MÄLARDALENS HÖGSKOLA
ESKILSTUNA VÄSTERÅS

Literature survey – fire and smoke spread in underground mines

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Summary

This report is part of the research project "Concept for fire and smoke spread prevention in mines", conducted by a research group at Mälardalen University.

The project is aimed at improving 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.

This report deals with the first step in the project: the literature survey.

The main purposes of the literature survey are:

- To investigate and present what has been done in the non-coal underground mine fire field in the past.
- To give recommendations on the continued work with regard to fire safety in underground non-coal mines.

A large amount of articles in scientific publications and material on internet were found during the literature survey.
Most of the material was from USA, Canada, South Africa, Australia, Sweden, India, China, Russia and United Kingdom.

The following conclusions were made based upon the findings of the literature survey:

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

There is at the moment no need for any extensive research with respect to the ignitability and flammability of pressurized hydraulic fluids, as an extensive work has already been conducted. Still the type of hydraulic fluid being used in the Swedish mines should be investigated and fire-resistant hydraulic fluid should be recommended being used whenever possible.
The results from the articles can be used when examining the equipment that is used containing hydraulic fluid (i.e. what potential ignition sources can be found on the equipment), what type of hydraulic fluid being used and what actions that can be taken to minimize the risk of a spray fire.

A major concern is the lack of documented fire experiments in vehicles/mobile equipment. This is essential knowledge when designing new mine sections and overlooking existing sections. Thus there is a great need for HRR curves, also due to for example the fact that a majority of the fires in underground mines involve vehicles/mobile equipment.

Taking into account that conveyor belt fires are not a dominating fire cause in non-coal mines and the fact that a very intensive work has dealt with for example ignitability and flammability, HRR curves etc. The focus should not be on this type of design fire during the project. Nevertheless a relatively easy and effortless task would be to investigate and list the principal causes of belt conveyor fires in underground non-coal mines.

Another interesting issue would be to investigate the minimum ventilation velocity for belt surface-to-roof distances much greater than 0.22 m, which is applicable for the LKAB mines. Research material so far has mainly dealt with cases where the surface-to-roof distances are equal to or less than 0.22 m.

Taking into account the enormous volume of cables present in an underground mine and the fact that the statistics put cable fires high on the list, some efforts should be made with respect to this type of fire.

Generally there is a demand for investigation of the friction losses of fire gases in a mine drift (as not all CFD models will be able to take this into account). Further work is needed within this discipline.

When performing full scale experiments in an underground mine, models and equations describing the heat exchange between fire/fire gases and rock should be validated at the same time. The articles *Simplified method to calculate the heat transfer between mine air and mine rock* /18/ and *Modelling of heat exchange between flowing air and tunnel walls* /19/ contain methods for calculating the heat exchange that could be worth looking further into and validating during the future fire experiments.

Regarding the movement of fire gases in a mine ventilation network, the earlier work will have to be supplemented with fire experiments with more complicated and varying geometry (opening area, inclination, aspect ratio), larger test area, reversing/increasing the ventilation, and larger, non-steady state fires are needed. Besides performing the fire experiments the results should also be examined against the results of corresponding CFD/ventilation network simulation program. A practical issue that would greatly affect the fire safety in production areas is the difficulty in preventing smoke spreading from a fire affected production area, as no fire barriers are possible (the blasting taking place every day would destroy the fire barriers), other methods will have to be looked into.

The use of a CFD model together with a ventilation network simulation program would be very interesting to investigate. The results should be compared with corresponding fire experiments. Ventilation network simulation programs could at the same time be validated for a non-coal mine.

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).

Besides the investigation of the above factors the investigation should also include the implementation of CFD models and suggestions on improvements should be made.

Conveyor belts, cables etc. are regulated with respect to their flammability but others are not. In order to get a good picture of the fire risk in Swedish underground an inventory and an investigation should be performed.

The use of fire suppression systems and rapid fire detection systems should be considered for manned cabs in Swedish mines. The reason for this is the rapid fire behaviour of spray fires.

A large part of the earlier mine safety research has been conducted with respect to detecting fires in mines and conveyor belts. No further work is identified at the moment.

As organic material stored in abandoned, backfilled parts of mines could be applicable to tourist mines, the risk of spontaneous combustion is a subject in these cases.

During the search no material related to tourist mines was found.

Finally, the three activities with the highest priority are:

- Conducting fire experiments with respect to cab/vehicle fires, resulting in HRR curves.
- Conducting an extensive work on CFD modelling (validating the results with corresponding fire experiments), 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).
- Investigating the use of a CFD model together with a ventilation network simulation program. The results should be compared with corresponding fire experiments.

Preface

This report is part of the research project "Concept for fire and smoke spread prevention in mines", conducted by a research group at Mälardalen University.

The project is aimed at improving 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.

The following organisations are participating in the project: Mälardalen University, LKAB, Sala Silvergruva, Stora Kopparberget, Brandskyddslaget and Swepro Project Management.

The project has been funded by the Swedish Knowledge Foundation.

Västerås, December 2008

Rickard Hansen

Contents

1. Introduction

Research regarding fire safety in mines has so far mainly been directed towards coal mines. Thus the need for recommendations, models, engineering tools etc for non-coal underground mines are in great need.
The aim of the current research project "Concept for fire and smoke spread prevention in mines" is 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. The fire safety record in mines in Sweden is in general good with very few fire accidents that have occurred. The main reason is that there is a great awareness of the fire safety problems in mines. The awareness comes from the fact that escape routes from mines are generally limited. The reason why there is a limited amount of escape routes is that it is expensive to construct extra escape routes which are not a part of the tunnel mining system. The costs to build extra escape tunnels may be better spent on different safety equipment or systems for fire prevention or evacuation. Such systems can be ventilation systems, fire fighting equipment or rescue chambers located at different places in the mines.

The project consists of different steps, where each step is based on results and knowledge from the earlier steps. The steps are: literature survey, inventory of technical and geometrical conditions, calculation of design fires and smoke spread, model and full scale tests and reports and recommendations. All results will be compared and evaluated against earlier experiences.

This report deals with the first step in the project, i.e. the literature survey.

The main purposes of the literature survey are:

- To investigate and present what has been done in the non-coal underground mine fire field in the past.
- To give recommendations on the continued work with regard to fire safety in underground non-coal mines.

The main source for this survey has mainly been the following organisations, scientific journals and other scientific publications:

- NIOSH
- US Bureau of Mines
- GRAMKO
- HSE
- The Mining Engineer
- Fire Safety Journal
- Journal of Mining Science
- Proceedings of US Mine Ventilation Symposium
- Fire and Materials
- The Journal of The South African Institute of Mining and Metallurgy
- Canadian Mining Journal
- Journal of Fire Sciences
- Tunnelling and Underground Space Technology
- Fire Technology
- Journal of the Mine Ventilation Society of South Africa

The following books have been used during the study:

- *Mine ventilation and air conditioning,* Hartman H.L. et al. (1997), New York, John Wiley&Sons
- *Prevention and combating mine fires*, Banerjee S.C. (2000), Rotterdam, A.A. Balkema
- *Flammability testing of materials used in construction, transport and mining,* Apte V.B. (2006), CRC
- *Subsurface ventilation and environmental engineering,* McPherson M.J. (2007), Springer
- *Mine fires,* D.W. Mitchell (1996), Chicago, Maclean Hunter Publishing Co

The output of the project will mainly consist of: performed tests, written reports and recommendations within the mining companies regarding fire safety work, recommendations and the engineering tools for calculation of fire development and smoke spread in mines, and the mathematical models and the test results for future validation.

1.1 Delimitation

The literature survey covers fire and smoke spread in underground non-coal mines. Material from coal mines, tunnels and surface mines were only included when applicable for underground non-coal mines.

2. Background

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 operation is hard to perform when the attack routes often are equal with the possible path for smoke to reach the outside. The possibilities for a safe evacuation and a successful fire and rescue operation are strongly linked to the fire development and the smoke spread in these kinds of constructions.
For mining companies the problems with evacuation and rescue operations in case of fire are closely linked to policies, work environment protection and their systematic fire safety work. An accident not only can cause injuries, or in the worst case deaths, but also large costs due to production losses, reparations and loss in good-will.

The main problem with mines today is that they have become more and more complicated, with endless amount of shafts, ramps and drifts, and it is difficult to control the way 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 very few fires that occur, the experience of attacking such fires in real life is little. New knowledge about fire and smoke spread in complicated mines consisting of ramps is therefore of importance in order to make reasonable strategies for the personnel of the mining company and the fire and rescue services. The main experience from fighting mine fires comes from old coal mines, which are usually quite different in structure compared to mines in Sweden which mainly work with metalliferous rock products. In Sweden the 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 the challenging techniques are developed, the measures to guarantee the safety of personnel need to be adjusted. The new technology means new types of fire hazards, which in turn requires new measures to cope with the risks. New equipment means new types of fire development. The knowledge about fire developments in modern mines is relatively limited. 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 mainly be in the amount of liquid (e.g. hydraulic oil) and the size of the rubber tyres.

A relatively straightforward conclusion here is that the need for improvements is great and so is the challenge ahead of us.

3. Method

To find out what has been done and what is being done in the fire safety area regarding non-coal underground mines around the world, a literature and an article survey was performed. A large amount of articles in scientific publications were found, some literature and a large amount of material on the internet was also found.
Most of the material was from USA, Canada, South Africa, Australia, Sweden, India, China, Russia and United Kingdom.
The following search tools were used during the search:
- LIBRIS
- ELIN
- Samsök beta
- ebrary
- Google scholar
- Google

The following key-words were used during the search:
- Gruvbrand (Swedish)
- Brand + gruva (Swedish)
- Brandförlopp + gruva (Swedish)
- Mine/s + fire
- Mining + fire
- Underground + fire
- Mining + protection
- Mine + protection
- Mining + hazard
- Mine + hazard

The search was mainly aimed at fire and smoke spread in non-coal underground mines. Material related to coal mines, tunnels etc, were examined if they were deemed applicable to this project.

4. Statistics and fire causes

The report *GRAMKO annual report 2005* /1/ lists the Swedish statistics of fires in the mining industry in Sweden.
During 2001-2005 there was an average of 75 fire incidents per year (also including fire incidents above ground). The average number of fire incidents below ground was for the same period 35 per year. Figure 1 below displays the number of incidents below ground (black), above ground (grey) as well as the total number of incidents (red) during the period 2001-2005.
During the period 1997-2001 the average number of fire incidents was 55 per year.
The number of serious incidents has decreased and the number of less serious incidents has increased during the last years (the latter probably due to better reporting routines). The major part of the increase in fire incidents are those above ground.
The major fire causes are: low voltage and hot surface, 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, hot surface is the dominating cause.
During the period 2001-2006 the following types of vehicles were most common in vehicle fires:

1. Service vehicles
2. Drilling rigs
3. Loader (diesel)
4. Loader (electric)

As mentioned above the most common type of fire is a vehicle fire caused by flammable liquid or material on a hot surface.

