiments as opposed to the ignition temperature criterion which was ruled out and found not to be applicable. Furthermore the work could also be applied when calculating the required time of a refuge chamber with respect to the fire duration. Also, the extensive data from the experiments in Paper IV could be used for comparison with CFD models, studying the heat losses as a function of the distance in a mine drift with longitudinal ventilation etc.

5. Further work

The effect of the longitudinal ventilation flow on the flame tilt and the effect of obstacles on the flow conditions in the mine drift would be two issues worth analyzing further. This is important as the possible tilting flames will lead to faster flame spread, ignition of adjacent fuel items and more severe fire behaviour. Any obstacles in the direction of the longitudinal ventilation direction may block the flow and reduce the tilting effect and increase the time to ignition for adjacent items. As both factors will influence the time to ignition they will also affect the heat release rate of the object. Also the construction of the mining vehicle may create funnels partly or entirely enclosed on the sides through which the air masses may be diverted – passages within the larger passage composed by the mine drift. A question here worth analyzing further would be the mass flow situation within a partly enclosed funnel, where the fire gases pushed through the funnel will partly escape on the sides and not contribute to the ignition of fuel items further ahead and thus affecting the ignition time of the items. Possible tests in a model-scale tunnel could shed light on this issue. As the two full-scale experiments were conducted in a mine drift with almost no inclination, it would be highly interesting to further investigate the influence on fire spread between fuel components. The inclination of a ramp in an underground mine may in many cases be considerable (a ramp is used for vehicle access to the mine and will decline downwards connecting with different parts of the mine) and large amounts of vehicles can be found in a ramp.

Yet another issue worth analyzing further would be the influence of the rough surfaces of a mine drift, ramp etc. A mine drift or a ramp is often characterized by the rough surfaces which will result in friction losses and turbulence to the flow of fire gases. These losses and turbulence will in turn decrease the stratification of the fire gases as well as influencing the possible occurrence of backlayering and in the long run the smoke spread in the area. Experimental data recorded for Paper IV could possibly be used during the analysis.

The environment in an underground mine will be particularly tough on equipment and the surfaces of materials, for example the wear and tear on vehicle tyres, hydraulic hoses etc will often be considerable. A question that arises with respect to rough surfaces is the influence on ignition time that the roughness and structure of the fuel surfaces will have? This is a question that

should be investigated further, possibly performing small-scale experiments in a cone calorimeter to study the influence on the ignition time.

A specific fuel surface on an important fuel item would be the surface of the tyres on the vehicle. The deep threads on the mining vehicle tyres will act as voids with separate and protected atmospheres, enclosing portions of the fire gases. An increasing longitudinal ventilation velocity will increase the air supply into the voids and thereby increase the heat release rate. This influence on the heat release rate should be analysed further.

When calculating the overall heat release rate of the two mining vehicles in Paper V and VI a lack of data was encountered, namely the lack of available flame spread data for the hydraulic hoses. Considering the frequent use of hydraulic hoses on mining vehicles, this lack of data could possibly be solved by conducting flame spread experiments with and without hydraulic oil as the influence of the hydraulic oil will also have to be analyzed.

Regarding the depiction of the heat release rate of a mining vehicle, a suitable criterion for the end of the incipient phase should be analyzed further. Establishing a suitable criterion will be important when determining the heat release rate, as the exit from the incipient phase is distinguished by a clear increase in the heat release rate. A criterion based upon the change of heat release rate over time could possibly be applied, as suggested in Paper II. Also the difference in the retard index when varying the distance between the fuel items will have to be looked into further. In Paper III an initial decrease in the difference in the dn value was found, where an increase was expected.

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This research journey has been long and not always clear and distinguished. The aim has varied and at times it has been tough, facing ill will and disbelief. But the journey has also been full of rewards, meetings with inspiring people, experiencing situations and seeing things that I will cherish during the rest of my life. The journey that started with a wildfire on a mountain slope in Washington state in June 1989 has taken me from the deep gorges of Hells Canyon to the dense forests of Minnesota, from the iron mines in northern Sweden to the nickel mines in Ontario and the coal mines in France, from the Highveld of South Africa to the endless wilderness of River of No Return. I have been privileged to meet and work with people such as Daniel Rogers, Edward Christy, Aaron Boots, Joseph Nielsen, Joseph Carvelho, Mark Whitney, Johan Heine, Tore Eriksson, Per Cederlund, Lars Aidanpää and many, many others.

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