DESIGN FIRES IN UNDERGROUND HARD ROCK MINES

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Abstract

During several decades considerable research activities have been conducted with respect to fire behaviour and fire safety in coal mines, but the research activities with respect to hard rock mines have been limited. As the hard rock mines are getting deeper and the complexity is growing the need for deeper understanding of fires in underground hard rock mines are getting more in demand. One of the more urgent demands is the need for more specific heat release rate curves as design fires. Thus fire experiments are in great need and also any possible method that would allow for the calculation of the total heat release rate curve of an object such as a mining vehicle. This thesis presents a number of examples on design fire curves applicable to underground hard rock mines; it also presents the results of model scale fire experiments as well as methods for calculating the total heat release rate of several fuel objects at uniform as well as non-uniform conditions. Tests were carried out in a 1:15 model scale tunnel using piles of wooden pallets as fire load. The parameters tested were the free distance between piles of wooden pallets and longitudinal ventilation rate. It was found that an increasing ventilation rate also increases the peak heat release rate. When studying the curves of heat release rates it was found that when the distance between the ignited pile and the second pile to ignite increased to a certain level the ignition of the second pile will be delayed resulting in that the peak heat release rate of all the adjacent piles will not occur simultaneously. In cases with short distances between the piles the ignition of adjacent piles took place almost simultaneously and resulted in a total heat release curve where all the following piles burn at their maximum practically simultaneously. The ignition data indicated that the time to ignition of adjacent piles would decrease as the longitudinal ventilation was increased.

A number of possible methods for calculating the total heat release rate were investigated, where the results from the model scale fire experiments were used for validation. The comparison was carried out in two steps, each one resulting in a scientific paper. The first step was to compare the method for uniform conditions using tests carried out in 2002, and the second step was to use the data obtained here for non-uniform conditions. A method using a critical heat flux as ignition criterion exhibited very good agreement with the corresponding fire experiments for both uniform as well as non-uniform conditions. This shows the feasibility of the method when constructing an overall heat release curve for uniformly as well as non-uniformly separated solid objects in longitudinal flow in a tunnel or a mine drift configuration. The methods using the ignition temperature as ignition criterion did not agree very well with the corresponding fire experiments with uniform conditions as well as non-uniform conditions. But the accuracy improved considerably – in the case of non-uniform conditions - as the distance between the piles of pallets was increased. Several suggestions on further work are discussed and brought forward.
This thesis is based on the following papers and reports:

**Appended:**

**Paper I**
An Engineering tool to calculate heat release rates of multiple objects in underground structures

R Hansen, H Ingason
Fire Safety Journal, 2010

(Accepted) (Full peer review process)

**Paper II**
Overview of fire and smoke spread in underground mines

R Hansen
Proceedings from the Fourth International Symposium on Tunnel Safety and Security, Frankfurt am Main, Germany, March 17-19, 2010

(Accepted) (Peer review of Abstract)

**Paper III**
Heat Release Rates of Multiple Objects at Varying Distances

R Hansen, H Ingason
Fire Safety Journal, 2010

(Submitted) (Full peer review process)

**Not appended:**

**Report I**
Literature survey – fire and smoke spread in underground mines

R Hansen
MdH SiST 2009:2

**Report II**
Site inventory of operational mines – fire and smoke spread in underground mines

R Hansen
MdH SiST 2010:1

**Report III**
Design fires in underground mines

R Hansen
MdH SiST 2010:2

**Report IV**
Smoke spread calculations for fires in underground mines

R Hansen
MdH SiST 2010:07

**Report V**  
Model scale fire experiments in a model tunnel with wooden pallets at varying distances  
R Hansen  
H Ingason  
MdH SiST 2010:08

**Report VI**  
Final recommendations – GRUVAN project  
R Hansen  
MdH SiST 2010:09
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Overview of the thesis

The work presented in this thesis was performed between the autumn of 2007 and summer of 2010 at the School of Sustainable Development of Society and Technology at Mälardalen University, except for the model scale experiments which were conducted at the Fire Technology laboratory of SP Technical Research Institute of Sweden in Borås. The thesis aims to elaborate on the subject of design fires in underground hard rock mines.

The first two chapters deal with the background for carrying out the research work and a description of the problem with fires in underground mines. These chapters are aimed at giving the reader a broad understanding of the subject area and specific knowledge about design fires in underground mines. Most of the knowledge is obtained from the technical Reports I-IV and VI, which were not appended to this thesis.

In chapter three a number of suitable design fire scenarios are developed for different parts of a mine. The position of the design fires with respect to adjacent installations, egress, interruptions in the production etc and the influence of ventilation on the fire growth and its influence when working out the design fires is discussed. All of the results are obtained from Report III.

Although a great deal of the thesis work was obtained to map the knowledge about fires in mineral mines, the most important scientific part of the thesis is found in the two journal Papers I and III and the proceeding Paper II. The focus was on developing a methodology to create design fires by calculating the total heat release rate of several separate fuel objects. In order to validate the model, fire experiments were carried out to produce a number of heat release rate curves in order to validate the tentative methodologies. Also comparison with tests available from other research was carried out. Chapter four presents the essential results of those scale model experiments, which were carried out in a model tunnel at scale 1:15. During the experiments scaled down pallets – scale 1:4 of a full size EUR pallet – placed in piles were used as fuel elements. Each pile of pallets contained the same amount of pallets and was placed in the model tunnel with longitudinal ventilation. In order to obtain the heat release rate of a single pile of wooden pallets under varying ventilation velocities, single piles consisting of five pallets were burned in the model scale tunnel at different centreline ventilation velocities.

Chapter five presents the results of validating the empirical models to be used for calculating the heat release rate of multiple objects, using the results from chapter four and the results of earlier performed fire experiments at SP Fire Technology.
1 Introduction

The fire safety problems in mines are in many ways very similar to the problems discussed in road, rail and metro tunnels under construction. There is usually a limited amount of escape routes and the only safe havens are the safety chambers consisting of steel containers with air supply within and rescue rooms which have a separate ventilation system and will withstand a fire for at least 60 minutes.

Rescue operations are hard to perform when the attack routes often equal the possible paths for smoke to reach the outside. The possibilities for safe evacuation and a successful fire and rescue operation are strongly linked to the fire development and smoke spread in these kinds of facilities.

The main problem with mines today is that they have become more and more complex, with endless amount of shafts, ramps and drifts, and it is difficult to control which ways the smoke and heat spread in case of a fire. The ventilation strategy is of the greatest importance in such cases, in combination with the fire and rescue strategies. Since there are fortunately few fires that occur, there is little experience of attacking such fires in real life. New knowledge about fire development and smoke spread in complex mines consisting of ramps is therefore of importance in order to create reasonable strategies for the personnel of the mining company and the fire and rescue services. The main experience from preventing and fighting mine fires comes from coal mines, which are usually quite different in structure compared to mines in Sweden which are all hard rock mines. In Sweden mines consist of either active working mines with road vehicle traffic and elevator shafts for transportation of people and products or old mines allowing visitors. In some cases it is a combination of both types.

As the mine industry is changing and challenging techniques are developed, the measures to guarantee the safety of personnel needs to be adjusted. The new technology means new types of fire hazards, which in turn require new measures to cope with the risks. New equipment means new types of fire development and heat release rates. The knowledge about fire development in modern mines is limited. There is a lack of applicable heat release rate curves. The fire development of vehicles transporting material inside the mines is usually assumed to be from ordinary vehicles, although the vehicles may be considerably different in construction and hazard. The difference may be mainly in the amount of liquid (e.g. hydraulic oil, diesel fuel) and the size of the rubber tyres. Thus there is great need for applicable design fires in underground mines. Therefore, any method that could be used for calculating the resulting heat release rate of multiple objects in underground mines would be of great use.

The motivation to perform the series of model scale experiments was to validate empirical models that could be applied in future attempts to determine resulting heat release rates for large
scale multiple objects in underground mines. The models could be used when determining the overall heat release rate of construction vehicles, calculating the ignition time of the different components of the vehicle and adding the individual heat release rate curves. The heat release rate curves could then for example be used for determining the smoke spread in the mine, the time available for evacuation etc.

1.1 Aim

This thesis mainly deals with design fires in underground hard rock mines. The issue of design fires is an important part of the fire safety in underground hard rock mines, and this is discussed in chapters 2 and 3. These chapters provide a basic knowledge about design fires, the importance of design fires etc.

The thesis aims to elaborate on the subject of design fires in underground hard rock mines. It also aims to supply tools for determining design fires in underground hard rock mines and to improve fire safety in mines in order to obtain a safer working environment for the people working for the mining companies in Sweden or for visitors in mines open to the public.

1.2 Method

The methods used in this thesis are literature surveys, site inventories, hand calculations, simulations and model scale experiments.

The software used in this thesis is a mine ventilation network simulation program – Ventgraph – [1] and a computational fluid dynamics program – FDS [2].
2 Background

The risk of fires in underground mines has been known for a long time. Fires in underground mines have in the past resulted in numerous disasters. During the twentieth century the work on making underground mines safer resulted in great progress. An example is the US Bureau of Mines (USBM), which was established following the aftermath of two great mining disasters. During the time period when the USBM was active the safety in mines was improved considerably. Also several legislative measures were undertaken in many countries, which also had a great impact on the positive trend regarding the safety in mines.

The aftermath of some mine fires also lead to progress in some specific fields, for example when after the Sunshine mine fire disaster in 1972 an extensive work started with developing a software tool that could simulate the interaction of mine fires and ventilation system. The end result was the MFIRE software.

In table 1 below some examples of historical mine fire disasters in hard rock mines are listed.

Table 1. Some examples on devastating fires in hard rock mines [3-11].

<table>
<thead>
<tr>
<th>Date</th>
<th>Site</th>
<th>Number of fatalities</th>
<th>Sequence</th>
<th>Type of mine</th>
</tr>
</thead>
<tbody>
<tr>
<td>October 12th 1912</td>
<td>Mount Lyell Mine; Tasmania, Australia</td>
<td>42 miners killed</td>
<td>The fire started in a pump house at the 700 ft level.</td>
<td>Copper mine</td>
</tr>
<tr>
<td>June 8th 1917</td>
<td>Granite Mountain Mine; Montana, USA</td>
<td>168 miners killed</td>
<td>A shaft fire caused by ignition of oil soaked insulation on a power cable. The shaft was the main intake airway which led to a rapid spread of smoke throughout the mine.</td>
<td>Gold mine</td>
</tr>
<tr>
<td>August 27th 1922</td>
<td>Argonaut Mine; California, USA</td>
<td>47 miners killed</td>
<td>A fire occurred in the main shaft which was the main intake airway and the smoke spread rapidly throughout the mine. The cause of fire could not be fully established.</td>
<td>Gold mine</td>
</tr>
<tr>
<td>February 10th 1928</td>
<td>Hollinger Mine, Ontario,</td>
<td>39 miners killed</td>
<td>No local or regional resources existed at the time to fight the fire. Mine rescue resources from Pittsburgh had to be called in. As a result an Ontario mine</td>
<td>Gold mine</td>
</tr>
<tr>
<td>Date</td>
<td>Location</td>
<td>Miners Killed</td>
<td>Description</td>
<td>Type</td>
</tr>
<tr>
<td>------------</td>
<td>---------------------</td>
<td>---------------</td>
<td>-----------------------------------------------------------------------------------------------</td>
<td>----------</td>
</tr>
<tr>
<td>June 1945</td>
<td>Braden Mine; Chile</td>
<td>354 miners</td>
<td>An oil container being warmed up ignited at a maintenance shop just outside the portal of the lower production level.</td>
<td>Copper</td>
</tr>
<tr>
<td></td>
<td></td>
<td>killed</td>
<td></td>
<td>mine</td>
</tr>
<tr>
<td>April 23rd 1947</td>
<td>Malartic Mine; Quebec, Canada</td>
<td>12 miners killed</td>
<td>A fire started in a lunch room and smoke quickly filled a shaft nearby.</td>
<td>Gold</td>
</tr>
<tr>
<td>March 5th 1968</td>
<td>Belle Isle Mine; Louisiana, USA</td>
<td>21 miners killed</td>
<td>The fire occurred in the only shaft existing in the mine. The cause of fire was never determined.</td>
<td>Salt</td>
</tr>
<tr>
<td>May 2nd 1972</td>
<td>Sunshine Mine; Idaho, USA</td>
<td>91 miners killed</td>
<td>The fire occurred below the 3100 feet level.</td>
<td>Silver</td>
</tr>
<tr>
<td>September 16th 1986</td>
<td>Kinross Mine; South Africa</td>
<td>177 miners killed</td>
<td>The fire was caused by a welding accident that lead to a gas explosion. The fire occurred in a passageway connecting two main shafts and quickly spread to three other levels.</td>
<td>Gold</td>
</tr>
<tr>
<td>November 22nd 2004</td>
<td>Shahe Mine; China</td>
<td>49 miners killed</td>
<td>The fire was caused by the ignition of wooden supports from sparks from electric cable.</td>
<td>Iron</td>
</tr>
</tbody>
</table>

Even if the safety in coal mines world-wide has improved considerably, there are still countries with mine industry showing a very high rate of accidents. Examples are China where the miners are even today put to great danger.