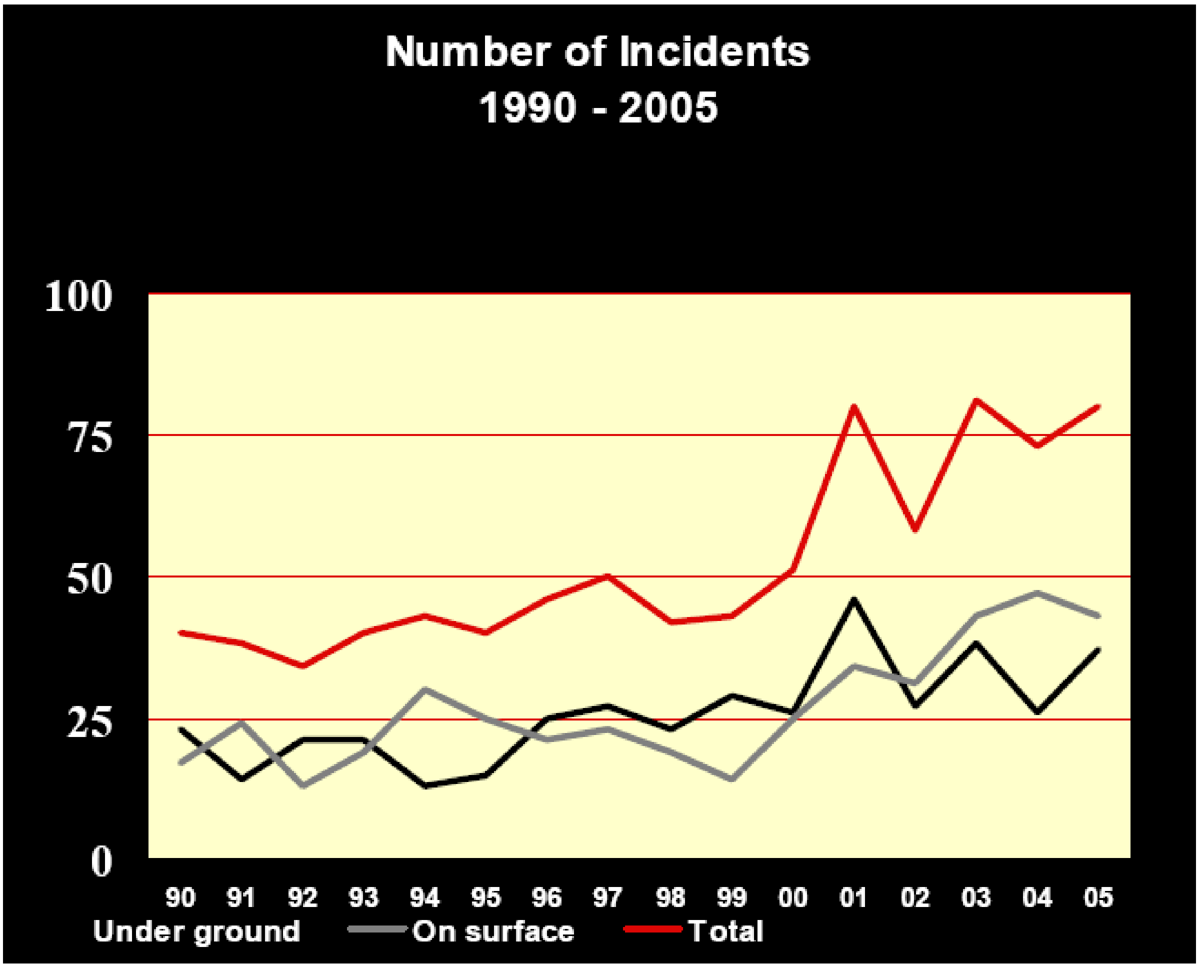

Figure 1. Number of incidents in the Swedish mining industry, 1990-2005 /1/.

In the report *Analysis of mine fires for all US metal/non-metal mining categories, 1990-2001* /3/ all types of fires underground are examined.
A total of 65 fires occurred during the time period.
The most common ignition sources were:

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

Other ignition sources other than hydraulic fluid/fuel included: engine/motor mechanical malfunctions, spontaneous combustion (involving timber), hot material, conveyor belt/equipment friction, heat source (heater), overheated oil, and explosion/ignition of explosives. Fires caused by spontaneous combustion/hot material and electrical short/arcing ignition sources were usually detected long after they had started due to the lack of combustion gas/smoke detection systems.
The most frequent detection method was miners noticing smoke/flames.
Most common type of equipment involved in fires were: mobile equipment followed by oxyfuel torches, beltlines, electrical systems, batteries, chargers, heaters, cutting saws, explosive boxes, and air compressors.
Most common locations of fire were mobile equipment working areas, followed by flame cutting/welding areas, and mine face, section, crosscut and drift areas. Other fire locations were battery and pipeline areas, motor barns, belt entries, shops, refuse and maintenance areas, decline slopes, chute and chrusher areas, panel and tunnel areas, and goblins and abandoned areas.
Most often burning materials were: hydraulic fluid/fuel, electrical cord, cables, wires, batteries, oxyfuel/clothing/grease and materials such as rubber tires and hoses, refuse, wood, chute liner, and shaft material. Other burning materials included belt material, flammable liquids, oil etc.

From the USA the report *Analyses of mobile equipment fires for all US surface and underground coal and metal/non-metal mining categories, 1990-1999* /2/ examines the mobile equipment fires for all US surface and underground coal and metal/non-metal mining categories.
Risk rate values are derived, and ignition source, methods of fire detection and suppression, and other variables are examined.
US regulations require machine fire suppression systems on all underground coal mine diesel equipment and electrical powered mine face equipment using non-fire-resistant hydraulic fluids. This has greatly improved the fire safety throughout the years.
Only a small number of fires being extinguished within 30 minutes and not resulting in any injuries, are included in the statistics (as those fires are not required to be reported to MSHA). Thus the statistics does not account for the total amount of fires.
A total of 24 equipment fires occurred in underground metal/non-metal and stone mines, involving mostly scoops, locomotives, haulage/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 flammable liquid/motor/fuel oil on hot surfaces.
Operators/miners detected most of the fires when they started as flames/flash fires, smoke, or power loss. Most of the hydraulic fluid fires grew out of control because of the continuous flow of fluids due to engine shutoff failure, lack of an emergency line drainage system, or lack of effective and rapid local fire-fighting response capabilities. At least twice the cab was suddenly engulfed in flames, forcing the operator to exit the cab under difficult conditions most likely due to the ignition of flammable vapours and mists that penetrated the cab.
The conclusions of the report are that the greatest number of equipment fires and injuries during 1990-1999 occurred at surface mines and that in the future equipment fires and injuries may be prevented, reduced or suppressed at their earliest stage by improving techniques and strategies,

developing new technologies, and improving safety training programs. The following suggestions - to prevent or reduce the fires and injuries - are listed in the report:

- Schedule more frequent and more thorough inspections of hydraulic, fuel, and electrical systems.
- Develop new technologies for emergency engine shutoff system and line drainage system. A large number of hydraulic fluid/fuel fires grew out of control because of the continuous flow of fluids from pumps and tanks due to engine shutoff failure. Furthermore, some fires after engine shutoff continued to be fuelled by the fluids entrapped in the lines.
- Develop cab fire detection and fire prevention/suppression systems.
- Develop effective and rapid local fire-fighting response capabilities.
- Schedule more frequent fire emergency preparedness training for equipment operators.

The conclusions and suggestions are most conventional and highly applicable for Swedish mines as the statistics of the two countries are very similar. One of the suggested activities (developing effective and rapid local fire-fighting response capabilities) is already being considered in one of the LKAB mines.

Based upon the two articles regarding statistics from US mines, a conclusion is that 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 working areas.

From the United Kingdom comes the report *Development of a fire and explosion risk assessment methodology for underground mines* /4/, which lists statistics on underground mine fires in the UK (non-coal mines).
During a ten year period (1992—2002) there were a total of 23 fires. Out of those, 11 occurred in steered vehicles and 6 occurred due to electrical causes.

Regarding the statistics from New South Wales in Australia, the article *Fires on underground mobile equipment, metalliferous mines, New South Wales* /5/ lists the statistics on mobile equipment fires together with ignition source statistics.
The statistics comprises the time interval 1990-2001.
From the statistics it was found that 46% of the fires were caused by flammable liquid sprayed onto hot surface (fuel spillage, burst hydraulic hose etc.). Out of those fires, 50% occurred in loaders.
The second largest fire cause was electrical shorting.

References /4/ and /5/ confirms the assumption that the most common type of fire object is a vehicle and the most common fire cause to be hydraulic fluid/fuel sprayed onto a hot surface.

<u>Summary:</u>

Seen from the statistical material, the most common fire cause in underground mines is flammable liquid sprayed onto hot surface, followed by electrical shorting/arcing and hot works. Conveyor belt/equipment friction is found to be a less frequent cause.
Efforts should therefore be devoted to spray fires, fire caused by flammable liquid ignited by hot surface, vehicles (including drilling rigs) fires (including rubber tires) and cable fires.
Regarding interesting locations in underground mines, mobile equipment working areas should be first priority due to the high risk of fires in mobile equipment.
The types of mobile equipment to focus on should be: service vehicles, drilling rigs and loaders.
The following suggestions are examples taken from US mine safety research - and highly

applicable to Swedish mines - that can be used in order to prevent, reduce or suppress equipment fires in underground mines:

- Schedule more frequent and more thorough inspections of hydraulic, fuel, and electrical systems.
- Develop new technologies for emergency engine shutoff system and line drainage system.
- Develop cab fire detection and fire prevention/suppression systems.
- Develop effective and rapid local fire-fighting response capabilities.
- Schedule more frequent fire emergency preparedness training for equipment operators.

5. Experimental and theoretical work on fuel loads

5.1 Hydraulic fluid

In the article *Ignition of hydraulic fluid sprays by open flames and hot surfaces* /6/ a study of the ignition of non-fire-resistant hydraulic fluid sprays is described.
Both an open flame and a hot steel surface were used as the external heat sources. With the open flame as the heat source, the minimum oil temperature and minimum spray nozzle pressure that resulted in an ignition were measured.
The effects of the distance between the open flame and the nozzle orifice diameter on the ignitability of the hydraulic fluid sprays were examined.
With the hot surface, the minimum surface ignition temperature was determined.
The degree of oil atomization and the relative direction of oil injection with respect to the hot surface are discussed.
The ignition of oil sprays from the impingement of oil jets onto a vertical surface was also investigated.
Finally, the results are compared with those obtained for fire-resistant hydraulic fluids.