A fire in an underground mine will pose several hazards and problems both to the evacuating personnel and to the rescue personnel. The research so far has mainly been aimed at coal mines and thus the need for new knowledge regarding fires in hard rock mines is in great demand. In Paper II an extensive literature study is found with respect to earlier studies regarding fire safety and fire behaviour in underground hard rock mines. Some of the most important findings in Paper II and Report I are summarised below.
2.1 Statistics and fire causes

A report by GRAMKO [12] lists the Swedish statistics of fires in the mining industry in Sweden. During 2001-2005 there was an average of 35 fire incidents per year below ground. Figure 1 below displays the number of fire incidents below ground (black), above ground (grey) as well as the total number of fire incidents (red) during the period 1990-2005 (the reported fire incidents include all fires ranging from the very small fire extinguished easily by the personnel to the devastating fires destroying an entire vehicle, installation etc.). The number of serious incidents has decreased and the number of minor incidents has increased during the last years. The major fire causes are low voltage electrical circuits and hot surfaces, representing 44 out of 80 fires. Concerning fire objects, vehicle fires stand for 35% of the total number of fire incidents. Among the vehicle fires, a hot surface is the dominating fire cause. During the period 2001-2006 the following types of vehicles were most common in vehicle fires:

1. Service vehicles (e.g. cars, pickups, smaller lorries)
2. Drilling rigs
3. Loaders (diesel)
4. Loaders (electric)
Figure 1. Number of fire incidents in the Swedish mining industry, 1990-2005 [12].

In the report by de Rosa, 2004 [13] all types of fires in underground hard rock mines in the US were examined. The most common fire causes were:

- Hydraulic fluid/fuel sprayed onto equipment hot surfaces (25%)
- Hot works (20%)
- Electrical short circuits/arcing (19%).

Most common type of equipment involved in fires were mobile equipment and most common locations of fire were mobile equipment in working areas (place where the extraction of the mineral takes place).

From the USA the report by de Rosa, 2004b [14] examines the mobile equipment fires for all US surface and underground mines. A total of 24 equipment fires occurred in underground metal/non-metal and rock mines, involving mostly scoops, locomotives, haulage or utility trucks, loaders and power scalers. Most fires were caused by pressurized hydraulic fluid sprayed onto equipment hot surfaces (50%) followed by electrical short/arcing and other flammable liquids on hot surfaces.
Based upon the two articles regarding statistics from US mines, a conclusion is that the most common type of fire object is a vehicle and the most common fire cause is hydraulic fluid/fuel sprayed onto a hot surface. Most common place for a fire is mobile equipment in working areas.

From the United Kingdom comes the report by Thyer [15], which lists statistics on underground mine fires in the UK (hard rock mines). During a ten year period (1992—2002) there were a total of 23 fires. Out of those 11 occurred in vehicles and 6 occurred due to electrical causes.

Regarding the statistics from New South Wales in Australia, an Australian article [16] lists the statistics on mobile equipment fires together with ignition source statistics. The statistics comprise the time interval 1990-2001. From the statistics it was found that 46% of the fires were caused by flammable liquid sprayed onto a hot surface. Out of those fires 50% occurred in loaders. The second largest fire cause was electrical shorting.

References [15] and [16] confirm the findings that the most common type of fire object is a vehicle and the most common fire cause is hydraulic fluid/fuel sprayed onto a hot surface.

### 2.2 Fuel loads and heat release rates

The fire load of a burning vehicle will dictate the duration of the fire if the fire is fuel controlled (excess access to oxygen). If the fire is ventilation controlled (limited access to oxygen) the mass flow of air will have a major impact on the duration of the fire. The heat release rate dictates for example the smoke layer temperature, the descent of the smoke layer, possible fire spread to adjacent items etc. Thus the heat release rate will largely dictate the fire behaviour in an underground mine.

The environment in underground hard rock mines generally consists of non-continuous fuel loads – occasional flammable objects with non-combustible hard rock sections in between. The few places with continuous fuel loads are for example larger workshops with several vehicles, storage facilities, office buildings, parking drifts with large number of vehicles. Even though the environment typically consists of a limited number of islands of flammable objects the fuel objects underground can have considerably high energy content, such as large loader tyres, storage areas with flammable liquids etc. The maximum heat release rate of fuel objects underground can in some cases be several tens of megawatts - such as in the case of larger pool fires and fires in larger vehicles – causing great problems to the personnel in the mine and to the fire and rescue personnel.

Based primarily on the findings of Report I and II the following types of fuel loads in an underground mine were identified as of higher interest, based upon the amount of combustible material and energy content:

- Hydraulic fluid.
- Cab/vehicle.
- Conveyor belt.
- Pools with flammable liquid.
- Cables.

2.2.1 Hydraulic fluid

Hydraulic fluids are used widely and in large quantities in underground mines – for example in drilling rigs, crushers, loaders, draw points etc. Pressurized hydraulic fluid that is ignited will lead to a spray fire. Spray fires are recognised by a rapid development and by higher and steady state heat release rates. The heat release rate of hydraulic fluid spray fires can be determined by the exit fluid velocity and chemical heat of combustion [17]. The efficiency of combustion is sensitive to exit fluid velocity and variations in efficiency of combustion, and combustion intensities are due to variations in the chemical structures and additives, volatility and degree of atomization.

The following empirical relationship has been established [17]

\[
\dot{Q} = 0.11 \cdot \Delta H_{ch} \cdot u_0
\]  

(1)

Further studies have shown that when an open flame is used as the heat source, fluids with lower viscosity are easier to ignite than those with higher viscosities [18]. Regarding hot surface ignition, it was shown to be dependent on the degree of atomization, the relative direction of oil spray with respect to the hot surface and the local flow conditions.

2.2.2 Cab/vehicle

Vehicles are generally found in large numbers in underground mines, especially in mines with a main ramp accessible for vehicles. Vehicles can be found in any part of the mine – production areas, ramps, workshops etc. The vehicles in a mine generally consist of several types – cars, loaders, service vehicles, drilling rigs etc.

During a literature survey only one publication was found that described a full-scale fire experiment with a larger vehicle in an underground mine, despite the fact that the statistics indicate that vehicle fires should have the highest priority when evaluating fire safety. In the report by Svenska Gruvföreningen [19], a full-scale fire experiment with a mobile rescue chamber is described. The experimental fire was in a loader CAT 960, containing 2200 kg rubber and 600 litres of oil. During the experiment the CO-level and temperature inside and outside the rescue chamber were continually measured. The smoke density at the rescue chamber and the airflow in the drift (unidirectional flow) was also measured. Unfortunately the report contains no HRR curves.

The conclusions of the report were:
- The longitudinal velocity was between 1 and 2 m/s depending on the HRR of the fire. The purpose of the longitudinal flow was to steer the smoke in one direction, but it is unclear whether any backlayering was allowed or not.
- The fire had decreased considerably in intensity after 3-4 hours and could then be extinguished with relatively simple fire extinguishing equipment (based upon this time interval, the duration of the air supply in rescue chambers was set to a minimum of 4 hours in Sweden).

2.2.3 Conveyor belt

Conveyor belts can often be found in underground mines and can cover large distances and cause extensive fire spread and smoke production in case of a fire. Even though non-combustible conveyor belts are used the smoke production and spread can be considerable, causing extensive problems to the evacuees and the fire and rescue personnel.

Several experiments were reported in literature in order to determine the heat release rate of conveyor belts. In figure 2 below the heat release rate from a slow-burning chloroprene conveyor belt is shown [20]. The experiment comprised a full-scale experiment with a conveyor belt and the ignition source was a pile of burning wood. A large part of the HRR was due to the burning wood.

![Figure 2. The heat release rate of a slow-burning chloroprene conveyor belt [20].](image)

2.2.4 Pool fires

Pool fires are dependent upon the diameter of the pool, the depth of the pool, the type of surface below it and the physical properties of the liquid. During free burning tests the heat release rate will rapidly reach a constant value that depends on the diameter of the pool and the liquid in question.

The type of surface below the pool will dictate how much of the fuel that will be absorbed into the surface and the size of the fuel surface, for example a gravel surface will decrease the heat
release rate of the pool fire as the distance between the fuel surface and the upper level of the gravel is increased.

The depth of the pool will also affect the heat release rate of the pool fire, a larger depth will result in a higher heat release rate.

Several fire experiments have been conducted with respect to pool fires, developing the following expression for the heat release rate per unit area [21]

\[ \dot{q} = \chi \cdot \Delta H_c \cdot \dot{m}_w \cdot \left(1 - e^{-k_D} \right) \]  

(2)

The assumption that the heat release rate increases with increasing diameter and the expression (2) above, is valid for pool fires with a diameter larger than 0.2 m.

The size of the pool fire will be determined depending on whether the spill is confined or unconfined. A confined fuel release will result in a pool fire with a known area. Besides the issue of confined or unconfined fuel release another determining factor is whether the fuel release is continuous or static with respect to when the pool is ignited. The area of a non-burning pool in case of a continuous spill will increase until a physical obstacle is encountered. A continuous spill that is on fire will reach an equilibrium spill area where the flow rate is equal to the burning rate of the fuel. Generally a confined fuel release will result in a pool with a greater depth than the depth of an unconfined fuel release.

In case of a leakage from a container the flow rate will decrease with time as the level of the liquid descends in the container. The flow rate from a circular hole at the bottom of a container can be calculated using the following expressions [22]

\[ q = 2000 \cdot A_h \cdot k \cdot \left(\sqrt{h} - k \cdot t \right) \]  

(3)

\[ k = \frac{C_s \cdot \pi \cdot D^2 \cdot \sqrt{2 \cdot g}}{8 \cdot A_T} \]  

(4)

For many pool fires the Heskestad flame height correlation is quite useful due to its wide range of applicability [23]

\[ L_f = 0.23 \cdot \dot{Q}^{2/5} - 1.02 \cdot D \]  

(5)

2.2.5 Fire in tyres

Few heat release rate curves for fires in tyres are available.

In a conducted fire experiment a rubber tyre with the dimensions 26.5R25 – used for front wheel loaders – was used, resulting in the heat release curve seen in figure 3. The tyre was ignited by burning diesel fuel in a pan with gravel.
Figure 3. The heat release rate of a front wheel loader tyre [24].

A fire in a tyre occurs at the surface and its area will decide the heat release rate. An approximate value of the maximum heat release rate is possible to decide by estimating the maximum tyre area involved in a fire and multiplying with a factor 0.11-0.21 MW/m² [24].

When calculating the radiative heat flux from a rubber tyre an approximate expression has been developed [24]

\[
\dot{q}^* = \eta \cdot \frac{\dot{Q}}{4 \cdot \pi \cdot x^2}
\]  \(6\)

The critical heat flux of natural rubber – which could be assumed to correspond well to a tyre as natural rubber generally is a major component in sidewalls and the tread part of a tyre [25] – can be set to 17.1 kW/m² [26].

2.2.6 Cable fires

Electrical cables can be found in large numbers in underground mines, in cable shafts, cable vaults etc. A cable fire in an underground mine may be severe and cause extensive smoke spread depending upon the type of insulation, orientation and amount of cables and the ventilation rate. The heat release rate curve found in figure 4 (curve H5) is an example of a cable fire where a
horizontal cable tray was used, containing a mixture of low voltage, telephone and data cables and with a ventilation velocity of 1.5 m/s.

![Comparison H5-H6](image)

Figure 4. The HRR curve for a mixture of various types of cables on a horizontal cable tray (curve H5) [27], curve H6 describes the HRR for the same mixture of cables but with a ventilation velocity of 3 m/s.

### 2.3 Smoke spread in underground mines

The smoke spread in underground mines will dictate the egress safety and the likelihood of successful intervention by the rescue services. Fire and rescue operations are hard to perform as the number of possible attack routes is generally very limited and the possible attack routes often equal the paths for smoke to reach the outside. The smoke spread and available tools for steering the smoke spread will be decisive for the likelihood of a safe evacuation and a successful fire and rescue operation. The complex nature of an underground mine with endless amounts of shafts, ramps and drifts, makes it difficult to successfully steer the smoke in a desired direction. Further information with respect to ventilation systems and smoke control in underground mines can be found in a study by Nyman [28].
2.3.1 Ventilation systems in underground mines

A ventilation system in an underground mine is meant to control the level of gas and dust contaminants, temperature and humidity. A mine ventilation system is generally very large and complex. The system may contain several hundred airways, nodes and meshes. The ventilation system can be designed in various ways depending on the type of mine, whether shafts are used or not etc. For example in the Kiruna mine there are two ventilation systems operating in the mine production area and one system that operates the facilities of the infrastructure part. The shafts look similar independently of what part you are looking at. When it comes to the amount of blower or exhaust fans at the different levels, it varies from one to two fans per level. The area above the 775 level (the level system in the Kiruna mine gives reference to the distance between the top of the mountain Kiirunavaara and the level in question) is supplied by fresh air from an older ventilation system which is complicated to steer at a possible fire. Along the main ramps the intake air is taken from intake air shafts and pushed upwards along the main ramp using fans. PVC tubes are connected to the fans in order to obtain a better effect. The fans are positioned at certain positions along the main ramp.

2.3.2 Ventilation phenomena in underground mines

The behaviour of the smoke spread in a mine drift is largely determined by smoke stratification. The smoke stratification on the other hand is highly dependent upon the air velocity in the mine drift and the position relative to the fire. Three typical air velocity ranges are identified when describing smoke stratification:

- Low or no forced air velocity (0-1 m/s). Within this range the smoke stratification is high in the near area of the fire.
- Moderate forced air velocity (1-3 m/s). Within this range the smoke stratification in the near area of the fire is largely affected by the air velocity.
- High forced air velocity (>3 m/s). Within this range the smoke stratification is low downstream from the fire. [29]

The smoke stratification will also be dependent on the distance from the fire to the point of interest, and further away from the fire the vertical temperature gradient will decrease and thus also the smoke stratification.

Another influencing phenomenon is the so called backlayering, i.e. smoke travelling in the opposite direction of the longitudinal ventilation flow. Backlayering usually occurs when the air velocity is within the low or moderate range. Backlayering may cause severe problems to the rescue personnel when trying to extinguish a fire or rescue victims.

A fire with a high heat release rate may cause two types of effects that will influence the smoke spread as well as the ventilation:

- Throttle effect.
- Buoyancy effect.