The conclusions of reference /6/ are:

- When an open flame is used as the heat source, the test results show that lower viscosity fluids are easier to ignite than those with higher viscosities.
- For oil droplet sizes ranging from 40 to 100 μm the droplet size had very little effect on the minimum ignition flow rate. With the increase of the oil temperature, the minimum ignition flow rate decreased. In figure 2 below, the minimum oil flow rate versus nozzle orifice area is displayed.
- When a hot surface was used as the heat source, the minimum hot surface ignition temperatures ranged from 350ºC to 440ºC. The fluid viscosity appeared only to affect the atomization and not the combustion, while the flashpoint had no impact on the minimum hot surface ignition temperature.
- Hot surface ignition was also dependent on the degree of atomization, the relative direction of oil spray with respect to the hot surface and the local flow conditions.
- An oil spray from the impingement of a primary oil jet onto a vertical surface was ignitable with the open flame. This ignition only occurred when the vertical surface was in a certain distance range from the nozzle.
- Of the four types of fire-resistant hydraulic fluids, only high-water containing fluids and water glycol exhibited strong fire resistant characteristics with the open flame and the hot surface. The synthetic fluid and water-in-oil invert emulsion were ignited and burned when released in the form of fine droplets.

An important reflection of the information given in /6/ is whether LKAB uses fire-resistant hydraulic fluids in the equipment or not. An inventory is recommended to be performed and fire-resistant hydraulic fluid being used whenever possible.
Furthermore the results from the article can be used in the further work with respect to examining hydraulic fluid/fuel sprayed onto a hot surface: i.e. examining the equipment that is used containing hydraulic fluid (i.e. what potential ignition sources can be found on the equipment), what type of hydraulic fluid being used and what actions that can be taken to minimize the risk of a spray fire.
In figure 3 below, a spray fire is shown.

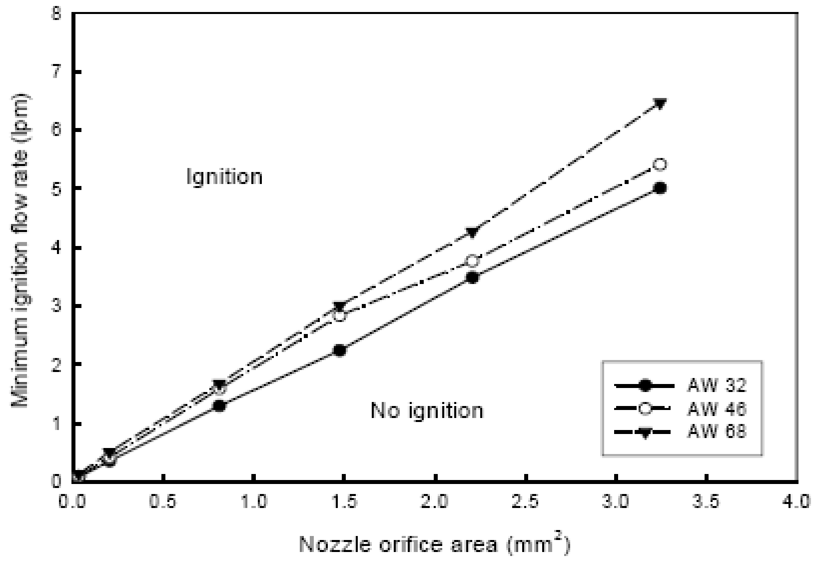

Figure 2. Minimum oil flow rate versus nozzle orifice area /6/.

Figure 3. A hydraulic fluid spray fire /6/.

5.2 Cab/vehicle

In the report *Alternativ till utrymningsväg från gruva och annan underjordsanläggning* /7/, 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 liters of oil. The experiment was videotaped during 5 hours (from ignition until the fire was practically out). 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. See figure 4 below, for the layout of the test area.

The conclusions of the report were:

- The critical velocity was between 1 and 2 m/s depending on the HRR of the fire.
- The fire was almost completely burned out 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 4 hours in Sweden).

This is the only article describing the fire behaviour of a vehicle fire in an underground mine that was found. Unfortunately it contains no HRR curves.

The time interval of 3-4 hours is well in accordance with other fire experiments involving larger vehicles, where the total fire duration was ~2 hours. But setting the time limit for rescue chambers to 4 hours is a bit too short, as the smoke may linger for a long time after the fire is out and the risk of a tyre explosion may persist for several hours.

Furthermore, one or more of the occupants of the rescue chamber may be injured and access by vehicle may be required. The required clearance of the affected drift may take several hours. The time limit must be investigated further and possibly revised.

It is a bit unfortunate that a unidirectional flow was measured in the drift, which makes the flow picture incomplete as unidirectional flow is a very rough assumption.

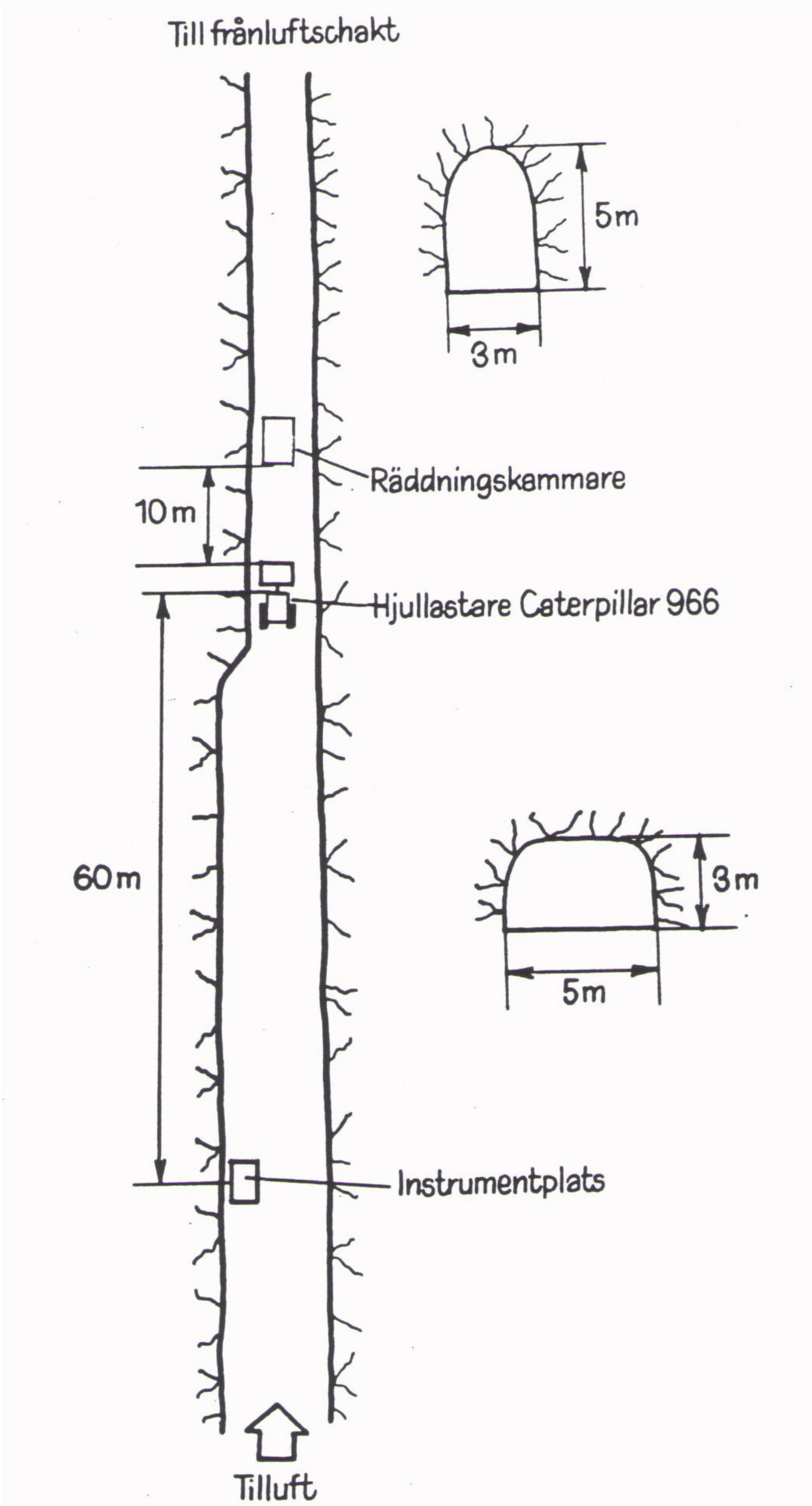

Figure 4. The layout of the test area: the experimental fire in a loader CAT 960 /7/.

5.3 Conveyor belt

In the article *Experimental study of flame spread on conveyor belts in a small-scale tunnel* /8/ a series of conveyor belt flame spread tests were conducted in a small-scale tunnel. The purpose of the study was to investigate the effects of belt type, a varying ventilation velocity, belt surface-to-roof distance and ignition source power on the flame spread properties.

The following types of belts were tested:

- Non-fire resistant styrene-butadiene
- Fire resistant styrene-butadiene
- Fire resistant neoprene
- Fire resistant polyvinylchloride belt.

In figure 5 below, the flame front velocity for the fire resistant styrene-butadiene belt as a function of the air velocity with the surface-to-roof distance of 0.11 m and 0.22 m is shown.
The conclusions of the article were that the experiments indicate that the flammability of various conveyor belts is greatly dependent on the test method. With a sufficient igniter heat output, 21 kW, a ventilation velocity of 1.02 m/s and the belt surface-to-roof distance of 0.22 m in this study, all belts could be ignited and the flame propagated to the end of the belts in the small-scale tunnel. The fire resistant conveyor belts have lower values of heat of combustion resulting in smaller flame spread rates compared with the non-fire resistant belts. PVC belt only burned on the surfaces. The ventilation velocity and the belt surface-to-roof distance were found to affect each other. With the ventilation velocity greater than 1.52 m/s, the belt could not propagate flame at a belt surface-to-roof distance of 0.22 m, while the flame spread on the belt occurred at the belt surface-to-roof distance of 0.11 m. Flame spread typically occurred for $\varphi>1$, and that fuel-rich combustion could result in dramatic increases in flame front velocities.
The results make sense as a greater belt surface-to-roof distance will for example result in a decrease in the re-radiation to the belt. The greater ventilation velocity will result in a decrease in the fuel-rich environment.
An interesting continuation of the results of the article would be to investigate the minimum ventilation velocity for belt surface-to-roof distances much greater than 0.22 m, which is applicable for the LKAB mines.

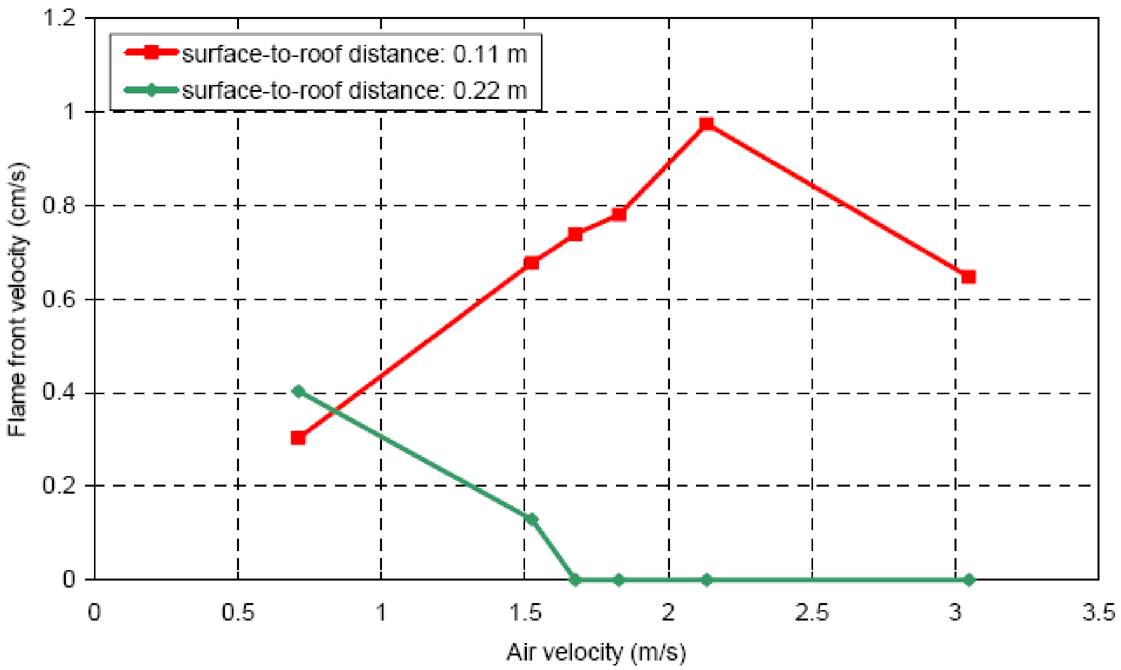

Figure 5. Flame front velocity for the fire resistant styrene-butadiene belt as a function of the air velocity with the surface-to-roof distance of 0.11 m and 0.22 m /8/.

In the article *The computational modelling of flame spread along a conveyor belt* /9/, the results of an experimental and computational study conducted to characterize the initiation and spread of fire

along the upper and lower surfaces of a conveyor belt mounted within a ventilated full-scale experimental fire test gallery are presented.
The experimental data that were obtained during the test were: temperature gradients and airflow profiles produced within the gallery due to the spread of the flame front under various ventilation flow rates.
Computational models were constructed using the CFD code FLUENT. A novel modelling method is proposed to represent the observed flame spread along the conveyor belt surfaces.
The conclusions of the article were that the experimental test programme that was conducted had successfully determined the aerodynamic and thermodynamic characteristics of a full-scale fire gallery. A subsequent series of experiments were performed to identify the initiation and flame spread characteristics of conveyor belting subjected to a British standard flammability test. Following the completion of the above experimental programme, a series of CFD models were constructed. The results produced by these models were validated by the experimental test data. It was concluded that the model simulations were able to successfully reproduce the aerodynamic and thermodynamic characteristics of the experimental test gallery. A novel discrete particle-based model was proposed to represent the physical presence, combustion and flame spread along the conveyor belt surface. The simulation results produced by this initial model were confirmed to qualitatively replicate the steady spread of flame observed during the experimental studies along the surface of the belt material.
While the CFD DPM (Discrete Phase Model)-based method proposed has been demonstrated to reproduce qualitatively the characteristic of flame spread along the surface of a conveyor belt it is anticipated that the methodology would benefit from refinements to the definition of the material characteristics. The pyrolysis of PVC-based materials is undeniably complex. In order to take advantage of the computational framework proposed and tested in these studies an intensive programme of TGA (Thermal Gravimetric Analysis)-based analysis of a range of type 10 conveyor belt samples to define common characteristics is necessary. Predictive models of static fires offer significant potential in the design and optimization of mitigation, control and escape planning. The true nature of underground fires demands that dynamic models such as that proposed in this paper be refined and developed. This model has demonstrated the initial potential and capabilities of the utilization and application of a commercial CFD code to these problems. Further improvements to the model could be obtained by including a model to replicate the belt "burn through" observed in the vicinity of the burners during some of the experiments conducted additionally, a full quantitative evaluation of the flame spread rate would provide further validation to the CFD DPM simulation method.
The type of model being developed here is not of an interest to the present project as conveyor belt fires are not a common type of fire in Swedish underground mines and that in vehicle fires (which are the dominating type of fire) the fuel is not continuous as in the case of conveyor belts. Furthermore the proposed model has not been able to quantitatively replicate the flame spread, thus limiting the use of the model.

In the article *Modelling the flow-assisted flame spread along conveyor belt surfaces* /10/, fire development and spread along conveyor belts in ventilated ducts were investigated experimentally and theoretically. Various types of conveyor belts used in mining applications (fire resistant belts were among the tested) were ignited and burned in a full-scale gallery under various flow conditions. A theoretical model was developed in order to correlate the fire spread with material properties of the conveyor belts and the fire environment. Agreement between the theory and the experimental results was found to be good.
The conclusions of the article were that the experimental results of flow-assisted flame spread along horizontal conveyor belts indicate that the radiative heat transfer plays a major role in its spread mechanism. A simple theory using only the radiative heat transfer from the flame front appears to be able to explain a peak in the spread rate when the air speed is approximately at 1.5

m/s. At this value of the air speed, the flame tilt, the flame length, and the burning-zone length combine to provide a maximum heat transfer to the fuel surface. The burning-zone lengths employed in the computation were experimental values.
Most of the conclusions are in accordance with the conclusions of *Experimental study of flame spread on conveyor belts in a small-scale tunnel* /8/. As the radiative heat transfer plays a major role in the spread mechanism, a greater belt surface-to-roof distance will result in a decrease in the re-radiation to the belt and a greater ventilation velocity will result in a decrease in the fuel-rich environment. Thus the conclusion of the report regarding the peak value at an air speed of 1.5 m/s is only valid for larger belt surface-to-roof distances. A weakness of the article is that the influence of the belt surface-to-roof distance was not investigated.

In the article *A laboratory-scale gallery fire-test on rubber conveyor belts with fabric skeletons* /11/, small-scale fire tests were conducted on nine different rubber conveyor belts with fabric skeletons. An inclined gallery as well as a horizontal gallery was used.
The main purpose of the study was to study the flammability properties of conveyor belts. The test results were compared with those from some other small-scale flammability tests (i.e. the small-scale flame, the oxygen index and the hot plate ignition tests). As a result, it has been found empirically that determination of both the time to ignition and the flame-propagation speed could be significant in case the flame propagated over the whole length of the belt specimen in the gallery, so that the fire resistance of the belt samples could be classified in detail.
The conclusions of the article were that the results of the laboratory-scale gallery fire test have shown that both ignitability and the flame-propagation property of a belt sample depends on both specimen width and ventilation flow conditions. In addition, the correlation between ignitability in the gallery fire test and other small-scale flammability test results of the samples tends to depend largely on the ventilation flow condition, but that between flame-propagation speed in the test and other flammability properties seems to be almost independent of whether the ventilation flow in the gallery is horizontal or upward. On the other hand, correlations between the flame-propagation speed in the fire test and other flammability properties seem to be fairly consistent among the different conditions of the gallery test. The fire-resistance specification as to length of the intact part of the belt specimens appears to be a severe requirement for this kind of flammability test. Thus it seems to be desirable to determine both the time to ignition and the flame-propagation speed in case the flame propagates over the whole length of the belt specimen, so that the fire resistance of belt samples can be classified in more detail.
The conclusions regarding the dependence of specimen width and ventilation flow conditions with respect to ignitability and flame-propagation property, is quite obvious as the specimen width corresponds to the fire load. But the finding that the flame-propagation speed seems to be almost independent of whether the ventilation flow in the gallery is horizontal or upward, is not consistent with the conclusions of articles such as *Modelling the flow-assisted flame spread along conveyor belt surfaces* /10/. One would expect that the tests with upward ventilation flow (where the inclination of the gallery was adjusted to 10º) would result in larger flame-propagation speed than for the horizontal case, as the view factor would increase and thus also the radiative heat transfer to the fuel ahead. One reason for the different finding could be that the belt surface-to-roof distance was small (85 mm) in the tests, thus resulting in an early deflection of the flame.

In the article *Heat release rate in evaluation of conveyor belts in full-scale fire tests* /12/, a full-scale experiment with a 42 meter long and 0.5 meter wide conveyor belt was conducted.
The following parameters were measured: temperature, CO, CO_2, and O_2.
The type of conveyor belt was slow-burning chloroprene belts. A total of six different types were burned during the experiments.

The paper assumes that the amount of heat released can be determined by using that the amount of heat released during the combustion of organic substances per unit of mass of oxygen consumed in the process of burning is a constant value and equal to 13.1 MJ/kg.
Ignition source was a pile of burning wood. A large amount of the HRR is due to the burning wood.
The peak HRR measured during the experiments was 4-7 MW.
The reason why the belt was ~40 meter long was that this length is the maximum admissible length of the belt section which can undergo burning so that the belt could still be assumed as a safe one (self-extinguishment characterization).
During the tests a full-scale testing gallery was used and not a cone calorimeter (see figure 6 below, for the appearance of the testing gallery).
The conclusions of the article were the following:

- On the basis of measurements of the amount of oxygen consumed in the process of burning belts in the fire testing gallery, it was possible to calculate the heat release rate.
- The dependence of the amount of heat released in the course of combustion of the conveyor belt in the fire testing gallery defines the dynamics of the belt combustion process. This relationship provides valuable information for the need to determine the hazard related to the use of conveyor belts in mines.
- The calculations of the heat release rate during burning conveyor belts in the fire testing gallery can be the basis for development of a new method for conveyor belt testing.

The conclusions are quite obvious and not very innovative. The conclusions above confirm well known facts from before.
Something from the article that could be used in the future work are the HRR curves of the conveyor belts. The HRR curves could be used when looking into different fire scenarios in different parts of the mine.

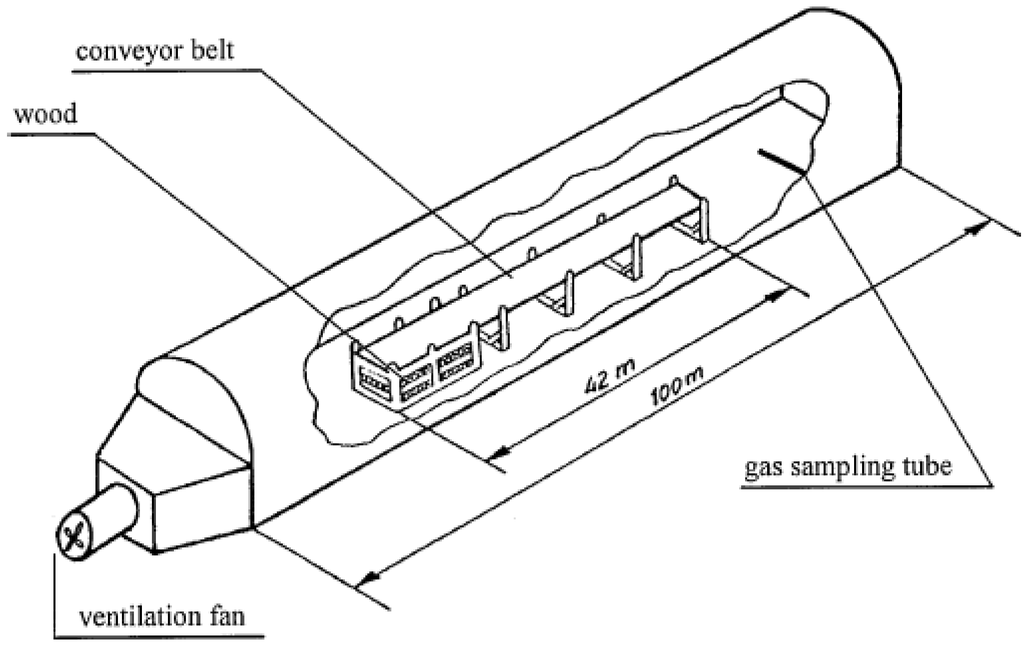

Figure 6. The full scale testing gallery for conveyor belt fires /12/.