The throttle effect is caused by the increase in volume of the air mass as it passes through the fire site. The increased volume in the mine drift immediately downstream of the fire site requires additional ventilation pressure to overcome the throttle effect and maintain the flow. The throttle effect occurs at the area closest to the fire site.

The buoyancy effect occurs in a mine drift with an inclination where the heat from the fire causes an increase in the temperature and thus a decrease in the density of the air and the smoke downstream of the fire. This effect will work with the ventilation in rising drifts and work against the ventilation – causing reversal - in declining drifts.

2.3.3 Movement of fire gases in a ventilation network

The movement of fire gases in an underground mine will be influenced by several different factors such as: heat exchange with the rock wall, friction losses, presence of water, mixing with the surrounding air, the direction and velocity of the ventilation flow.

The heat exchange with the surrounding rock wall will be determined by factors such as the rock properties (temperature, thermal conductivity and diffusivity), airflow rates and the heat release rate of the fire. Regarding the heat exchange with the surrounding rock several studies have been conducted in this field. In an article Xintan and Greuer [30] approached the problem of describing the heat transfer between mine air and mine rock in connection with efforts to provide transient-state simulations of ventilation systems. A rigorous mathematical approach was used, and it was proved that general solutions can be obtained.

In an article by Wolski [31] a simple method for determining air temperature gradients along a tunnel with time-dependent intake air properties is presented. The variable intake air properties may be the flow direction and rate, air temperature and humidity, and the carbon dioxide content. The transient intake air properties are simulated by a series of steady intake air conditions, using a superposition method. The mathematical model was verified by reduced-scale experiments in the Waldo mine – an experimental and research mine situated near the town of Magdalena, New Mexico- where several fire experiments were conducted during the early 1990’s. The method is best suited for rough estimates where the computation speed is more important than the precision of the results. The model constitutes part of the fire simulator of the PCVENT program.

The friction losses will depend on parameters such as the length and friction factor of the airway, its temperature, perimeter, cross-sectional area, inclination and airflow rate. The resistance can change due to the temperature increase or decrease in a mine drift (i.e. the throttle effect). Also the buoyancy effect will have an influence on the friction losses in a mine drift.
The mixing of fire gases and surrounding air is determined by the smoke stratification which is dependent upon the velocity of the ventilation flow and the distance to the fire.

2.3.4 Smoke control in underground mines

In case of a fire in an underground mine the ventilation system will play a very important role in order to improve the environment to the personnel and the fire and rescue personnel. During evacuation a widely used concept is to let the ventilation system run without changes, in order to avoid that the flow directions change or that the ventilation velocity exceed the velocity of the evacuating personnel. When the evacuation phase is finished the ventilation system may be changed in order to improve the environment to the fire and rescue personnel attempting to extinguish the fire or rescue personnel that has taken cover in a refuge chamber. In some mines it is possible to oversteer the existing ventilation system and for example reverse the fans and thus change the direction of the ventilation flow. An important tool when using the ventilation system and its fans to control the smoke spread in an underground mine is a ventilation plan. A ventilation plan contains an instruction on how to steer the smoke in the right direction in a specific area of the mine. When working on a ventilation plan a mine fire simulator will be of tremendous help as the complexity is considerable for a large mine ventilation network and a non-steady state fire.

In order to increase the chance of a successful ventilation operation during a mine fire, early detection of the fire is essential. Early detection will mean that the evacuation will be finished at an earlier stage and thus the ventilation system can be used sooner for smoke control.

Besides using fans and the existing ventilation system for fire control in an underground mine there are other tools available such as inflatable feed-tube partitions that can rapidly block large openings and simultaneously provide a feed-tube for high-expansion foam generators.

2.4 Modelling of fires in underground mines

When quantifying the smoke spread the calculation models are divided into two main groups based upon the number of possible dimensions: one- and two-dimensional calculation models and three-dimensional (CFD, Computational Fluid Dynamics) calculation models. The difference between the models is that they are based upon different assumptions and algorithms, for example the one- and two-dimensional calculation models may not always account for stratification. Below some of the important findings of Report IV are summarised.

2.4.1 Hand calculations for one dimensional bulk flow

If assumed that the bulk flow of the fire gases is completely mixed – which is the case for the furthest region from the fire where there is insignificant stratification and the smoke layer has
descended to the floor level - the average gas temperature and visibility can be calculated as a function of the distance from the fire.

The average gas temperature over the entire cross-section at the fire can be calculated using the following equation [29]

$$T_{avg, x=0}(\tau) = T_a + \frac{2}{3} \frac{Q(\tau)}{m_a \cdot c_p}$$  \hspace{1cm} (7)

The transport time, $\tau$, is calculated using the following expression

$$\tau = t - \frac{x}{u}$$  \hspace{1cm} (8)

The average gas temperature over the entire cross-section of the drift or the tunnel at distance $x$ from the fire and at time $t$ can be calculated using the following equation, assuming that the wall temperature is the same as the ambient temperature [29]

$$T_{avg}(x, t) = T_a + \left[T_{avg, x=0}(\tau) - T_a\right] \cdot e^{-\frac{h \cdot P \cdot x}{m_a \cdot c_p}}$$  \hspace{1cm} (9)

The average visibility over a cross-section in a mine drift or a tunnel (at location $x$) can be calculated using the following expression [29]

$$V = 0.87 \cdot \frac{u \cdot A \cdot H_{ec}}{Q(\tau) \cdot D_{mass}}$$  \hspace{1cm} (10)

In Report IV these algorithms were used for quantifying the smoke spread and the temperature profile in mine drifts for a number of design fire scenarios in an underground mine. The result was compared with the output from a CFD program and from a ventilation network simulation program.

2.4.2 Computational Fluid Dynamics (CFD)

Computational Fluid Dynamics (CFD) models are used to simulate and predict fluid flows, heat transfer, chemical reactions etc. The number of applicable areas is vast; you will find it being used in areas such as aerodynamics, hydrodynamics, marine engineering, meteorology, combustion and fire dynamics.

As with other tools a CFD models, it must be used with caution due to the limitations of the underlying assumptions. After a simulation the user must make a judgement whether the results are reasonable or not. Thus a validation of the results must be conducted, if possible comparing with experimental results or field measurements. It is important to know that calculation results
from CFD models can never fully replace results from fire experiments, but CFD can work as a powerful complement when solving fire problems [32].

A CFD model is based upon a number of governing equations representing the conservation laws of physics:

- The mass of the fluid is conserved.

- The rate of change of momentum equals the sum of the forces on a fluid element.

- The rate of change of energy is equal to the sum of the rate of heat transfer to or from and the rate of work performed on or by a fluid element.

The governing equations contain the viscous stress components. Substitution of the stresses results in the well known Navier-Stokes’ equations.

The issue of turbulence can be solved by for example Large Eddy Simulations (LES) where a spatial filtering operation obliterates the smaller eddies [32].

### 2.4.3 FDS

A widely used CFD model is FDS (Fire Dynamics Simulator) [2]. FDS solves numerically a form of the Navier-Stokes equations suitable for the low-speed, thermally driven flow connected with smoke and heat transport from fires.

Turbulence can also be solved by means of the Smagorinsky form of the LES. It is also possible to perform a Direct Numerical Simulation (DNS) if the underlying numerical mesh is fine enough to solve the unsteady Navier-Stokes equations. In DNS the simulations compute the mean flow and turbulent velocity variations.

FDS uses a single step chemical reaction the products of which are tracked via a two-parameter mixture fraction model. The mixture fraction is a conserved scalar quantity that represents the mass fraction of one or more components of the gas at a given point in the flow field.

The radiative heat transfer is in most cases solved through the radiation transport equation for a gray gas.

The result of FDS can be presented in a separate visualization program called Smokeview.

In Report IV this program was used for quantifying the smoke spread and the temperature profile in mine drifts for a number of design fire scenarios in an underground mine. The result was compared with the output from hand calculations and from a ventilation network simulation program.
2.4.4 Ventilation network simulation program

The mine ventilation system of an underground mine is often referred to as the mine ventilation network. The mine ventilation network consists of a complex system of airways, fans and other installations. The purposes of the network are to ensure adequate supply and quality of air, and to provide a tool for smoke evacuation [33].

When solving a complex mine ventilation network, parameters such as the characteristics of the flowing air, airways, fans; the relationship of flows and head losses in series and parallel circuits etc. are combined and solved iteratively using an equivalent of Kirchhoff’s current and voltage laws [33]. The sheer complexity of a mine ventilation network generally makes it solvable only by using applicable software. Most software programs use techniques such as the Hardy Cross iterative technique to converge to a solution, i.e. the airflow, pollutant and temperature distributions. The software can either assume compressible air or incompressible air. All mine ventilation network software assumes unidirectional flows in the mine drifts, thus not accounting for the flow situation near the fire where multidirectional flows can be found. Most software assumes immediate and complete mixing of gases, thus not accounting for the issue with stratified flow.

Some software’s are based upon the assumption of constant airflow rates – either the airflow rates that prevailed before the fire or those which result from an equilibrium between fire-generated thermal forces and ventilating forces. The first assumption would apply to the early stages of a fire. The second assumption means combining steady-state with real-time calculations.

2.4.5 Ventgraph

A widely used mine ventilation network software is Ventgraph [1].

Ventgraph is an integrated set of computer programs providing tools for solution of ventilation problems in mines. Ventgraph uses earlier work from Polish scientists [34] regarding the description of phenomena influencing unsteady processes of flow of air and mixtures of air and fire gases.

When working on fire simulations the user mainly uses three of the modules:
- Module for creation of input data: in this module input data such as the network structures, calculation of resistance values of branches and pressures in nodes etc. are specified by the user.
- Module for design of graphical representation of the mine ventilation network: diagrams can be drawn consisting of branches, nodes, symbols of fans, arrows showing the flow direction etc. [1]
- Fire module: the module consists of for example the following parts:
- Location of the fire: the user will start with pointing out the site of the fire and selecting the kind of fuel burnt among the following options: oil, coal, conveyor belt and wood. Thus no other type of fuel can be selected. The fuel calorific value, the maximum length of the fire zone and a so called fire intensity – using a scale from 0 to 10 – are specified. The assumed content of carbon monoxide and hydrogen in combustion products and a time constant of the fire development are specified. Thus it is not possible to directly specify the heat release rate values of the fire in question. Instead the user will have to adjust the fire intensity value, the time constant of the fire development etc. in order to try to replicate the desired heat release rate curve. Obviously it is very difficult to get an exact copy of the heat release rate curve. A possibility of obtaining a relatively accurate curve is for a pool fire where the heat release rate is fairly constant over a longer time period.
- Fire parameters: this option is similar to the part “Location of the fire”, but can also be used for changing the fire parameters during the simulation (transient effects).
- Sensors: locating and specifying the kind of a sensor and its measuring range.

Temperature, contents of carbon dioxide and carbon monoxide are some examples of parameters that can be measured with the sensors.

In Report IV this program was used for quantifying the smoke spread and the temperature profile in mine drifts for a number of design fire scenarios in an underground mine. The result was compared with the output from a CFD program and from hand calculations.

### 2.5 Extinguishing systems

Extinguishing systems can be found in various places in an underground mine. Depending upon where the risks are identified as unacceptable, extinguishing systems can for example be found in parking drifts, on larger vehicles, in cable vaults etc. The type of extinguishing system varies with the type of combustibles, size of the compartment etc.

When selecting a design fire curve it is important to account for the effects of an extinguishing system. The effect of a sprinkler system on the heat release rate was described in an article by Arvidson [35]. In the article a number of large-scale fire experiments – simulating a fire on a ro-ro deck of a ship containing heavy goods freight trucks and trailers - are described. Parameters such as the water discharge density and whether the goods was shielded or not were investigated. The experiments showed that where the fires were fully exposed to the water spray there was a clear relationship between the level of sprinkler performance and the water application rate. For example a discharge density of 10 mm/min provided fire suppression, i.e. the fire decayed after the sprinkler activation. The goods used in the experiments conducted by Arvidson [35] were cartons filled with Polystyrene cups.
The fire decay caused by an extinguishing system can be expressed as [36]

\[
\dot{Q} = \dot{Q}_{\text{act}} \cdot e^{-\frac{1}{3}\left(\frac{1}{2} - \frac{1}{3}\right)}
\]

(11)

\[
\tau = \frac{3.0}{\mu^{1.85}}
\]

(12)

The correlation is based on work by Evans [37] and the test commodities were wood cribs and office fuel packages.

### 2.6 General theory: Design fires

An extensive study regarding design fires was conducted in Report III. A summary is given below.

In the literature, different aspects of design fires are described.

Fitzgerald [38] defines the design fire as the load against which to evaluate the active fire protection and the resultant risk to exposed people, property, and building operations. More specifically, a design fire describes assumed fire characteristics such as for example the heat release rate, smoke generation etc. both in time and in space.

Klote and Milke [39] emphasize that during the initial stage of the work, performance criteria will have to be established. The following work will then focus on the development and analysis of design alternatives to meet the earlier established criteria. Several criteria can be addressed and a different set of design fire scenarios can be required for each criterion.

The Technical Committee ISO/TC 92 [40] points out that the design fire characteristics can be modified during the process based upon the outcome of the analysis. For example, if flashover in an enclosure is likely, it is necessary to modify the design fire in order to account for the characteristics of ventilation controlled or fuel controlled post-flashover fire.

A full specification of the temporal evolution of a design fire is described by ISO/TC 92 [40] as to include the following phases:

- Incipient phase;
- Growth phase;
- Fully developed phase;
- Decay phase;
- Extinction.

Figure 5 displays an example on a design fire, with its different phases.
2.6.1 Identifying and defining tentative design fire scenarios

When identifying possible fire scenarios, several tools can be used. In an SFPE publication [41] some examples are given:

- Historical fire incident data for the specific facility and associated processes or equipment could be used. Operational manuals and checklists for processes or equipment could be used when identifying possible fire causes.
- Statistical data.

Following selection of the design fire scenarios the next step will be to describe the assumed characteristics of the fire on which the scenario quantification is based. These assumed fire characteristics are referred to as “the design fire”.

Figure 6 displays the overall process of identifying and selecting design fire scenarios.
In NFPA codes [42], [43] an interesting approach is presented, where a number of required design fire scenarios are described in detail. The design process is not only limited to the listed design fire scenarios in the codes, but also other applicable design fire scenarios for the specific situation could be included. The approach of NFPA 101 and 5000 could very well be suited for use in mines, but would need some adjustments due to the special nature of the facilities.

2.6.2 Quantifying the fire

If calculations are necessary in the process, two general approaches for accomplishing this are available - probabilistic and deterministic.

In SFPE publication [41] the deterministic approach is defined as resting upon analysis based on physics and chemistry or correlations developed from fire experiments to predict the outcome of a fire. Fire scenarios can be evaluated for use as design fire scenarios by determining whether the
results of a given scenario exceed the performance criteria. In a deterministic analysis, the probability of the possible fire scenario does not need to be evaluated.

The probabilistic approach typically deals with the statistical probability that a fire will occur and the outcome, if a fire does occur. A probabilistic approach could for example use data sources such as statistical and historical information, hazard/failure analysis and risk.

The deterministic approach seems to be most appropriate as the actual number of fires in underground mines in Sweden is relatively small and thus evaluating the frequency of a possible fire scenario could be difficult.

ISO/TC 92 [40] states that design fires are usually characterized in terms of the following variables with respect to time:

- heat release rate;
- toxic species production rate;
- smoke production rate;
- fire size;
- temperature;
- heat flux.

Regarding the rate of heat release, Fitzgerald [38] says that the rate of heat release for growing fires is often represented – i.e. for design purposes - by an exponential or power law. This represents an upper bound to the large range of possible, actual fire growths in the scenario. ISO/TC 92 [40] says that the decay is often assumed to begin when 80% of the available fuel has been consumed. This value is of course very dependent on fuel type, configuration and ventilation conditions. The rate of decay may be taken as a linear decline over a time period where the integral of the heat release rate over the decay period equals the 20% of remaining energy in the fuel.

ISO/TC 92 [40] discusses the location of the fire. The location of the fire typically involves characterization of the compartment in which fire begins, as well as characterization of the specific location of the fire within the compartment.

2.6.3 Smoke generation and smoke spread

The design fire characteristics for a smoke movement analysis are described by Fitzgerald [38] to include factors such as a relationship of time and the volume of smoke generation, visibility and smoke temperature.

Visibility is the most appropriate and useful tenability measure with respect to life safety. The following questions should be asked regarding tenability:
- What possible smoke movement paths to the target room can be identified?
- Will enough smoke reach the boundaries of the target room to make that room untenable?
- If enough smoke can reach the boundaries of the target room, will enough smoke accumulate in the target room to make it untenable?

### 2.6.4 Fire protection

Fitzgerald [38] lists fire protection as for example fire detectors, automatic suppression systems, structural frame behaviour and fire brigade extinguishment.

ISO/TC 92 [40] discusses the effect of an automatic suppression system on the heat release rate. The heat release rate following activation of a sprinkler system can be assumed to remain constant, unless it can be showed that the sprinkler system has been designed to suppress the fire within a specified period. In the latter case, the heat release rate can be assumed to for example decrease in a linear manner over the specified period.

With respect to fire brigade extinguishment Fitzgerald [38] states that it evaluates the building’s ability to work with the local fire brigade. The performance measure for a building is the fire area and number of rooms destroyed by the fire before the fire is extinguished. Barrier fire endurance is rarely a factor in fire propagation to adjacent rooms within the time frame associated with fire brigade suppression.

### 2.6.5 Probability, consideration of consequence and risk ranking

The issue on probability is discussed to some extent by ISO/TC 92 [40]. The probability of occurrence of each event should be estimated using available data such as fire incident data.

ISO/TC 92 [40] says that when estimating the consequence of each scenario, available loss data should be used. The consequence should be expressed as for example the possibility for life loss or injury or the expected cost.

One important tool when identifying important design fire scenarios during the qualitative design review stage is to construct an event tree. An event tree represents alternative event sequences from fire ignition to the final outcome of a fire scenario. Events define changes in the characteristics of the fire, the status of systems and features, the responses of occupants etc.

In SFPE publication [41] the response of people is discussed. The actions that people take can have a significant impact on the course of the fire or the movement of smoke and should be considered in this step. Factors such as number of occupants, familiarity, commitment etc may describe the occupant characteristics.
Furthermore in SFPE publication [41] factors such as the influence of trained staff etc are discussed. Depending on the nature of the building environment, trained staff or an industrial fire brigade can have a large influence during the early stages of a fire. Positive actions by municipal fire personnel can also be considered, particularly for objectives related to property protection or business continuity. On the other hand, poorly trained staff or casual visitors can for example leave key doors open, allowing for rapid fire development and smoke spread. Any of these effects will largely affect the outcome and can introduce new tentative fire scenarios.

2.6.6 Final selection and documentation

For each fire safety objective, the highest ranked fire scenarios are selected for quantitative analysis. The selected scenarios should represent the major portion of the total risk.

Based on what is described in chapters 2.6.1 through 2.6.5 it was possible to come up with a method to determine and quantifying suitable design fire scenarios for an underground mine.

2.6.7 Previous research on design fires

Extensive studies have so far been conducted with respect to design fires in various types of installations and premises such as tunnels, commercial stores etc. But no research has been found with respect to design fires in underground hard rock mines.

Zalok, Hadjisophocleous and Lougheed [44] performed an extensive study including series of experiments to develop data to characterize design fires for different types of commercial premises – based upon an extensive fire load survey. The results showed large differences in burning characteristics of different stores. In the study the fire growth rate, the emission of products of combustion etc from the fire in different types of premises is presented.

Ingason [45] presented a paper where different mathematical tools to represent design fires were described. The different mathematical tools for representing design fires were:

- Linear curve
- Quadratic curve
- Exponential curve
- Exponential constant curve

The different tools were compared with earlier performed tunnel fire experiments. A conclusion in the paper is that the exponential representation of a complete design fire curve is recommended as it gives a more realistic shape of the curve. The material from this paper could very well be used when for example reconstructing the heat release rate curve of an object in an underground mine.
Hertzberg, Sundström and van Hees [46] presented a report where a number of methods and models for creating design fires were described. The report especially presented models and tools that use test data from the ISO5660 cone calorimeter method in order to characterise the fire behaviour of involved materials and creating design fires. Using particular fire characteristics of materials as input data makes it possible to tailor fire curves for a specific compartment instead of relying on very general design fire curves.

Hertzberg, Axelsson and Cohe [47] presented a report where small-scale data were used when simulating two different large-scale fire tests with a CFD code. Good agreement was generally reached when comparing with experimental data, earlier zone model simulations and the results from a tool using data from cone calorimeter experiments [46].

Cheong, Spearpoint and Fleischmann [48] presented a study regarding design fires for vehicles in road tunnels. The study presents an overview of the methodology to estimate the heat release rate of a vehicle fire in a road tunnel using a performance based approach where firstly a risk analysis is performed and thereafter CFD modelling is executed. This in order to determine the heat release rate accounting for factors such as ventilation conditions, geometry etc. The results from the CFD modelling were compared with the corresponding results from the Runchamar fire experiments [49] and found to reasonably estimate the fire characteristics.

Carvel [50] presented a paper regarding design fires for tunnel water mist suppression systems, where instead of focusing on the peak heat release rate the focus was shifted to the characteristics of the growth rate. The paper reviews the growth rates of a number of performed tunnel fire experiments and makes observations with respect to the influence of ventilation on the growth rates, finally proposing a number of design fires for water mist systems.

Even though the publications above are mainly aimed at tunnels, the results from them could be used for underground mines as well, for example when reconstructing a heat release rate curve using a CFD tool or accounting for the effects of an extinguishing system. One of the main concerns in fire safety in tunnels as well as for underground mines is vehicle fires. Thus applicability of the material is very high with respect to underground mines.
3 Design fires in underground mines

The main risk to people in an underground mine during a fire is poor visibility and smoke inhalation. Suitable criteria with respect to life safety (egress) would then be visibility and toxic gas concentrations. The focus – when establishing the design fire scenarios - should be on determining the spread of the smoke.

Regarding continuity of business, suitable criteria could be the chlorine level in the smoke - as this will have a large effect on the surroundings and may demand extensive decontamination and thus longer interruptions in the production – and the damages caused by the heat from the fire.

As the costs due to interruptions in the production generally by far exceed the costs due to property damage in the mining industry, only the life safety aspect and the continuity of business aspect seem relevant to use when working out design fire scenarios for underground mines. During contingency planning for underground mines it is obvious that the main objective is to get the production started again since a tremendous amount of money will be lost for every day that production is stalled. The possible loss of market shares enhances this main objective even more. In contrast to building applications - where pre-flashover fires are of primary interest for life safety analysis - for mining applications fully developed fires are also of interest for life safety because of the large smoke spread distances involved. Fully developed fires will also have an impact on the mining structure, equipment and structural components.

The occurrence of flashover is highly unlikely in underground hard rock mines due to the limited amount of flammable material (both in quantity and spatial coverage). Thus the flashover phenomenon should generally not be considered during the work on the design fire scenarios in underground mines.

The relatively low temperatures generated from smouldering fires and the case where smoke is being spread longer distances in mine drifts, mean that there is little buoyancy in the combustion products and thus little likelihood of smoke stratification under the mining roof as with hotter fires. This will increase the hazards to personnel during egress and must be considered during the development of design fire scenarios.

The growth of a fire in a mine is highly dependent on the arrangement of the combustibles and the way oxygen can be drawn in. As the fire grows in size, the rate of growth accelerates. If the fire remains localised to the item first ignited, the fire becomes fuel-controlled and decays after a certain period of burning. However, if the fire spreads to other combustible items, this may cause onset of rapid transition from a localised fire to the combustion of several other items nearby. But as the fuel in underground mines is generally limited with respect to spatial extent, a majority of the design fire scenarios will deal with fires limited to the item first ignited.
Regarding the human factor, the influence of mining personnel, fire brigade etc on the development of a fire will most likely be smaller than when comparing with a facility above ground. The major reasons for this are:

- The fact that the number of miners working at one time in the mines is low and it is only in a few places that miners are present throughout most of the day’s hours.

- The time it takes for the fire brigade to arrive at the scene of the fire is considerable and will at least not affect the fire during the early phases. This will also limit the number of possible actions available to the fire personnel.

**3.1 Accounting for different types of installations and equipment**

With respect to existing fire statistics, possible design fire scenarios should mainly focus on fires caused by flammable liquid sprayed onto a hot surface, electrical shorting/arcing and hot works according to Report I.

The difference in type of ventilation system, fuel load, fire statistics etc should be considered when evaluating different parts of a mine, such as the production area and the infrastructure part.

According to Report II, large amounts of wood in two iron ore mines were found at for example the transport level, at the visitor mine, some shafts and in most warehouses. Larger amount of tyres were found at some workshops and depots. Self extinguishing conveyor belts were found at the distribution levels, transport drifts and loading areas. Larger amount of cables are found at pumping stations, media shafts, crusher level and cable vaults. Larger amount of flammable liquid were found at the tank stations, draw points, the main ramp, shaft hoisting level, media drift, production area and larger workshops and warehouses. Three sites were identified with having a much higher density of people than the other parts of the mines: the visitor mine, canteens and the main ramp. The following types of installations were chosen as being representative based upon the recommendations from Report II: warehouse, workshop, visitor mine, cable shaft and vaults, canteen, main ramp, pumping station, crusher level, tank stations, draw points, media drift, distribution level and shaft hoisting level. Besides the specific installations vehicles were also chosen as being representative for design fire scenarios for an underground mine. The reasons for this are that vehicles are found in large numbers throughout every mine, they are not restricted to a certain number of places underground and the fire statistics puts them high on the risk list. According to Report I the types of mobile equipment to focus on should be: service vehicles, drilling rigs and loaders.
3.2 Factors influencing the consequences of various design fire scenarios

In Report III the following influencing factors were used during the selection process of representative design fire scenarios for various types of installations and equipment in two iron ore mines:

- Maximum HRR.
- Number of people in the area.
- Growth of HRR.
- Fuel load.
- Smoke spread.
- Smoke production.
- Fire spread.

Based upon the result of the selection process the following design fire scenarios were selected for further studies since they showed the largest number of negatively influencing factors, i.e. a high maximum HRR, a large number of people in the area, a rapid growth of HRR, high fuel load, extensive smoke spread, extensive smoke production and a fast and extensive fire spread:

- Vehicle fire in the main ramp.
- Pool fire in the main ramp.
- Pool fire at a tank station.
- Pool fire in the media drift.
- Vehicle fire in the media drift
- Pool fire at the distribution level.
- Pool fire in a shaft hosting level.
- Vehicle fire in the production area.
- Pool fire in the production area.
- Vehicle fire in a parking drift.

3.3 The positioning with respect to ventilation

Generally the differences in the ventilation system within a mine should be regarded when selecting tentative design fire scenarios. The ventilation system may for example be different in the production area compared with the infrastructure area. The ventilation system may also be different at different levels of the mine.

Within a certain area the position of the fire with respect to the ventilation should be regarded when developing suitable design fire scenarios (for example positioning the fire at certain distances from the end of the intake air tube).
The impact on the fire behaviour of a change in the ventilation system – for example a ventilation tube being burnt up in an area - should be regarded when working on suitable design fire scenarios.