In the article *Investigations of conveyor belts flammability. Comparison of flammability assessment using the large-scale gallery test and cone calorimeter* /13/, a correlation was found between results of conveyor belt flammability obtained using both the large-scale gallery method and using cone calorimeter.

Only difference from the article *Heat release rate in evaluation of conveyor belts in full-scale fire tests* is that the in the test a cone calorimeter is used.
In the cone calorimeter test the following parameters were measured:

- Time to sustained ignition
- Total heat released
- Average mass loss rate
- Average HRR after 180 s
- Average HRR after 300 s
- Peak HRR
- Average effective heat of combustion

In figure 7 below, the correlation between the heat released in a full-scale test, Q, and the predicted of heat released, based on cone calorimeter test (THR) is shown.
The following conclusions were drawn:

- On the basis of conveyor belt flammability investigations using the large-scale gallery test a relationship was found to exist between the amount of heat released during combustion and the length of belt section burnt in the gallery, defined by a linear equation. The correlation coefficient determined amounts to 0.96.
- On the basis of test performed using the cone calorimeter it can be stated that this investigation technique is fully suitable for determining conveyor belt flammability, while obtained results show satisfactory repeatability.
- There are relationships, defined by linear equations, between the amount of heat released during conveyor belt combustion in fire-testing gallery, Q, and corresponding amount of heat calculated on the basis of flammability tests conducted by applying the cone calorimeter method. There is also the total heat release (THR), Q_{THR}, and average effective heat of combustion (HOC), Q_{HOC}. The correlation coefficients calculated amount to: 0.92 and 0.97, respectively.
- There is a relationship, described by a linear equation, between the amount of heat released during conveyor belt combustion in fire-testing gallery, and its corresponding theoretical amount of heat, calculated from the heat of combustion of belts. The correlation coefficient calculated amounts to 0.96.
- On the basis of parameters determined using the cone calorimeter method, which defines the total amount of heat released and the average effective heat of combustion it is possible, applying the relationships defined in the first and fourth conclusions, to determine the predicted amount of heat that would be released during conveyor belt flammability investigations. This is carried out by applying the large-scale gallery test and the equivalent length of belt section which would be burnt in the course of such testing.
- The criterion of conveyor belt fire-resistance for the flammability investigation method based on cone calorimeter is defined by the inequality, according to which the amount of heat that would be released during conveyor belt combustion, calculated on the basis of total heat release and the average effective heat of combustion, cannot exceed the theoretical amount of heat calculated from the conveyor belt heat of combustion, which would be released during combustion of a 40 m section of belt in a fire-testing gallery.

The findings are very straight-forward and obvious but not of any use in the present project. Flammability testing of conveyor belts is not part of the project. Heat release rate curves for conveyor belts would be useful for the project, but this article only contains data about the heat release of conveyor belts. Data about heat of combustion for the conveyor belts could also be useful in the project.

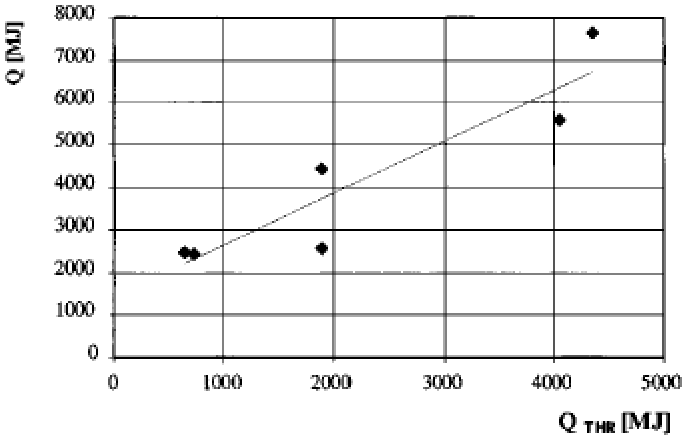

Figure 7. Correlation between the heat released in a full-scale test, Q, and predicted of heat released, based on cone calorimeter test (THR) /13/.

In the article *Underground fires* /14/, different types of fire causes involving conveyor belts are listed.
Fires associated with belt conveyors are initiated by the frictional generation of heat.
The principal causes are: bearing failures and belt friction in jibs, driveheads, loop take-ups, return ends or structure.
The article also gives recommendations with respect to conveyor belt fires.
General recommendations for Swedish mines (with respect to conveyor belt fires) could be written based partly on the findings in reference /14/.

In the article *Reducing the fire hazard of mine conveyor belts* /15/, a program undertaken by MSHA to study the flammability of conveyor belts in large- and small-scale tests are described. Large-scale tests were conducted on various types of mine conveyor belts using a range of airflows from 0 to 6.1 m/s. Data were obtained to evaluate the effect of airflow on flame spread and other combustion properties of the conveyor belts. The test results showed the highest flame spread rates when the airflow was 1.5 m/s. The results from the large-scale tests were utilized to develop a new MSHA laboratory-scale test for evaluating the flame resistance of conveyor belts used in underground coal mines. MSHA also performed a series of fire tests with wood samples using the new laboratory-scale tunnel apparatus. These tests were conducted at airflows from 0.5 to 5.1 m/s to determine the effect on flame spread and burn damage.
The conclusion of the report regarding the peak value at an air speed of 1.5 m/s is only valid for larger belt surface-to-roof distances. A weakness of the article is that the influence of the belt surface-to-roof distance was not investigated.

<u>Summary</u>

MSHA, Factory Mutual, HSE etc. have performed an extensive work with respect to the ignitability and flammability of pressurized hydraulic fluids and there is at the moment no need for any extensive research within this field. But nevertheless an inventory is recommended to be performed in the mines with respect to the type of hydraulic fluid being used and fire-resistant hydraulic fluid should also be recommended being used whenever possible.
When examining hydraulic fluid/fuel sprayed onto a hot surface - i.e. examining the equipment that is used containing hydraulic fluid (i.e. what potential ignition sources can be found on the equipment), what type of hydraulic fluid being used and what actions that can be taken to minimize the risk of a spray fire - the results can be used in the further work.

There is clearly a lack of documented fire experiments in vehicles/mobile equipment. The main focus has so far been cab fire detection and suppression. The fact that a majority of fires in underground mines involve vehicles/mobile equipment highly increases the demand for HRR curves for vehicles/mobile equipment.

A majority of the articles regarding conveyor belts deals with the ignitability and flammability of the belt conveyors. Besides that, an extensive research work has been conducted regarding HRR curves, mass loss rate, flame propagation speed and some fire modelling. But the focus in the present project – with respect to design fires – should not be on conveyor belt fires as they are not a dominating fire cause in non-coal mines.
But nonetheless a relatively easy and effortless task would be to investigate the principal causes of belt conveyor fires in underground non-coal mines.

As the surface-to-roof distance – with respect to conveyor belts – are greater than 0.22 m in the LKAB mines, it would be interesting to investigate the minimum ventilation velocity for belt surface-to-roof distances much greater than 0.22 m, as the research work so far has concentrated on distances less or equal to 0.22 m.

As the statistics put cable fires high on the list and large loads of cables can be found underground, some efforts should be made with respect to cable fires in underground mines.

A number of fire experiments and studies have been conducted where wood was uniformly distributed over the airway walls. This type of fuel configuration applies to coal mines, but is not applicable to for example the Swedish iron ore mines. These studies are thus of limited value for this specific project.

6. Smoke spread and fire behaviour

6.1 Friction losses

In the article *Fire tests in a blasted rock tunnel* /16/ fire tests were performed in a blasted rock tunnel with an average cross section of 9 m^2. The tunnel measured 3 m wide, 3 m high and 100 m long. The fire was located at two different locations in the tunnel. The tunnel is naturally ventilated through a 13 m high chimney located a one end of the tunnel. Tests with different ventilation conditions and fuels were carried out. The fuels used were: heptane, kerosene, methanol, polystyrene cups in paper cartons, a vehicle dummy and wood cribs. The effects of ventilation on the HRR and correlations between optical density and gas concentration at different locations in the tunnel were investigated. Comprehensive data for future comparison with CFD models were also obtained.
The conclusions of the article were that the fire tests show a slight difference between the degree of ventilation and heat release rate for pool fires whereas the difference for solid materials is more apparent. These results are in agreement with other investigations. Measurements of optical density and gas concentrations indicate that it is possible to correlate the gas concentrations and the optical density. A parameter for the type of fuel must be included.
The blasted rock tunnel used resembles the roughness of a mine, thus the output data could be used when validating for mine conditions.

6.2 Natural ventilating pressure

In the article *Estimation of the natural ventilating pressure caused by fire* /17/ the subject of natural ventilating pressure (NVP) caused by fire in inclined or vertical parts of the airway is dealt with. NVP: In a mine, air returning from the workings to the surface via the upcast shaft can be of a higher temperature than the air in the downcast shaft because of heat added to the ventilation current from the strata exposed in the mine. Thus, even in a mine with the fan stopped, the upcast air density is less than the downcast air density. This lack of balance in the two vertical air columns produces a pressure difference across the shaft bottom doors known as natural ventilating pressure.
NVP caused by fire is defined as the difference between NVP during the fire and NVP before the outbreak in the particular closed airway (mesh). This is the starting point for mathematical considerations which lead to a formula, assuming that the fire is a local source of heat. Temperature increase caused by fire was calculated for steady state along the airway and assumed conditions.
The resulting formula expresses the NVP caused by fire.
It would be worthwhile to investigate whether the mathematical expressions of the article are included in the mine ventilation network simulation programs. Most likely they are as the article is from the early 70's. Also a weakness of the article is the fact that it only considers steady state fires.

6.3 Heat loss to environment

In the article *Simplified method to calculate the heat transfer between mine air and mine rock* /18/ 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.
The conclusions of the article were that being aware of the great influence of water migration, evaporation and condensation on airway wall temperatures, the authors of the article hope that the calculations presented are a useful contribution for assessing this influence. Equations

presented in the article present "exact" solutions of this influence provided that the time intervals were properly set and the correction for the water influence was reasonably small. Such a requirement implies that the foregoing solution is suitable for the case of high relative humidity or low degrees of wall wetness. A computer program was written to realize this solution.
When a very strong influence of water evaporation on the wall temperature variations is introduced by large differences in the initial rock/air temperatures and humidity, an equation presented can be employed for a better convergence, if the transient state for only a short time interval is of interest.
As the method used in connection with transient-state simulations and the fact that the mines involved in the project are "wet" mines, it is of interest for the present project. Possibly measurements and validation of the model could be performed during coming fire tests.