The influence of the ventilation system on the evolution of the fire should be included as well as the influence on the smoke spread.

3.4 The positioning with respect to active fire protection

If it is possible to oversteer the ventilation system, the function and impact should be included and investigated in areas where this possibility exists.

The impact of a sprinkler system should be considered when developing suitable design fire scenarios for sites such as parking drifts, larger workshops etc.

3.5 The positioning with respect to surrounding risks

Surrounding risks may consist of adjacent fuel objects with a high fuel load, possibility of a rapid fire growth or an extensive smoke spread. The following types of fires and sites were identified in Report III as examples for the two iron ore mines of LKAB in Kiruna and Malmberget:

- Vehicle fire in a parking drift with densely parked vehicles.
- Vehicle fire in a heavy vehicle positioned in a workshop with several adjacent heavy vehicles.
- Rack storage fire in a warehouse.
- Larger vehicle running into a diesel tank in a main ramp, causing a pool fire and a vehicle fire.
- A pool fire at the distribution level causing a fire in a conveyor belt and thus resulting in an extensive smoke production and smoke spread. This type of fire was brought forward due to the risk of an extensive smoke spread.

3.6 The positioning with respect to sensitive surroundings

When evaluating sensitive surrounding sites and factors such as sites with high density of people, business continuity etc. should be regarded.

In Report III the following scenarios were listed as examples:
- Vehicle fire on the outside of a visitor mine or a canteen.
- Pool fire in a drift outside the canteen.
- A vehicle fire (heavy vehicle) in a main ramp.
- A pool fire in a main ramp.
- Pool fire in a pumping station.
- Larger vehicle fire at the track level.
- Pool fire that also involves conveyor belts at the distribution level.
- Cable fire in a cable shaft.

### 3.7 Representative design fire curves

In Report III a number of specific design fire scenarios were finally picked out for further studies and quantification, based upon a selection process where for example the ventilation, active fire protection, surrounding risks, sensitive surroundings, rapid fire growth and extensive smoke spread were regarded.

The following design fire scenarios were selected for further studies and quantification:

- Pool fire in a main ramp (involving a diesel tank).
- Vehicle fire (heavy vehicle) in a parking drift which is protected by a sprinkler system.
- Vehicle fire (loader/drilling rig) in the production area.
- Cable fire at the visitor museum, with no automatic fire alarm at the site of the fire.
- Vehicle fire (bus) outside the visitor museum.

The main criteria for the selection of each design fire were the maximum HRR, the number of people in the area, the growth of HRR, the fuel load, the smoke spread and smoke production, the fire spread, the positioning with respect to ventilation, sprinkler systems and sensitive surroundings. In the following chapters a summary of the development of the design fire curves is found. A full description of the development is found in Report III.

### 3.7.1 Pool fire in the main ramp

The chosen site of the pool fire was along one of the main ramps, where a diesel tank containing 6 m³ of diesel is situated. The tank was assumed to be punctured at the bottom, resulting in a leakage from a circular hole with a diameter of 10 mm.

Calculating the flow rate through the hole (assuming an initial liquid height of 1.5 m in the tank, a horizontal surface area of 5 m² and a flow contraction coefficient of 0.7) using equation (3) and (4), results in the following spill flow as a function of time:
Figure 7. The spill flow as a function of time.

Concluding that the depth of the pool fire will be a thin fuel bed, it is assumed that the fuel depth will correspond to a heat release rate per m² fuel of 0.25-0.30 MW/m² for a diesel fire [51], [52]. Calculating the maximum spillage area using an expression by Ingason [53]

\[
A_{\text{max}} = \frac{q \cdot \rho}{1000 \cdot \dot{m}} \quad (13)
\]

The calculations resulted in a maximum spillage area of ~7 m². This will imply a maximum heat release rate of 1.75-2.1 MW. The peak value of 2.1 MW was used when constructing the heat release rate curve, as a conservative approach.

Studying the growth phase and decay phase of a diesel pool fire in figure 3 presented by Lönnermark, Kristensen, Helltegen et al. [54] the duration of the growth phase and decay phase respectively was assumed to be ~30 seconds.

The following heat release curve of the diesel pool fire would result for the first hour (figure 8):
3.7.2 Vehicle fire in the production area

Regarding the vehicle fire – involving a heavy vehicle - in the production area, the site of the fire was chosen in a transversal drift – underneath a PVC-tube - in a random production area. The fire is thus assumed to burn off the PVC-tube at the site.

The ventilation in the production area differs depending upon whether you are in a longitudinal drift (along the footwall) or in a transversal drift (across the ore from the footwall to the hanging wall). In the transversal drift the air is distributed using fans and PVC-tubes. The tube has a length of approximately 200 m in each direction. Where the tube ends, air is being ejected. The ventilation velocity in the transversal drift is \( \sim 0.24 \, \text{m/s} \). In the longitudinal drift air is transported into the drift and ejected approximately 30 metres from the end of the drift. The ventilation velocity in the longitudinal drift is \( \sim 0.2 \, \text{m/s} \) according to Linnsén [55].

Assuming first that the vehicle in question is a loader (a Toro 0011), a summation method presented by Ingason [45] was used in order to establish the heat release rate curve.

The fire was assumed to start by the ignition of leaking hydraulic oil from a burst hose, the hydraulic oil spreading and forming a pool at the left rear tyre. The fire spreading further on to the right rear tyre and then on to the hydraulic hoses and other hoses in the front part of the vehicle. Finally the left, front tyre and the right, front tyre are also ignited. It is assumed that the fire load of the cab is low and thus it will not contribute significantly to the heat release rate.

The pool fire underneath the left, rear tyre:

The loader is equipped with a hydraulic oil tank containing 450 litres of hydraulic oil [18]. It was assumed that the leaking hydraulic oil was more or less instantaneously ignited by for example a
hot surface. Assuming that the hydraulic pump will run continuously during the fire and that the leaking hydraulic oil comes from an hydraulic hose with an inner diameter of 1/2", a working pressure of 190 bar, a density of 760 kg/m³ and a hole diameter of 0.5 mm, the fluid velocity was calculated to ~220 m/s - using the Bernoulli equation – which corresponds to a massflow of ~0.03 kg/s. Calculating the maximum spillage area using an expression by Ingason [53] resulting in a maximum spillage area of ~0.7 m². Assuming a heat release rate per unit area of 1 MW/m² for a pool fire with hydraulic oil [52], results in a maximum heat release rate of 700 kW.

Resulting in the following heat release curve of the hydraulic oil pool fire for the first hour:

![Pool fire graph](image_url)

Figure 9. The heat release rate of the pool fire at the left, rear tyre.

The fire in the tyres:

When calculating the maximum heat release rate of a fire in one of the tyre, a maximum heat release rate per exposed surface area – presented by Ingason [24] - of 0.20 MW/m² was used. Estimating the exposed surface of one tyre to be approximately 10.5 m², the maximum heat release rate was calculated to 2.1 MW. Studying the ascent and the general appearance of the heat release rate curve of a fire in a loader tyre presented by Ingason [24], it was found that the initial maximum heat release rate was attained after less than 90 minutes (the first peak value at ~3 minutes was mainly contributed by the diesel fire). The weight of the tyre was estimated to ~700 kg [56]. Using a heat of combustion of 27 MJ/kg [24], the energy content of a tyre is calculated to 18.9 GJ.

The heat release rate curve of the tyre fire is then constructed based upon the peak value and energy content listed above:
Figure 10. The heat release rate of the tyre fire.

The heat release rate curve in figure 10 has the following expression, which is found in Report III

\[ \dot{Q} = 2100 \cdot 4.4 \cdot 2.4 \cdot (1 - e^{-0.00267t})^{3.4} \cdot e^{-0.000267t} \quad (14) \]

When calculating the heat flux from the pool fire and fires in the tyres, only the radiative heat flux from the fire was accounted for as this mechanism will be the dominating one in this specific case. Ignition is assumed to occur when the external radiative heat flux is equal to a critical heat flux, assuming a - \( q_{cr}^* \) - of 17.1 kW/m\(^2\) listed by Babrauskas [26], which applies to natural rubber.

The distance between the flames and the target is set to 0.01 m (which is the distance to the left, rear tyre which was assumed to be ignited first). The critical heat flux was attained almost instantaneously. Proceeding with the same procedure with the other three tyres, the following heat release rate curve was calculated:
Figure 11. The heat release rate of the fire involving the diesel pool and four tyres.

The fire in the hydraulic hoses and other hoses:

The hydraulic oil container and a major part of the rubber hoses are situated on the right side of the cab. Assuming that the hydraulic hoses and the other types of hoses were made of a mixture of polyvinyl chloride and nitrile rubber, the following heat release curve – presented by Wetterlund and Göransson [57] - was used for the hydraulic hoses and other hoses case:

Figure 12. The heat release rate of the hose fire.

The total weight of the hoses was assumed to be ~60 kg. The duration of the hose fire was ~2 hours. The following critical heat flux value of nitrile rubber – presented by Babrauskas [26] - was used for the hoses: 26.3 kW/m². The construction of the vehicle will shield the hoses from the tyres on the left side. As the hoses are situated on the right side, it is assumed that the hoses will
be ignited by the two tyres on the right side and the pool fire. Assuming a distance between the major part of the hoses and the right, rear tyre of ~0.5 m and a distance of ~1.5 m to the right, front tyre and a distance of ~3 m to the pool fire, the hoses were calculated to ignite after ~ 37 minutes.

Resulting in the following expression and total heat release rate curve for all the involved components of the vehicle:

![Image of HRR curve]

Figure 13. The heat release rate curve of the fire in a loader in the production area.

3.7.3 Vehicle fire in a parking drift

The site of the fire was chosen as a parking drift – at a transportation level - protected by a sprinkler system. Assuming that the vehicle in question is a heavy vehicle corresponding to the loader Toro 0011, resulting in the same heat release rate curve as in figure 13 (for the free burning case).

Calculating the activation time of the sprinkler system:

\[ T_{act} = 341 \text{ K} \]

\[ RTI = 50 \text{ (ms)}^{1/5} \]

\[ r = \sqrt{8} \text{ m} \]

\[ H = 5 \text{ m} \]

Using the following expressions for \( r/H > 0.18 \) [58]:


\[ T_g = \left( \frac{5.38 \cdot (\dot{Q}/r)^{2/3}}{H} \right) + 283 \]  

\[ u = \left( \frac{0.2 \cdot \dot{Q}^{1/3} \cdot H^{1/2}}{r^{5/6}} \right) \]  

\[ \Delta T_d = \left( T_g - T_u \right) \cdot \left( 1 - e^{-\frac{\Delta Q^{0.5}}{K H}} \right) \]  

Using a spreadsheet the following activation time is calculated: \( \sim 60 \) seconds.

The effect of the sprinkler system on the heat release rate curve was accounted for by considering the results of Arvidson [35]. The actual flow rate of the sprinkler system at the 1045 level is 10 mm/min. Thus the case of the heat release rate of the vehicle fire was assumed to decay in accordance to the findings of Arvidson [35] for the non shielded case. The fire decay was calculated using equation (11) and (12). The time interval between the activation of the sprinkler system and when the suppression effects are being noticed is assumed to be one minute, in accordance with the findings of Madrzykowski and Vettori [59].

After 2 minutes the HRR is \( \sim 700 \) kW, resulting in the following heat release curve:

![Fire in a loader, in a drift protected by a sprinkler system](image)

Figure 14. The heat release rate curve of the fire in a heavy vehicle which is parked in a drift that is protected by a sprinkler system.
3.7.4 Cable fire at the visitor museum

With respect to a cable fire outside a visitor museum, a suitable site was chosen to be the drift just outside the museum where no automatic fire alarm exists.

When designing a HRR curve for a cable fire, a horizontal cable tray with a mixture of low voltage, telephone and data cables was assumed. A ventilation velocity of 1.5 m/s was assumed. The HRR curve of H5 in figure 4 - corresponding to the above assumptions - was used during the work.

3.7.5 Bus fire at the visitor museum

Regarding the bus fire at the visitor museum, the site of the fire was chosen to be the drift just outside the museum where the buses park and unload the visitors. There is no automatic fire alarm in the drift in question. A ventilation velocity of 0.3 m/s was assumed for the drift.

Assuming first that the vehicle in question is a Volvo bus (model 8500), the summation method by Ingason [45] was used in order to establish the heat release rate curve.

The fire was assumed to start by the ignition of leaking diesel fuel at the rear of the bus, resulting in a pool fire. The fire spreads further on to the rear tyres, then into the passenger compartment and finally to the front tyres. It is assumed that only the tyres, the diesel and the seats will significantly contribute to the total heat release rate of the bus, thus all other combustible material was not accounted for when constructing the total heat release rate curve.

The pool fire underneath the rear tyres:

The diesel tank of the bus is assumed to contain 500 litres of diesel [60]. It was assumed that the leaking diesel comes out from a hole with an approximate diameter of 10 mm, thus it will form a thin fuel bed (see conclusions for the pool fire in main ramp). The thin fuel depth will correspond to the following heat release rate per m² fuel: 0.25-0.30 MW/m² [51]. The maximum spillage area was calculated to ~2.4 m². Thus the maximum heat release rate is calculated to 0.6-0.72 MW. The peak value of 0.72 MW was used when constructing the heat release rate curve as a conservative approach.

This results in the following heat release curve of the diesel pool fire for the first two hours:
Figure 15. The heat release rate of the pool fire underneath the bus.

The fire in the rear tyres:

The tyre dimensions are: 295/80R22.5 [60], implying a width of 0.295 m, 0.236 m high vertical surface and a rim diameter of 0.575 m. The exposed rubber area is calculated to ~2.17 m². When calculating the maximum heat release rate of the fire in the tyre, a maximum heat release rate per exposed surface area – presented by Ingason [24] - of 0.20 MW/m² was used, resulting in a maximum heat release rate of ~0.43 MW. The maximum heat release rate was assumed to be attained after approximately 30 minutes [61]. The weight of the tyre was estimated to ~57 kg [62]. Using a heat of combustion of 27 MJ/kg [24], the energy content of a tyre is calculated to ~1.54 GJ.

The heat release rate curve of the tyre fire is then constructed, based on the peak value and energy content listed above:
Figure 16. The heat release rate curve of the bus tyre.

The heat release rate curve in figure 16 has the following expression which can be found in Report III

\[ \dot{Q} = 430 \cdot 3.1 \cdot 2.26 \cdot (1 - e^{-0.00063t})^{2.1} \cdot e^{-0.00063t} \] (18)

The same algorithm was used as for the loader tyre when calculating the external heat flux. Assuming a critical heat flux of 17.1 kW/m² and a distance of 0.1 m between the pool fire and the rear tyres, the ignition of the rear tyres was calculated to be almost instantaneous after the ignition of the pool fire, resulting in the following heat release rate curve for the pool fire and the fire in the two tyres:

Figure 17. The heat release rate curve of the pool fire and the fire in the two rear tyres.
The fire in the passenger compartment:

It is assumed that the bus seats will contribute most to the heat release rate of the passenger compartment, thus all other combustible material in the passenger compartment was not accounted for. The passenger compartment is simplified by assuming that it consists of thirteen rows of seats with four seats in each row and with an average distance of ~0.2 m between each row. The critical heat flux of a bus seat is assumed to be 7.8 kW/m² [63]. The following heat release rate curve – presented by Johansson and Axelsson [64] - was used for each bus seat:

![Heat Release Rate Curve](image)

Figure 18. The heat release rate curve of a bus seat [64]. The unit of the heat release rate is kW.

The heat release rate curve in figure 18 was reconstructed mathematically where the heat release rate of the burner was subtracted from the total heat release rate:
Figure 19. The HRR curve of the bus seat reconstructed mathematically and taken from Report III.

\[ \dot{Q} = 230 \cdot 2.12 \cdot 2.04 \cdot (1 - e^{-0.0075t})^{1.12} \cdot e^{-0.0075t} \]  

(19)

The fire is assumed to spread to the passenger compartment from the wheel houses via the floor and the side wall. The ignition of bus seats will occur due to flames occurring through an opening between the wheelhouse and the side wall and side windows [65]. Thus the primary spread mechanism is assumed to be flame radiation.

The Heskestad correlation (equation (5)) was used when calculating the flame height of the tyre fire.

When calculating the flame height of a tyre fire, the mid-height of the tyre was used as the origin. Calculating the flame height and only accounting for the flame part above the wheelhouse, the following graph was produced:
Figure 20. The flame height above the wheelhouse.

The distance – horizontally – between the opening and the closest bus seat is assumed to be 0.1 m. The length of the opening is assumed to be half the diameter of the tyre, i.e. ~0.52 m. The flame is assumed to be of rectangular shape. The radiative part of the total heat release rate is assumed to be 30%.

The radiative heat flux was calculated as a function of time, resulting in the following graph:

Figure 21. The heat flux at the bus seat closest to the flames.

The critical heat flux – 7.8 kW/m² – was exceeded after ~460 seconds. For simplicity the row above the wheelhouse was assumed to be ignited at this stage, via the two wheelhouses in the rear. Assuming that the fire environment of the passenger compartment is a two layer equivalent,
the calculations of the total heat flux from the fire to adjacent seat rows are separated into two parts:

- Radiant heat flux to the seats from the upper gas layer.
- Radiant heat flux to the seats from the flames.

The two radiant heat fluxes are added to receive the total heat flux.

The following equation was used when calculating the radiant heat flux from the upper gas layer to the seats [66]

$$\dot{q}_{\text{gas layer}} = \left[(\gamma + 1) \cdot (1 - \varepsilon) \cdot e^{-1} + \left(F \cdot (1 - \varepsilon_g)\right)^{-1}\right]^{1} \cdot \sigma \cdot T_w^4 + \left[F \cdot e_{g}^{-1} + (1 - \varepsilon) \cdot e^{-1}\right]^{1} \cdot \sigma \cdot T_g^4$$

(19)

We are facing a pre-flashover situation, thus we will use the correlation of McCaffrey, Quintiere and Harkleroad (MQH) [67] in order to calculate the upper gas layer temperature, \(T_g\). The correlation assumes a two zone approximation (a hot zone with an upper, hot gas layer and a fire plume and a cool zone with a lower, cool gas layer) and that the zones are uniform.

$$T_g = T_a + 6.85 \left(\frac{Q^2_{\text{a}}}{A_0 \cdot \sqrt{H_0 \cdot h_k \cdot A_T}}\right)^{1/3}$$

(20)

Assuming a two layer ventilation flow and mass conservation, the position of the interface layer was calculated using the following expression

$$\dot{m}_g = \frac{2}{3} \cdot C_d \cdot A_0 \cdot \sqrt{H_0} \cdot \rho_a \cdot \left[2 \cdot g \cdot \frac{T_a}{T_g} \left(1 - \frac{T_a}{T_g}\right)^{1/2} \cdot \left(1 - \frac{X_N}{H_0}\right)^{3/2}\right]$$

(21)

Using the plume equation of Zukoski [66]

$$\dot{m}_p = 0.0762 \cdot \dot{Q}^{1/3} \cdot z^{5/3}$$

(22)

and assuming that the interface height is equal to the neutral plane height leaves us with the following expression:

$$0.0762 \cdot \dot{Q}^{1/3} \cdot X_N^{5/3} = \frac{2}{3} \cdot C_d \cdot A_0 \cdot \sqrt{H_0} \cdot \rho_a \cdot \left[2 \cdot g \cdot \frac{T_a}{T_g} \left(1 - \frac{T_a}{T_g}\right)^{1/2} \cdot \left(1 - \frac{X_N}{H_0}\right)^{3/2}\right]$$
When calculating the incident radiant heat flux to the seats from the flames it is assumed that the boundaries of the flames of a row of seats on fire have the shape of a rectangle.

$$\dot{q}_{rad} = \frac{\dot{Q}_{rad}}{2 \cdot (A_{\text{width}} + A_{\text{depth}})} \cdot F \cdot \tau$$  \hspace{1cm} (23)

When calculating the flame height the Heskestad correlation was used. Using a spreadsheet when calculating the incident heat flux from the upper gas layer and the flames and assuming a distance of 0.2 m between each row of bus seats, a depth of 0.4 m for each row, an effective width of 2 m and that both doors are open – as egress has taken place – with a height of 2 m and a width of 1 m, the following matrix displays the ignition times of the various rows of bus seats (the rows are numbered starting with the row in the far back and the first row to be ignited is row number six):

<table>
<thead>
<tr>
<th>Row #</th>
<th>Ignition time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>362</td>
</tr>
<tr>
<td>2</td>
<td>311</td>
</tr>
<tr>
<td>3</td>
<td>253</td>
</tr>
<tr>
<td>4</td>
<td>185</td>
</tr>
<tr>
<td>5</td>
<td>100</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>100</td>
</tr>
<tr>
<td>8</td>
<td>185</td>
</tr>
<tr>
<td>9</td>
<td>253</td>
</tr>
<tr>
<td>10</td>
<td>311</td>
</tr>
<tr>
<td>11</td>
<td>362</td>
</tr>
<tr>
<td>12</td>
<td>409</td>
</tr>
<tr>
<td>13</td>
<td>452</td>
</tr>
</tbody>
</table>

Table 2. The ignition times of the various rows of bus seats.

Resulting in the following heat release rate curve for the passenger compartment:
Figure 22. The heat release rate of the passenger compartment.

The fire in the front tyres:

It is assumed that the front tyres will ignite at the time of flashover in the passenger compartment, as flames will most likely burst out of the bus windows and rapidly increase the flame radiation to the front tyres.

Adding all individual heat release rate curves, the following total heat release rate curve of the bus is received:

Figure 23. The total heat release rate of the bus.
Earlier bus fire experiments have been conducted at SP [65] and during the Eureka 499 [68] test program. In figure 24 the experimental results from SP and Eureka 499 are shown together with the calculated total heat release rate curve from figure 23.

![Bus fires](image)

Figure 24. The heat release rate curves from bus fire experiments conducted at SP and within the Eureka 499 test program, together with the earlier calculated total heat release rate curve.

When comparing the different heat release rate curves in figure 24 it can be seen that the general shape of the curves are identical, i.e. a sudden increase at the early stages of the fire followed shortly afterwards with a sharp decline and a slow decay. While the calculated heat release rate curve matches very well the resulting heat release rate curve from the SP fire experiment, the sudden increase in the heat release rate of the Eureka 499 tests takes place at an earlier stage compared with the other two curves. Also the heat release rates from the Eureka 499 tests are at a much higher level than the other two curves. The reasons for these differences could be difference in fire load, ignition source, initial fire object etc.
4 Model scale experiments

This chapter describes a number of model scale fire experiments conducted in May 2010 in a model tunnel at SP facilities in Borås, Sweden. In this chapter a summary is found based upon the findings in Report V.

The main purposes of the experiments were:

- To obtain data which can validate models to calculate the total heat release rate of multiple objects
- To investigate the influence on the heat release rate curve that a varying distance – non-uniform conditions - between the fuel objects will have.
- To investigate the influence on the heat release rate, fire growth rate and time to ignition for adjacent fuel objects. The effects of ventilation are taken into account in the model.

4.1 Scaling theory

The conducted fire experiments were model scale experiments. The use of scale modelling is very convenient as it allows us to translate the results from model scale fire experiments into a full scale system. The scale modelling technique uses the theory of dimensionless groups as a basis.

The model tunnel in the fire experiments was built in linear scale 1:15, which means that the size of the tunnel was scaled geometrically according to this ratio. Neglecting the influence of the thermal inertia of the involved material, the turbulence intensity and radiation, but scaling the HRR, the time, flow rates, the energy content and mass, we end up with scaling models found in table 3.

Table 3. List of scaling models [69].

<table>
<thead>
<tr>
<th>Unit</th>
<th>Scaling model</th>
<th>Equation number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat release rate [kW]</td>
<td>( \dot{Q}_F = \dot{Q}_M \left( \frac{L_F}{L_M} \right)^{5/2} )</td>
<td>(24)</td>
</tr>
<tr>
<td>Velocity [m/s]</td>
<td>( u_F = u_M \left( \frac{L_F}{L_M} \right)^{1/2} )</td>
<td>(25)</td>
</tr>
<tr>
<td>Time [s]</td>
<td>( t_F = t_M \left( \frac{L_F}{L_M} \right)^{1/2} )</td>
<td>(26)</td>
</tr>
<tr>
<td>Energy [kJ]</td>
<td>( E_F = E_M \cdot \left( \frac{L_F}{L_M} \right)^3 \cdot \frac{\Delta H_{v,M}}{\Delta H_{v,F}} ) (27)</td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>---</td>
<td></td>
</tr>
<tr>
<td>Mass [kg]</td>
<td>( m_F = m_M \cdot \left( \frac{L_F}{L_M} \right)^3 ) (28)</td>
<td></td>
</tr>
<tr>
<td>Temperature [K]</td>
<td>( T_F = T_M ) (29)</td>
<td></td>
</tr>
</tbody>
</table>

In table 3, \( L \) is the length scale, the index \( F \) relates to the full scale and the index \( M \) relates to the model scale. Thus in our actual model \( F \) is 15 and \( M \) is 1.

### 4.2 Experimental setup

A total of 12 tests were carried out in a 1:15 scale model tunnel. The parameters tested were the distance between the piles of wood pallets and the longitudinal ventilation rate. Furthermore, the effect of different distances between piles of wood pallets was investigated.

The heat release rate in the fire experiments was determined by measuring the mass flow rate and gas concentrations in an exhaust duct connected to the model tunnel. See Report V for more details.

Longitudinal wind velocities of 0.3 m/s, 0.6 m/s and 0.9 m/s were used in the test series.

According to equation (26), the corresponding full scale velocities were 1.16 m/s, 2.32 m/s and 3.49 m/s.

The tunnel itself was 10 m long, 0.6 m wide and 0.4 m in height. The corresponding full scale dimensions were thus 150 m long, 9 m wide and 6 m high.
Figure 25. The 1:15 model scale tunnel used in the project, photo: H Ingason.

4.2.1 Fire load

The fire load consisted of piles of wood pallets (pine), where each pile consisted of five individual wood pallets. Test fire 1, 4 and 12 were reference tests and consisted of a single pile of pallets, whereas in the other tests the fire load consisted of four piles of wood pallets placed at different distances.

The wooden pallets were geometrically scaled 1:4 using the standard European measurements 1200 mm by 800 mm. These pallets were originally designed and built for use in another project on fire safety on board ships [35].

The scaled-down pallets had an overall dimension of 300 mm by 200 mm by 36 mm (L × W × H).

The total the different piles of wood pallets ranged from 1.651 kg to 1.755 kg. The variation is because each wood pallet was manufactured by hand.
More detailed information about the different tests and piles of wood pallets for each test is found in Report V.

4.2.2 Instrumentation

Various measurements were conducted during each test. The first pile of wood pallets was placed on a weighing platform. In the case when more than one pile of wood pallets was used in the tests, only the first pile was weighed. The temperature was measured with welded type K thermocouples. Four plate thermometers were placed at the floor level during the tests in order to measure the heat flux at the locations. Two bi-directional probes were placed at the centreline of the tunnel. The gas concentrations (O₂, CO₂ and CO) were measured by two measuring probes consisting of open copper tubes, except O₂ at the centre line. They were located at two different heights above the floor. The gas concentrations in the centre of the exhaust duct at the floor level and 3.7 m horizontally away from the tunnel inlet were also measured. See figure 26 below for a graphic description of the instrumentation.