In the article *Modelling of heat exchange between flowing air and tunnel walls* /19/ 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. The method may be useful in conditions where the computation speed is more important than the precision of the results. The model is more simplified than for example a ventilation network simulation program.
The conclusion of the article was that the attempt to represent the down of a source of heat air, wall, and rock temperatures in a non-steady state by a simple mathematic model was successfully completed. The method was extensively tested using reduced-scale experiments. There is a good agreement of the results of the experiments with those of the model. The model can be used in ventilation network and fire simulation computer programs, and is part of the fire simulator of the PCVENT program.
The simplicity, the accessibility and the fastness of the model may make it worthwhile to look into further during future fire tests (i.e. to validate the results of the model with actual measurements in a mine).

In the article *Cooling of fire gases in mine workings and ventilation networks* /20/ a number of interrelated processes in a mine ventilation network are described by a set of non-steady state equations:

- Cooling of fire gases in a mine working (rock mass etc.).
- Movement of fire gases in a ventilation network.

The mathematical model presented in the article has been incorporated in a number of computer systems such as VENT-4.
The theory has obtained a limited spread around the world and seems to have been limited to Bulgaria. Thus it is doubtful whether the computer systems are presently available.

In the article *The relations between modulus of elasticity and temperature in the context of the experimental simulation of rock weathering by fire* /21/ rock disintegration caused by fire is described.
The simulation of fire in the laboratory and the monitoring of changes in rock modules of elasticity, reveal that different rocks respond differently to heating. Significant decreases in elasticity occur at temperatures as low as 200ºC and granites display particularly marked reductions. Extended periods of heating are not required for significant reductions to occur.
The conclusions of the article were that the experiments reported demonstrate that there is a variable material geotechnical response to simulated firing according to rock type, but that just one cycle of temperature change can lead to a substantial decrease in modulus of elasticity and that for some rock types, significant change occurs at temperatures as low as 200ºC. Additional cycles lead to additional decreases in elasticity values.

The length of time required to cause a marked decrease in elasticity at 500ºC is not great. This is significant in terms of the duration of high temperatures in natural fires in the field.
The degree of change in rock elasticity as a result of simulated fire is such that rock outcrops subjected to natural fires are likely to be sufficiently modified as to cause either disintegration or to increase their susceptibility to erosion and other weathering processes.
The article deals with surface fires (forest fires) affecting the rock underneath and does not directly relate to fires in underground mines.

In the article *Mathematical modelling of heat exchange between mine air and rock mass during fire* /22/ the heat exchange between the smoke and the rock mass was studied as it will play a role with respect to the behaviour and spread of smoke through the mine.
No experiments or tests are mentioned in the paper.
The presented mathematical relations allow calculation of a varied velocity and movement direction of air flows, their temperatures and smoke conditions during fire.
The model assumes that the smoke is transferred by moving air alone and that diffusion can be neglected due to this. The assumption is correct if the air movement is sufficiently intensive.
The model uses an algorithm for thermal-mechanical smoke transfer during a fire at an alternating temperature. Finding out how the temperature of air changes and how quickly hot air will get cold at a distance from the fire. When the air temperature is defined as a time t and distance z function T(t,z), the heat loss in the defined volume can be calculated and thus the calculation of smoke propagation.
Earlier works are based upon a non-stationary heat exchange coefficient, k. This model uses instead an exact numerical solution of the heat exchange problem with the help of Laplace transformation.
At mine fires it requires a special modelling approach to take into account the intereffect of the air movement mechanisms and the heat exchange between the air and rock mass.

Based upon the contents of the article one can question the practical use of the model as the strength of air movement will vary widely in a complex, three dimensional underground mine (an assumption of the model is that the air movement will have to be sufficiently intensive). But the theory could very well be tested in future fire tests in the present project.

6.4 Movement of fire gases in a ventilation network

In the report *Brandventilation i Kiruna järnmalmsgruva* /23/ a project aimed at testing the fire ventilation of the Kiruna mine was described.
The fire tests would answer mainly two questions:

- What egress time for a drift could be established at a fire?
- Would the existing ventilation system be capable to evacuate the smoke from the test fires?

Fire tests were executed as well as smoke tests, all of them down in the specific mine. In figure 8 below, one of the fire experiments performed in the Kiruna mine is shown.
Temperature, wind velocity and air moisture were measured and recorded. Visual observations were also conducted.
The conclusions were that the egress time was observed to take approximately 12-13 minutes in a drift. The existing ventilation system was not capable to fully ventilate the smoke from the test fires. A criterion should be established with respect to what risk that is acceptable underground.
A method should be found to prevent the smoke from spreading from the specific production area where the fire is located. Further fire tests should be performed.
For further studies, smoke spread through ore passes was recommended to be examined further.

The prevention of smoke spreading from a fire affected production area is something that should be included in the present project. As no fire barriers are possible (due to practical reasons: the blasting taking place every day would destroy the fire barriers), other methods will have to be looked into.

Figure 8. One of the fire experiments performed in the Kiruna mine /23/.

In the article *Modelling the movement of smoke and the effect of ventilation systems in mine shaft fires* /24/ physical principles governing mine ventilation systems and state of the art ventilation modelling are initially outlined.
Several computer programs for modelling the mine ventilation and mine fire interaction – which were developed during the last decade – are then described. An older program considers fires and ventilation systems as going through a sequence of steady-state conditions. Airflow rates, pressure losses, temperatures, fume and methane concentrations can be determined.
Newer programs allow transient state fume concentration calculations under the assumption of constant airflow rates as well as the determination of fume exposures of escaping miners. Recent work attempts the complete transient state simulation of fires and all ventilation properties. The article also describes the transient state concentration calculations.
It also lists the conservation equations used in the mine ventilation models.
The method that is used in the calculations is the Hardy Cross-method.
The assumption of time constant airflow rates for transient state concentration distribution calculations is justified for the early stages of a fire, when a weak fire does not influence the airflow distribution yet.
More work will be necessary until transient state simulations of ventilation systems can be considered to be a routine tool.
The article was written in 1985, but since then transient state simulations of ventilation systems are a routine tool to work with. This will limit the use of the article.

In the article *Computer simulation of air flow state in mine ventilation system under fire condition* /25/, a ventilation network simulation program is described together with the underlying algorithm.

The conclusion of the article was that the presented program in the article can be of some assistance in the preplanning of escape and ventilation control and during a fire emergency. The spread of the program is very much limited and the fact that no validation studies of the program is listed. Looking into the program in more detail does not seem worthwhile for the moment.

6.5 Reversing ventilation/increasing ventilation

In the article *Calculations for emergency ventilation conditions in mines with several main fans* /26/ mathematical models are described for the flow when using emergency ventilation (for example reversing fans, increasing fan capacity etc.).
Fire is considered as an additional source of draft.
The assumption of the fire as a source of draft can be questionized. Also, the models presented are mainly for coal mines. The findings of the article are of limited use in the present project.

In the article *Backdraft in descensionally ventilated mine fire* /27/ the backdraft phenomenon in an underground mine is studied.
Several experiments were executed during the work. The experimental system used comprised 18 airway branches and 11 nodes. The ventilation network was changed by opening or closing valves. The network had two combustion branches, where combustible material could be ignited. The combustion branch could change inclination and the fuel that was used during the experiments was kerosene.
Measured parameters were: airflow velocity, temperature, CO, CO2, O2. An inclination of 20º was used during the experiments.
The backdraft occurred with the reversing process of airflow in the tunnel: before the airflow reversal the inclination of flame is downcast under the suppression of airflow. As more and more fire gases are produced, the buoyant effect of them increases notably. When the buoyant force equals approximately to the mechanical ventilation pressure, airflow into the tunnel becomes less and less. The tunnel then becomes a relatively separated space with poor ventilation. The fire turns into a ventilation-controlled one and becomes much smaller. At this time, large quantities of flammable gases come out due to the thermal decomposition of the fuel under the high temperature of fire gases. When the buoyant force of fire gases becomes larger than the mechanical pressure, the airflow within the tunnel may reverse. When the reversed airflow containing fresh oxygen comes in contact with the fire gases, the backdraft occurs.
In the experiments, the proper time for a small-scale backdraft is ~2-5 minutes (from the time that the fire is ventilation controlled until the start of the reversal of ventilation).
The backdraft in a tunnel is a spontaneous behaviour to some extent (as opposed to a backdraft in a compartment fire, which is set off by a change in ventilation.
In the article it says that a backdraft can occur when the fire itself causes the reversal of the airflow.
The conclusions of the article were that through the initial experiments in the model tunnels, the article illustrates a specific backdraft in the process of a tunnel fire. The backdraft in a tunnel fire is different from that in a compartment fire although they have the same mechanisms. The precombustion of the former takes place in a flowing open system, and that of the latter takes place in a closed system. In addition, backdraft in a tunnel fire needs no newly formed vents, but in a compartment fire at least one vent is needed to achieve a backdraft. The backdraft in a tunnel is a spontaneous behaviour caused by the reversal of airflow. The investigation results extend the range where a backdraft can occur and promote the knowledge and understanding in backdraft phenomenon.
It is doubtful if the phenomena that occurred could really be classified as backdraft, unless the fire is within a fire barrier enclosure.

6.6 The effect of sprinkler system and ventilation system

In the article *The effects of ventilation and preburn time on water mist extinguishing of diesel fuel pool fires* /28/ water mist is being evaluated for the suppression of underground mine fires, such as in diesel fuel storage areas.
In the study a series of large-scale fire tests was conducted to investigate the effects of ventilation and preburn time on water mist extinguishing of three diesel fuel pool fires with HRR of 230 kW, 1 MW and 3 MW. The experiments were conducted in a simulated underground coal mine diesel fuel storage area under three ventilation conditions: no ventilation, natural ventilation, and forced ventilation and with two preburn times for the no ventilation condition.
The conclusions of the article were that the large-scale water mist experiments demonstrated that diesel fuel pool fires with HRR ranging from 230 kW to 3 MW could be extinguished using a water mist system under various ventilation conditions and preburn times. Because the water mist system used in the study is a local application system, there is always a direct interaction between mist droplets and fire plumes. For the 230 kW fire, surface cooling is the major extinguishing mechanism because of the fire's low plume thrust and small flame size. So under no ventilation and natural ventilation with 1-min preburn and no ventilation with 30-s preburn time conditions, the extinguishing times were nearly the same. Under the forced ventilation condition, the extinguishing time increased slightly probably due to a lower water flux because of mist droplet loss. For the 1 MW fire, the flame cooling, surface cooling, and oxygen depletion and displacement were all responsible for its extinguishment under the no ventilation condition. The flame cooling and the oxygen depletion and displacement reduced the flame HRR and size, and the remaining flamelets were eventually extinguished by surface cooling. Under the natural ventilation and 30-s preburn time conditions, the oxygen depletion and displacement effect is minimal, and extinguishing times increased compared with those under the no ventilation and 1-min preburn time conditions. The 3 MW fire was extinguished by flame cooling under the no ventilation and natural ventilation with 1-min preburn conditions with the help of oxygen depletion and displacement; it was extinguished by flame cooling, oxygen depletion and displacement, and surface cooling under the 30-s preburn time and no ventilation conditions; it was extinguished by flame cooling and surface cooling under the forced ventilation and 1-min preburn time conditions. The 3 MW fire under forced ventilation was the most challenging one to extinguish under these experimental conditions because of the lack of oxygen depletion and displacement and the large HRR.
The low-pressure water mist system used in the study proved to be suitable to extinguish diesel fuel pool fires up to 3 MW. High water pressure which produces finer droplets and larger water flow rates for the pressure type nozzles is desired. Lower pressure may result in failure to extinguish a fire under strong forced ventilation conditions.

The subject in the article is not part of the present project. Also the article does not specifically deal with fires in underground structures, but encompass the extinguishment of pool fires in most types of (enclosure) installations.

<u>Summary:</u>

Fire experiments conducted in a blasted rock tunnel resembling the roughness of a mine can be found in the article *Fire tests in a blasted rock tunnel* /16/, thus the output data could be used when validating for mine conditions.
As not all CFD models will be able to take the surface roughness of a mine drift into account, there is generally a demand for investigation of the friction losses fire gases in a mine drift.

The natural ventilating pressure has been investigated in many aspects but apparently there is a lack with respect to the non-steady state case, as for example in the article *Estimation of the natural ventilating pressure caused by fire* /17/. Further work could be needed with respect to this field.

Even though extensive theoretical material concerning heat exchange between fire/fire gases and rock has been presented through the years, there still seems to be a lack of full scale experiment validating the theoretical models/equations.
During the possible validation work the articles *Simplified method to calculate the heat transfer between mine air and mine rock* /18/ and *Modelling of heat exchange between flowing air and tunnel walls* /19/ contain methods for calculating the heat exchange that could be worth looking further into and used during the validation work.

Regarding the subject on the movement of fire gases in a mine ventilation network, more work is needed such as fire experiments with more complicated and varying geometry (opening area, inclination, aspect ratio), larger test area, reversing/increasing the ventilation, and larger, non-steady state fires are needed. The results should also be examined against the results of corresponding CFD/ventilation network simulation program.
A weakness in the previous work is the fact that fires have generally been considered as steady state fires, which is definitely not always the case.
Due to practical reasons no fire barriers are possible in a production area (as blasting operations take place every day it would thus destroy the fire barrier in question), this makes prevention of smoke spreading from a fire affected production area something that is very important and should be included in the present project. Obviously other methods will have to be looked into.

7. Calculations and modelling

7.1 General

In the article *Computational modelling of mine fires* /29/ three computational models are used to study the effect of fire in a British mine. A mine network model is used to consider the mine as a whole, one-dimensional gravity current techniques are used to compute the stratified flow up to breakdown and multidimensional CFD modelling is used to examine the near-fire flow in detail. The result of the models is in agreement with each other and highlights a possible mitigation measure to limit the spread of combustion products. Further developments needed in the models are suggested.
There may be benefits in integrating a CFD model with a network model (a CFD model having its advantages close to the fire and a network model further away from the fire), because at present the boundary conditions for the CFD are either assumed, or approximated, with little reference to their interaction with the rest of the mine network.
The conclusions was that the use of a mine network modelling code has suggested a possible means of mitigating the consequences of a fire in a particular part of a UK mine. CFD simulations of a 10 MW diesel pool fire in a portion of the mine are in broad agreement with the network-based models, and have demonstrated the potential of the technique for modelling mine roadway fires. To model the effects of fire on a mine tunnel network as a whole, network models, such as MFIRE, will continue to be an essential tool. However, they have serious limitations in making accurate predictions close to the fire itself. In this region, multi-dimensional CFD models have demonstrated the potential for simulating the near-fire flow. However, the physical and numerical models on which these techniques are based, need to be further developed and validated against experimental data.
The idea of integrating a CFD model with a network model is a highly interesting idea worth developing further.

In the article *Simulation of mine ventilation under the influence of mine fires* /30/ the fundamental strategies adopted in the simulation package "FIRES" developed for ventilation simulation under mine fires are discussed. These fundamental strategies include:

- Fire characteristic curves specifying the development of a mine fire with time.
- Simulation of smoke spread in a ventilation system.
- Determination of the aerodynamic effects of mine fires on flows.
- Dynamic simulation of flow state under mine fires.

The major functions of the simulation package are also addressed. The package has been used to simulate an experimental mine fire. A comparison is made between the simulation results and the measured data.
The article describes effects (mine fire versus ventilation) such as throttling effect, fire pressure. Both steady-state and non-steady-state simulation are used during the work.
The mass flow of smoke into the air is regarded to be very small and negligible compared to the mass flow of the air. Thus it is assumed that there is no increase in mass throughout the air flows in the network. Only the change of resistance due to the temperature raise or fall in an entry is considered in the simulation package.
It is also assumed that the heat transfer between the normal air flow and the surrounding rock is negligible.
The conclusions were that from the preceding comparison, it has been confirmed that the simulation package FIRES can perform a relatively accurate simulation for the dynamic processes of temperature changes, fume spread, and flow state in a ventilation network under mine fires on condition that correct fire characteristic curves are provided. This indicates that the associated mathematical models adopted in FIRES are appropriate. Therefore, the simulation package

developed can be used to simulate the dynamic processes of fume spread and the change of flow state in a ventilation network under mine fires.
It is unclear what type of program "FIRES" is (apparently no CFD model as it assumes that the mass flow of smoke into the air is negligible). If it would be possible, it would be most interesting to compare the results of FIRES with for example the results of MFIRE for the same fire.

7.2 CFD

In the article *CFD analysis of mine fire smoke spread and reverse flow conditions* /31/ a CFD program was used to predict spread from fires in an entry under zero airflow conditions.
At a location, 0.41 m below the entry's roof at a distance of 30 m from the fire, the measured smoke spread rates were 0.093 and 0.23 m/s for a 30 kW and a 296 kW fire (diesel was used as fuel), respectively.
The CFD program predicted spread rates of 0.15 and 0.26 m/s based upon the measured fire heat production rates. Based upon a computation with propane as the fuel, a predicted 5 ppm CO alert time of 70 s at a distance of 30 m from the fire is to be compared with the measured alert time of 148 s (the rate of smoke (POC) spread is significant for establishing sensor spacing requirements in a mine for low airflow conditions).
In a second application, the CFD program was used to analyze smoke flow reversal conditions, and the results were compared with visual observations of smoke reversal for 12 diesel fuel fires. The CFD predictions were in qualitative agreement with visual observations of smoke reversal.
The CFD program used was CFD2000, which includes a library of multiple step chemical reactions and a choice between laminar flow and turbulent flow described by the κ-ε model. Convective, conductive, and radiative heat exchange are part of the program. But the radiative heat exchange was not considered in this study. The program is menu driven and permits the selection of geometry, the number of spatial dimensions, and selection of finite difference method and numerical convergence criteria.
The Froude number is used in a one-dimensional model to determine if reverse flow will occur or not. This implies that if the air velocity is greater than some critical velocity, then reverse flow does not occur.
Small and steady state fires were used in the experiments.
Heat loss to rock mass was not included in computer simulations.
The average entry was 2×4.6 m and the length was: 30 m in each direction.
The conclusions were that for a 296 kW and a 30 kW fire the computational program predicted fire induced air velocities near the roof, which overestimated the POC measured spread rates. The overestimation is a result of not distinguishing the POC from the airflow in the computation. The predicted gas temperature near the roof 30 m from a 296 kW fire was higher than the measured values. This is a result of not including heat loss to the mine roof. When the CFD2000 program was used to model the CO generated by a hydrocarbon fire source, the qualitative agreement of the predicted and measured CO concentration was good, although the predicted time for a CO alert value of 5 ppm 30 m upwind of the 296 kW fire occurred earlier than the measured alert time. This difference was in part due to the sensor response time, and in part due to the transient fire growth. Application of the CFD2000 program to model the development of reverse flow conditions for a diesel fuel fire under positive ventilation conditions in a mine entry showed that the predicted critical velocity for reverse flow conditions was lower than predicted by a Froude model analysis. It was also determined that the measured extensive smoke reversal is more favourably predicted by the Froude model. The interpretation of smoke reversal as a reversal of the roof layer at the edge of the fire pan in the application of the CFD2000 program is possibly too stringent a definition of smoke reversal. Turbulent mass transfer of smoke from the ascending plume into a recirculatory zone established upwind of the fire would result in an increased critical velocity for reverse flow. Successful qualitative

application of the CFD program is dependent upon a proper description of the experimental conditions. When there is incomplete information, the CFD program can still yield useful qualitative information with regard to the parametric influence of experimental conditions on CFD predictions.

The results are of little value in the present project due to the following circumstances:

- Only small and steady state fires were used in the experiments. This is not very realistic when studying for example vehicle fires.
- Heat loss to the surrounding rock mass was not included in the computer simulations. The heat loss to the surrounding rock will largely influence the behaviour of the smoke, especially in a large and complex mine network.

An interesting finding was the better prediction of the smoke reversal by the Froude model, than when using the CFD program.

In the article *Experimental and modelling investigation of the effect of ventilation on smoke rollback in a mine entry* /32/ diesel fuel experiments were conducted to determine the critical air velocity for preventing smoke rollback.
The fire intensity varied from 50 kW to 300 kW.
Airflow in the 2 m high and 2.9 m wide coal mine entry was regulated during each experiment.
Experimental results for the critical air velocity for smoke reversal as a function of fire intensity compared very well with model predictions based upon a CFD simulator.
The extent of smoke rollback along the roof into the fresh air was determined by the ventilation velocity, airway dimensions, airway slope and fire intensity.
The dimensions of the mine entry were: 126x2.91x2.06 m (LxWxH). See figure 9 below for the plan view of the test area.
The turbulent flow velocity was uniform through the experiments.
The dimensionless critical air velocity v_c^* and heat release rate Q^* are defined.
Wall roughness and geometry of the fire source are found to be significant factors.

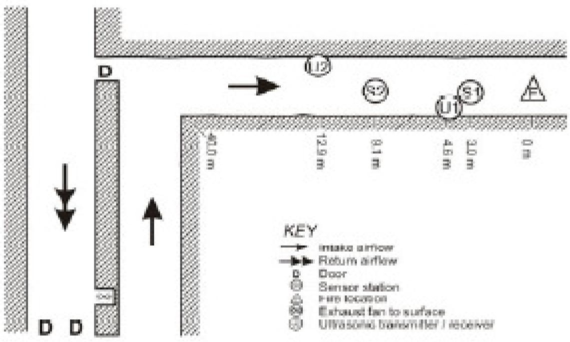

Figure 9. Plan view of the test area /32/.