Figure 26. The layout of instruments and measurements (dimensions in mm) [70].

4.3 Experimental procedure

The wood pallets used in each test were dried overnight in a furnace at 60 °C (<5% moisture). Before the tests, the weights of the wooden pallets were measured. In addition, the moisture of the upper wooden pallet was measured with a wood moisture meter. The first pile of wood pallets was placed on the weighing platform. A cube of fibreboard measuring 0.03 m, 0.03 m and 0.024 m was soaked in heptane (9 mL), wrapped with cellophane and was placed on the weighing platform board at the upstream edge of the pile of wood pallets. At 2 minutes from start of the
logging system, this cube was ignited. During tests with several piles of wooden pallets, the time of ignition of adjacent piles were clocked and documented manually. After each test, the left wooden pallets or char were dried overnight and then measured to determine the net weight loss during a fire test. In table 4 a short summary of the main parameters is given.

Table 4. Summary of main parameters for the conducted fire experiments.

<table>
<thead>
<tr>
<th>Test #</th>
<th>$u_c$ [m/s]</th>
<th>Number of piles</th>
<th>Arrangement of piles – free distance</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.3</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>0.3</td>
<td>4</td>
<td>0.6 m between pile #1 and #2; 0.9 m between pile #2 and #3; 0.9 m between pile #3 and #4.</td>
</tr>
<tr>
<td>3</td>
<td>0.6</td>
<td>4</td>
<td>0.4 m between pile #1 and #2; 0.7 m between pile #2 and #3; 0.6 m between pile #3 and #4.</td>
</tr>
<tr>
<td>4</td>
<td>0.6</td>
<td>1</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>0.6</td>
<td>4</td>
<td>0.5 m between pile #1 and #2; 0.7 m between pile #2 and #3; 0.8 m between pile #3 and #4.</td>
</tr>
<tr>
<td>6</td>
<td>0.6</td>
<td>4</td>
<td>0.5 m between pile #1 and #2; 0.8 m between pile #2 and #3; 0.9 m between pile #3 and #4.</td>
</tr>
<tr>
<td>7</td>
<td>0.6</td>
<td>4</td>
<td>0.5 m between pile #1 and #2; 0.8 m between pile #2 and #3; 1.1 m between pile #3 and #4.</td>
</tr>
<tr>
<td>8</td>
<td>0.6</td>
<td>4</td>
<td>0.5 m between pile #1 and #2; 0.8 m between pile #2 and #3; 1.3 m between pile #3 and #4.</td>
</tr>
<tr>
<td>9</td>
<td>0.6</td>
<td>4</td>
<td>0.6 m between pile #1 and #2; 0.8 m between pile #2 and #3; 1.1 m between pile #3 and #4.</td>
</tr>
<tr>
<td>10</td>
<td>0.6</td>
<td>4</td>
<td>0.7 m between pile #1 and #2; 0.8 m between pile #2 and #3; 1.1 m between pile #3 and #4.</td>
</tr>
<tr>
<td>11</td>
<td>0.6</td>
<td>4</td>
<td>0.7 m between pile #1 and #2; 0.9 m between pile #2 and #3; 1.1 m between pile #3 and #4.</td>
</tr>
<tr>
<td>12</td>
<td>0.9</td>
<td>1</td>
<td>-</td>
</tr>
</tbody>
</table>

4.4 Experimental results

In the following a shorter presentation of the test results is given for some of the parameters measured. A more extensive description of the test results are given in Report V.
4.4.1 Reference tests

In order to obtain the heat release rate of a single pile of wood pallets under varying ventilation velocities, single piles consisting of five wood pallets were burned in the model scale tunnel at centreline velocities of 0.3, 0.6 and 0.9 m/s.

The heat release rate results from these tests are shown in Figure 27.

The peak heat release rate from the test with a centreline velocity of 0.3 m/s was 116 kW, which corresponds to 101 MW at full scale according to equation (25), for the test with a centreline velocity of 0.6 m/s corresponding values were 154 kW and 134 MW, respectively, and for the test with a centreline velocity of 0.9 m/s the corresponding values were 169 kW and 147 MW, respectively. The heat of combustion, energy content, full-scale mass and full-scale energy content was calculated for the three reference tests.

The average value of the heat of combustion for the three cases is 18.1 MJ/kg. According to Tewarson [71] the net heat of complete combustion $\Delta H$ for pine is 17.9 MJ/kg and the chemical heat of combustion $\Delta H_c = 12.4$ MJ/kg.

![HRR - Reference tests graph](image)

Figure 27. The heat release rates of the three reference tests.

When studying the graphs of Figure 27, it can easily be seen that the maximum heat release rate increases with an increasing longitudinal ventilation. Also test fire #1 and #4 shows an almost identical fire growth rate, whereas the test fire #12 with the highest longitudinal ventilation displays a slower fire growth rate. This could possibly be explained by the fact that the height of the pile of wooden pallets (205 mm) was practically equal to the short side of the pile (200 mm) and the fire was started on the long side, thus as the longitudinal ventilation is increased less parts of the upper portions of the pile are exposed to the tilted flames, giving the result that less parts participate in the combustion during the growth phase and thus the fire growth rate decreases. Another explanation could be that the cooling effect of increased longitudinal ventilation will
have a decisive influence on the fire growth rate – reducing the fire growth rate - as the number of pallets in each pile stays constant in all experiments.

4.4.2 Heat release rate

When studying the resulting heat release curves it can be seen that the highest heat release rate is recorded for test #3: 504 kW. For test #5 through #11 the maximum heat release rate are ~470 kW. For test #3, 5, 6 and 7 (see figure 28) all pallet piles burn at their maximum almost simultaneously resulting in a total heat release curve where the effects of the delay of ignition is not really showing up in the time to reach maximum heat release rate.

![HRR](image)

Figure 28. The heat release rate curve of test #3, #5, #6 and #7.

For test #8, 9, 10 and 11 the distance between the two first piles has been stretched out, delaying the ignition of pile #2 and resulting in that not all piles are burned with their maximum heat release rate at the same time. The delay in ignition can be distinguished by a “hump” before the peak value in the heat release rate curves. See figure 29 for the resulting heat release rate curves.
Figure 29. The heat release rate curve of test #8, #9, #10 and #11.

It can also be seen that the peak value of the heat release rate decreases to some extent as the distances between the piles are increased – from ~500 kW down to ~450 kW – as the curve is stretched out in time.

4.4.3 Ignition time

When studying the ignition times, it can be seen that for test #2 the longitudinal ventilation was too low in order to obtain ignition of adjacent piles of wooden pallets. For test #3 it can be seen that the distance between the piles was so short that the ignition occurred almost simultaneously – within less than a minute all three piles were ignited - in the three adjacent piles.

The ignition data indicates that the time to ignition of adjacent piles will decrease as the longitudinal ventilation is increased.

Furthermore as mentioned above the maximum heat release rate increases with an increasing longitudinal ventilation and when increasing the distance between the two first piles, the ignition of the second pile will be delayed and resulting in that not all piles will burn with their maximum heat release will be delayed and resulting in that not all piles will burn with their maximum heat release rate simultaneously.

In the following chapter methods for calculating the heat release rate of multiple objects for both uniform and non-uniform conditions are investigated. The experimental data from the performed experiments in Borås is used when validating the methods.
5 Calculating the heat release rate of multiple objects in underground mines

Any method that would allow us to calculate the overall heat release rate of a cargo load, mining vehicle etc. would be of tremendous value as it would allow us to construct heat release rate curves without having to perform full-scale fire tests of the vehicles or other objects. The methods presented in this chapter all assume that the heat release rate curve of the first single object is known a priori from experiments. The first method reconstructs the heat release rate curve for additional sets of adjacent fuel objects by adjusting a retard index. The physical ignition phenomena are included in the mathematical treatment by summing up additional identical fire curves. In real life all heat release rate curves may not be known a priori and conditions cannot always be assumed to be uniform. The other methods – which are described in Paper I – are involving more physics, do not rely solely on summing up single fire curves like the previous method, do not assume uniform conditions and involve more physics.

5.1 Uniform conditions

In Paper I four methods were validated against earlier performed model scale fire experiments [69] involving wood cribs with equal distances.

The first method was proposed by Ingason [45] and estimates the HRR as a single exponential function of time instead of several functions for different time intervals. The method assumes fuel controlled fires, or fires with a small or negligible constant maximum HRR period and uniform conditions. The design parameters are the peak HRR ($\dot{Q}_{\text{max}}$), the total calorific value, $E_{\text{tot}}$ and the retard index, which is an arbitrarily chosen parameter with no physical meaning. Based on these parameters, the time to the peak HRR ($t_{\text{max}}$) and the fire duration ($t_d$) can be calculated. When designing a HRR curve where several objects are included, the retard index governs when the HRR curve of each object starts to develop (the higher retard index, the later the start), i.e. when the fire exits the incipient phase. Thus the method implicitly includes the incipient phase. The time difference when the fire spreads from one object to another is not constant as the difference tends to shorten as the fire spreads from the first object to the second etc. For every object, a value of the retard index is adjusted during curve fitting, so the incipient phase is exited approximately when it is expected that the fire will spread to that specific object. The method is based upon the assumption that the retard index increases linearly, as uniform conditions are a prerequisite. As a result of this assumption the time to ignition of the individual cargo items (objects) will not vary linearly.

Applying the least squares fit technique to three fire tests using a spreadsheet gives the result shown in Figure 30.
Figure 30. The measured HRR and the calculated HRR of fire test number 1, 3 and 4.

The difference in increase of the retard index for each object was found to be best fitted by $n_2 = n_1 + 7$ and $n_3 = n_2 + 7$ - using the least squares fit technique. This difference is an indication of the time delay between the ignitions of the three wood cribs.

As can be seen from the HRR curves in figure 30 the rate of rise of the calculated HRR curves stay constant at the ignition of the second and third wood crib respectively. This is due to the fact that the ignitions of the adjacent wood cribs take place before the peak value of the total HRR curve, thereby making the steepness of the curve constant.

The resulting calculated HRR curve of the method using a critical heat flux as ignition criterion and the measured values of the corresponding test fire – involving three wood cribs - is given in figure 31.
Figure 31. The HRR using the method with the critical heat flux as ignition criterion versus the measured HRR value.

As seen in figure 31, the method agrees very well with the measured values from the corresponding test fire. In order to further verify the results of the method, the total energy content of the calculated HRR curve and the energy content based upon the total mass of the involved wood cribs (i.e. the actual energy content) were compared. One conclusion based on the comparison is that the two methods for calculation of the energy content match well.

Using the calculated ignition time of the second wood crib and the third wood crib, the following retard index values were determined: \( n_1 = 5.1 \), \( n_2 = 10.5 \), and \( n_3 = 15.1 \). These values resulted in the heat release curves shown in figure 32.
Figure 32. The calculated total HRR curve of the summation method and the method using the critical heat flux as critical value.

When comparing the retard index values and the total HRR values with the values from the method using summation of objects HRRs, it is clear that a consistent value of the retard index can be established from the figures above (i.e. a retard index of approximately 5). Also the two calculated HRR curves are very similar.

The third and fourth methods also involve more physics and use ignition temperature as an ignition criterion. In the third method a numerical method was used when solving the applicable equations. The resulting calculated HRR curve and the measured values of the corresponding test fire are shown in figure 33:
Figure 33. The HRR using the method with the ignition temperature as ignition criterion versus the measured HRR value.

As seen from figure 33, the method does not agree very well with the measured values of the corresponding test fire. As for the case with the critical heat flux as ignition the total energy content of the calculated HRR curve and the energy content based upon the total mass of the involved wood cribs were compared and the total energy content of the method was found to match the actual one well.

The fourth method involves an algorithm by Babrauskas and Grayson [72] where the surface temperature of a thermally thick object accounting for a transient heat flux is calculated. The resulting calculated HRR curve and the measured values of the corresponding test fire are shown in figure 34.
Figure 34. The HRR using the method with the ignition temperature as ignition criteria versus the measured HRR value.

As seen in figure 34, the method does not agree well with the measured values of the corresponding test fire. In order to further verify the results of the method, the total energy content of the calculated HRR curve and the energy content based upon the total mass of the involved wood cribs (i.e. the actual energy content) were compared. The energy content of the method matches well the actual energy content.

5.2 Non-uniform conditions

In Paper III three methods were validated against earlier performed model scale fire experiments involving piles of wooden pallets with uniform conditions [35] as well as non-uniform conditions [28] where the distance between the piles was varied.

Figure 35. Uniform conditions and non-uniform conditions.
The first method was the summation method proposed by Ingason [45]. Applying the least squares fit technique to both sets of fire experiments, no consistent increase of the retard index for each object was found in any of the cases.

The second one was the method using a critical heat flux as ignition criterion [69].

When examining the resulting heat release rate curves with the corresponding values of the performed fire tests, it was seen that the calculated values from the tests from Report V fit very well with the measured values but tend to have too long ignition times in the case of short distances and too short ignition times in the case of longer distances. In the case of the tests of Arvidson [35] the calculated values fit very well with the measured values of test #3P(4) but in the case of the other tests it seems like the fires are ventilation controlled and not fuel controlled. Arvidson [35] also suspects in his report that the HRR was affected by the reduction of the access of fresh air.

In order to further verify the results of the methods, the total energy content of the calculated HRR curve and the energy content based upon the total mass of the involved piles of pallets were compared. One observation based on the comparison is that the values of the tests in Report V match very well, but the values from the tests of Arvidson [35] do not. This is also an indication that the fires were in fact ventilation controlled.

The third method was the method using an Abel integral in order to evaluate the surface temperature against an ignition temperature.

When using the Abel integral on the fire test from Report V it was found that the second pile of wooden pallets would not ignite as the surface temperature would not exceed the ignition temperature. When studying the calculations it seems that the longitudinal ventilation velocity was too great to achieve any higher surface temperatures.

But if the ignition times of the second pile from the calculations using the critical heat flux as ignition criterion are used and then the Abel integral is used for calculating the ignition of the third pile higher surface temperatures are achieved and ignition would occur. When comparing the results with the visually observed ignition times, it was seen that the method poorly determines the time of ignition when the distance between the fuel objects is small, but the accuracy improves as the distance increases.

When using the Abel integral on the fire tests performed by Arvidson [35], the resulting HRR curves were seen to some extent match the corresponding measured values.

In summary a number of tentative methods were evaluated when calculating the total heat release rate of an object. One method estimates the total heat release rate curve using a single exponential function of time. The method where the critical heat flux was used as ignition criterion resulted in very good agreement with the corresponding results of performed fire experiments for uniform as well as non-uniform conditions. But in the case of non-uniform
conditions the resulting ignition times tended to be too long in the case of short distances and too short in the case of longer distances. The methods using the ignition temperature as ignition criterion did not agree well with the corresponding experiments for uniform as well as non-uniform conditions, but the accuracy for the non-uniform conditions improved as the distance between the piles increased.
6 Conclusions

This thesis consists of different parts, where some of the results depend on measurements and calculations performed earlier. The conclusions are presented below. Not all questions have been answered and the suggestions for further work are discussed in the next chapter.

6.1 Design fire development and methods

The following conclusions were made based upon the findings of Report I and Report III:

Starting with the statistical material, the most common fire cause in underground mines was found to be flammable liquid sprayed onto hot surface, followed by electrical shorting/arcing and hot works. So based upon the statistics a conclusion would be to focus on spray fires, fire caused by flammable liquid ignited by a hot surface, vehicles fires (including rubber tires) and cable fires.

Continuing with the interesting locations in underground mines, mobile equipment working areas would be first priority due to the high risk of fires in mobile equipment. Furthermore the types of mobile equipment to focus on should be: service vehicles, drilling rigs and loaders.

A major concern was the lack of documented fire experiments in vehicles/mobile equipment. This is essential knowledge when designing new mine sections and overseeing existing sections. Thus there is a great need for applicable heat release rate curves, also because a majority of the fires in underground mines involves vehicles/mobile equipment.

Based upon various aspects and variables connected to underground mines, such as fire protection, ventilation etc the following five design fire curves were suggested as representative for underground mines:

- Pool fire in the main ramp where a diesel tank is involved.
- Vehicle fire – involving a heavy vehicle - in a parking drift which is protected by a sprinkler system.
- Vehicle fire – involving a loader or a drilling rig - in the production area.
- Cable fire at the visitor museum, which is not protected by an automatic fire alarm.
- Bus fire at the visitor museum, which is not protected by an automatic fire alarm.

6.2 Calculating the total heat release rate with uniform conditions.

Theoretical calculations of the HRR of fire load consisting of different objects were carried out and compared with the results from fire experiments using wood cribs. The results of the calculations were summarised as follows in Paper I:

- The method using the critical heat flux as ignition criteria exhibited very good agreement with the corresponding results of performed fire experiments. This clearly shows the
feasibility of the method for the problem when constructing an overall heat release curve for equally separated wood cribs in longitudinal flow in a tunnel or a mine drift configuration.

- The two methods using the ignition temperature as ignition criteria did not agree very well with the corresponding fire experiments. Most likely these methods were not suitable for this specific case due to the fact that ignition of the adjacent wood cribs took place early and therefore the amount of energy accumulated in the wood cribs was limited. The geometrical construction of the wood cribs may also play a role for the heating process. Therefore the idea of using a constant ignition temperature as the ignition criteria for a case with a transient heat flux is not ideal.

- All the prerequisites that were set up were fulfilled: the methods were kept relatively simple to be of practical use, and the cargo does not necessarily have to be of uniform composition.

6.3 Model scale tests with uniform and non-uniform conditions

Fire tests were carried out in a model scale tunnel using piles of wooden pallets as fire load. The parameters tested were: the free distance between piles of wooden pallets and longitudinal ventilation rate.

The effects of different ventilation rates on the fire growth rate and the heat release rate were investigated.

The aims were to obtain data which can be used in future studies to validate models to calculate the total heat release rate of multiple objects, to investigate the influence on the heat release rate curve that a varying distance between the fuel objects will have, and to investigate the influence on the heat release rate, fire growth rate and time to ignition for adjacent fuel objects that increasing ventilation will have.

It was found that an increasing ventilation rate also increases the maximum heat release rate, which is in accordance with the earlier findings of Ingason [69].

Also the ventilation rate will have an influence on the fire growth rate. In the tests the case with the highest ventilation rate displayed a slower fire growth rate than the other two cases. This could possibly be explained by the fact that the height of the pile of wooden pallets was practically equal to the short side of the pile and that the fire was started on the long side, thus as the longitudinal ventilation is increased less parts of the upper portions of the pile are exposed to the tilted flames, resulting in that less parts participate in the combustion during the growth phase and thus the fire growth rate decreases.

When studying the graphs of the various heat release rates it was found that when the distance between pile #1 and pile #2 increased to a certain level the ignition of pile #2 will be delayed resulting in that not all piles are burned with their maximum heat release rate at the same time.
The delay in ignition can be distinguished by a "hump" before the peak value in the heat release rate curves. In cases with short distances between the piles the ignition of adjacent piles took place almost simultaneously, resulting in a total heat release curve where the pallet piles burn at their maximum at practically the same time.

The ignition data indicated that the time to ignition of adjacent piles would decrease as the longitudinal ventilation was increased.

### 6.4 Calculating the total heat release rate with non-uniform conditions

Theoretical calculations of the HRR of fire load consisting of different objects were carried out and compared with the results from fire experiments using piles of wooden pallets. The results of the calculations were summarised as follows in Paper III:

- The method using the critical heat flux as ignition criterion exhibited very good agreement with the corresponding results of performed fire experiments, but tended to have too long ignition times in the case of short distances and too short ignition times in the case of longer distances. This shows the possibility of the method for the problem when constructing an overall heat release curve for variably separated piles of wooden pallets using intermediate distances and with a longitudinal flow in a tunnel or a mine drift configuration.

- The method using the ignition temperature as ignition criteria did not agree very well with the corresponding results of performed fire experiments. But the accuracy improved considerably as the distance between the piles of wooden pallets was increased. Thus the method shows potential when constructing an overall heat release curve for variably separated piles of wooden pallets using long distances and with a longitudinal flow in a tunnel configuration.

- The prerequisite that the burning objects should not necessarily have to be positioned at equal distance was fulfilled.

- The method using the critical heat flux as ignition criterion was shown to have great potential for cases such as the loader scenario or the bus scenario in Report III.
7 Future work

Considerable research activities have been conducted in the past with respect to fire behaviour and fire safety in coal mines. Meanwhile the research activities with respect to hard rock mines have been very few. But as the hard rock mines are getting deeper and their complexity is growing there is an increasing need for deeper understanding of fires in underground hard rock mines. One of the more urgent demands is to develop applicable heat release rate curves for design fires in underground mines. Thus full scale fire experiments are in great need, especially a fire test involving a mining vehicle.

With respect to tentative methods to calculate the total heat release rate curve of an object they should be compared with more fire model experiments and also full scale tests; they should be applied to fires showing slower growth. Further studies and experiments should take place that vary additional parameters besides the distance between the individual fuel objects. The heat release rate curves of design fires involving all common vehicles should possibly be reconstructed using the tentative theoretical methodology. The results of the theoretical models should be validated using results from performed full-scale tests.

The results from the full scale fire experiments should be compared with the corresponding results from one- or two-dimensional calculation models as well as three-dimensional CFD models in order to further validate these models with respect to fires in underground mines. The use of a CFD model together with a ventilation network simulation program should be further investigated. The results should be compared with corresponding fire experiments. The possible use of a CFD model in conjunction with a ventilation network simulation program is a very promising issue that could allow for simulating mine fires with large complexity, possibly keeping the accuracy at an acceptable level without increasing the computational demands to an unacceptable level.

The work on CFD modelling in underground mines has so far been fragmentary; a more extensive work is needed, where:

- The geometry is varied (opening area, inclination, aspect ratio etc.) and made more complicated in the vicinity of the fire.
- Non-steady state fires and larger fires.
- Friction losses/obstacles.
- Heat losses to surrounding rock.
- Changes in ventilation (non-steady state ventilation).

The results should be validated against corresponding full-scale experiments.
Further and deeper studies of the applied mine ventilation network simulation program should be performed, investigating for example the assumptions and calculation models behind the specific software.
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Notation

\( a \) = side of a rectangularly shaped flame (m)
\( A \) = cross-sectional area (m²)
\( A_{\text{depth}} \) = area of the flame along the side of the seat row (m²)
\( A_f \) = flame surface (m²)
\( A_H \) = horizontal surface area of a leaking container (m²)
\( A_{\text{max}} \) = maximum spillage area (m²)
\( A_0 \) = opening area (m²)
\( A_T \) = total area of the compartment enclosing surfaces (m²)
\( A_{\text{width}} \) = area of the flame along the full width of the seat row (m²)
\( b \) = side of a rectangularly shaped flame (m)
\( c \) = distance between the flame and the target (m)
\( c_p \) = heat capacity (kJ/kg·K)
\( C_d \) = ventilation flow coefficient,
\( C_r \) = flow contraction coefficient
\( D \) = diameter (m)
\( D_{\text{mass}} \) = mass optical density (m²/kg)
\( E \) = energy (MJ)
\( E_{\text{tot}} \) = total energy (MJ)
\( F \) = view factor
\( g \) = gravity constant (m/s²)
\( h \) = lumped heat transfer coefficient (kW/m²·K)
\( h_i \) = initial height of a liquid (m)
\( h_e \) = effective heat transfer coefficient (kW/m·K)
\( H \) = height (m)
\( \Delta H \) = net heat of combustion (MJ/kg)
\( \Delta H_c \) = heat of combustion (MJ/kg)
\( \Delta H_{\text{ch}} \) = chemical heat of combustion (kJ/kg)
\( H_{\text{ec}} \) = effective heat of combustion (MJ/kg)
\( H_0 \) = opening height (m)
\( k \) = thermal conductivity (kW/m·K)
\( k\beta \) = material constant for liquid fuels (m⁻¹)
\( L \) = distance between the flames and the target object (m)
\( L_f \) = 50 percentile intermittent flame height (m)
\( m \) = mass (kg)
\( m^* \) = spillage burning rate (kg/s·m²)
\( m_a \) = air mass flow (kg/s)
\( m_{f,\text{max}} \) = maximum mass burning rate (kg/s)
\( m_p \) = plume mass flow (kg/s)
\( m_w \) = fuel burning rate for a large diameter (kg/s·m²)
\[ n = \text{retard index} \]
\[ P = \text{perimeter (m)} \]
\[ q = \text{flow rate (l/s)} \]
\[ q_{cr} = \text{critical heat flux (kW/m}^2) \]
\[ q_{gaslayer} = \text{radiant heat flux from upper gas layer (kW/m}^2) \]
\[ q_{max} = \text{maximum heat flux (kW/m}^2) \]
\[ q_{rad} = \text{radiative heat flux (kW/m}^2) \]
\[ \dot{Q} = \text{heat release rate (kW)} \]
\[ \dot{Q}_{act} = \text{rate of heat release at sprinkler activation (kW)} \]
\[ \dot{Q}(\tau) = \text{heat release rate at time } \tau \text{ (kW)} \]
\[ \dot{Q}_{max} = \text{maximum heat release rate (kW)} \]
\[ \dot{Q}_{rad} = \text{radiative part of the heat release rate (kW)} \]
\[ r = \text{radial distance (m)} \]
\[ RTI = \text{response time index (m}^{0.5}\text{s}^{-0.5}) \]
\[ t = \text{time (s)} \]
\[ t_{act} = \text{time of sprinkler activation (s)} \]
\[ t_{d} = \text{fire duration (s)} \]
\[ t_{ign} = \text{time from ignition (s)} \]
\[ t_{max} = \text{time to maximum heat release rate (s)} \]
\[ t_{p} = \text{thermal penetration time (s)} \]
\[ T_{a} = \text{ambient temperature (K)} \]
\[ T_{act} = \text{activation temperature (K)} \]
\[ \Delta T_{d} = \text{temperature difference of the sprinkler element (K)} \]
\[ T_{s} = \text{temperature of fire gases (K)} \]
\[ T_{u} = \text{surface temperature of ceiling and upper walls (K)} \]
\[ u = \text{fluid velocity (m/s)} \]
\[ u_{c} = \text{centre line velocity (m/s)} \]
\[ u_{0} = \text{exit fluid velocity (m/s)} \]
\[ V = \text{visibility (m)} \]
\[ w = \text{spray density (mm/s)} \]
\[ x = \text{distance (m)} \]
\[ X_N = \text{neutral plane height (m)} \]
\[ z = \text{interface height (m)} \]
\[ \gamma = \text{ratio of the area of floor and the area of ceiling and upper walls} \]
\[ \delta = \text{thickness of compartment walls and ceiling (m)} \]
\[ \varepsilon = \text{emissivity} \]
\[ \varepsilon_g = \text{emissivity of upper gas layer} \]
\[ \eta = \text{ratio of radiative heat flux of the total heat release rate} \]
\[ \rho = \text{density (kg/m}^3) \]
\[ \tau = \text{atmospheric transmissivity} \]
\[ \chi = \text{combustion efficiency} \]
\[ \phi = \text{air-to-fuel mass ratio} \]
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