It was demonstrated with fire smoke reversal experiments that for a range of fire intensities between 50 and 300 kW in a mine entry 2 m high and 2.9 m wide that the critical velocity for preventing the development of a smoke layer upwind from the fire is proportional to the fire intensity to the 0.30 power. This is in substantial agreement with other researchers who present a one-third law dependence upon the fire intensity. The development of visibility obscuration 9 m upwind from a small 130 kW fire when the ventilation velocity was reduced by 54% from its critical value demonstrated the importance for maintaining the critical ventilation velocity for smoke control. For the fires considered, the results are in approximate agreement with an empirical result which is independent of fire intensity. CFD modelling of the dependence of the critical air velocity upon fire intensity showed good agreement with measured values.

For the tested fire conditions the results are in accordance with other articles, as stated in the conclusions above. But as the HRR of the fires were small and practically steady-state (as diesel pool fires were used) the results are of limited value for fires in underground mines as for example vehicle fires will have demonstrate a dramatically different fire behaviour. Also the dimensions of the mine entry are typical for coal mines, but not for iron mines in northern Sweden.

In the article *CFD modelling of smoke reversal* /33/ the CFD code CFD2000 was used – which is based on the standard κ-ε turbulence model – to model a floor-level fire in a ventilated channel. Re-circulating flow patterns, movement of the ceiling-layer front, and distribution of gas temperature and velocity were studied under various fire parameters.
The result of computations showed a qualitative behaviour of the movement of the combustion products in the fire channel.
The profiles of the gas velocity and temperature along channel cross sections were similar to those experimentally observed.
The applied boundary conditions were for a steady-state fire scenario – propane diffusion flame (constant value of pressure at the channel exit and a uniform flow of ventilation air velocity at the channel entrance). In a real fire scenario, fans drive the ventilation air, and as a fire develops, the ventilation current is reduced because of an increased flow resistance in the channel.
An uncomplicated geometry was used in the work (30×2.4×1.6 m).
The results were based on the computed flow field 30 seconds after the initiation of the fire.
The result of computations showed a qualitative behaviour of the movement of the combustion products in the fire channel. The profiles of the gas velocity and temperature along channel cross sections are similar to those experimentally observed.
The inclusion of a finite-rate reaction scheme resulted in very long computations. It may be possible to employ a simpler reaction scheme and simulate a more realistic fire scenario. This point requires further investigations.
The present computations use a constant value of pressure at the channel exit and a uniform flow of ventilation air velocity at the channel entrance. In a real fire scenario, fans drive the ventilation air, and as a fire develops, the ventilation current is reduced because of an increased flow resistance in the channel. Thus, the boundary conditions used in the present computations apply to the fire scenario at the steady state.
In various analytical and experimental investigations, the tunnel shapes and sizes will vary considerably. Because of the lack of geometrical similarity among various studies, caution should be exercised in the comparison of results obtained under dissimilar geometries. The same caution applies to the cases with dissimilar fire scenarios.
It has been shown how CFD analysis can be used to determine a correlation between smoke reversal length and tunnel ventilation. The resultant correlation can be used to provide guidance for smoke management control measures. For example, the correlations indicate that ventilation current proportional to the one third power of the fire intensity must be maintained to provide an evacuation path from the fire source clear of smoke and hot gases. This is an example of how a CFD modelling employed correctly and interpreted carefully, can be a useful design tool for fire protection. Future investigations with other CFD codes and additional experiments should result in improved reverse flow length correlations.

The conclusion regarding the reduction in ventilation current are somewhat simplified. There are actually several factors that are influenced by a fire: density decreases, material parameters (such as viscosity) etc. The material parameters also influence the pressure drop. The characteristics of the fan will influence the ventilation current. Other findings are in accordance with the findings of other researchers, but the steady-state nature of the fire scenario and uncomplicated geometry reduces the applicability of the results for fires in an underground mine. Also apparently no consideration were taken to heat losses to surrounding rock mass, as the results were based on the computed flow field 30 seconds after the initiation of the fire.

In the article *Smoke reversal interaction with diagonal airway – its elusive character* /34/ the reversal of smoke from a mine fire was determined in a mine section with an airway connection. See figure 10 below for the plan view of the test area.
Four diesel fuel fire experiments with HRR between 504 and 771 kW were conducted.
Smoke reversal propagated upwind from the fire with significant leakage into the upwind diagonal airway and without causing a complete reversal of airflow in the diagonal airway.
A control measure consisting of a brattice suspended half entry height from the entry roof was determined to abate the smoke rollback. See figure 11 below for an example of a brattice blockage of smoke.

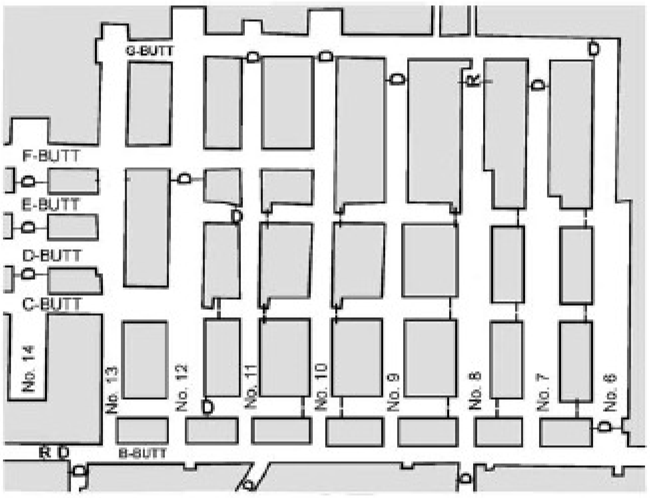

Figure 10. Plan view of the test area /34/.


Figure 11. Brattice blockage of smoke /34/.

CFD (using the FDS program /35/) analysis of the smoke movement agreed with the measurements.
Airflow reversal depended upon the pressure imbalances between the connected airways.
A ventilation change induced by the movement of equipment, by the opening and closing of doors can thus result in airflow reversals in a diagonal airway. The diagonal airway can be unstable with respect to airflow direction because its resistance can be less than that of the

airways it connects. The effect of the release of thermal energy in one of the main airways to which the diagonal airway is connected will have a more complex effect. The thermal expansion of the products from a fire will increase the local airway resistance, which could alter the ventilation pattern in the diagonal airway.

Beyond the application of FDS to a localized mine section, a standard mine ventilation network simulator can provide information on the spread of smoke and heat to the remainder of a mine if the smoke is well mixed over the mine entry. This suggests a coupling of the output from a CFD application to the input of a mine ventilation simulator to model the entire mine.

FDS does not account for the mine wall friction, which may delay the propagation of the smoke layer.

The conclusions were that smoke from a mine fire downwind from a diagonal airway can undergo reversal into the diagonal airway without causing a complete airflow reversal in the airway was demonstrated experimentally and modelled successfully with a CFD program. For fire intensities between 504 and 771 kW complete flow reversal did not occur in the diagonal airway. Instead of a total airflow reversal in the diagonal airway, the roof smoke layer flowed counter to the established airflow along the floor. A smoke reverse layer extended 8 m upwind from the fire to the diagonal and at least 40 m along the diagonal counter to the established airflow, as determined by the CO sensors in the diagonal. This event in a simple mine airway configuration is not modelled by standard mine-ventilation network simulators. Preventive planning with recommendations for miner egress and rescue are complicated by the smoke reversal into connecting airways. CFD analysis is a viable method to predict the formation of reversed smoke layers, and their movement provided the input parameters, such as mine dimensions, airflow quantities and fire intensity, are sufficiently known. It was demonstrated for a 771 kW fire that smoke reversal could be abated by a partial brattice coverage extending from the roof to approximately half the entry height. The 29 m distance of the brattice from the fire zone would make the ventilation effect localized. This is a possible smoke-reversal control measure for mine rescue. The FDS program was shown to be useful for determining the extent of fire-generated, roof-smoke reversal and the abatement of the smoke by a brattice suspended from the roof to mid-height. The turbulence model in FDS did not adequately account for the rate of smoke reversal. Additional research on the implementation of CFD methods needs to be conducted for a variety of conditions, which include airway dimensions, brattice cross-sectional area restriction, fire intensity and airflow. For each mine-entry configuration and partial entry blockage with a brattice, a critical ventilation velocity can be determined as a function of fire intensity which prevents smoke reversal. Given the complexities for conducting the experiments, a limited number of experiments could be modelled with a CFD application. Based on a successful comparison of predictions with experimental results, additional CFD applications could be used to determine a more comprehensive relationship between critical velocities, fire intensity, airway dimensions and smoke-control measures.

The geometry of the test area makes it highly applicable to fires in underground mines. Unfortunately only small, steady-state fires were used in the study, which highly limits the use of the results. The conclusion regarding the turbulence model in FDS is highly interesting and will have to be taken into consideration in future test fires. Also the idea of coupling the output from a CFD application to the input of a mine ventilation simulator in order to model the entire mine is brought forward.

In the article *Fire-generated smoke rollback through crosscut from return to intake – experimental and CFD study* /36/ two mine fire experiments demonstrated that smoke from diesel-fuel fires of 500 kW and 660 kW in a return airway can develop – without causing a complete air flow reversal – into a roof layer that can migrate upwind forming a counter flow to the primary airflow in a crosscut. See figure 12 below for the plan view of the test area.

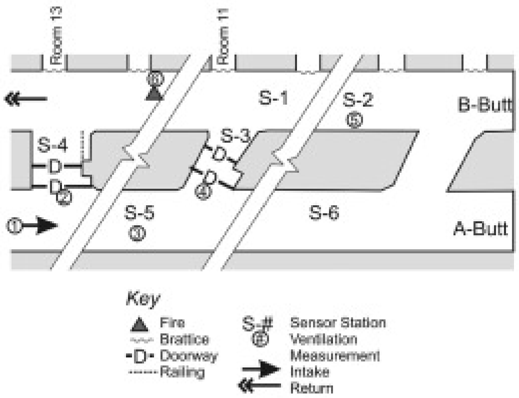

Figure 12. Plan view of the test area /36/.

Subsequently, smoke can penetrate into an intake airway and create a hazardous atmosphere in the intake airway upwind from the fire. Visibility conditions less than 13 m were created by the smoke in the intake airway downwind from the crosscut.
The following conclusions were determined from the experimental results and CFD simulations:

- The experimental mine fires in a return airway produced sufficient buoyancy to establish a smoke-laden roof layer that flowed through connecting crosscuts counter to the direction of fresh air from the intake entry.
- The density of the smoke that leaked into the intake was shown to yield insufficient visibility downwind from the last connecting crosscut in the intake entry for someone unfamiliar with the mine to find their way out easily.
- The CFD simulations showed good agreement with the experimental observations of smoke movement.

Smoke rollback along the roof from a fire counter current to the cooler airflow near the floor can be a mechanism for smoke to move from a mine return into a mine intake in low airflow sections (thus one can prevent the inflow of smoke from a crosscut by increasing the intake airflow). The realization of this possibility would not be predicted from a mine-network ventilation program which is based only upon unidirectional flow (thus it does not account for inflow at the ground and outflow of smoke). CFD modelling is a possible method for analyzing potential visibility hazards associated with smoke from a mine fire.

Even though an interesting geometry was used during the study, the steady-state nature and small HRR of the fires makes the results of little value for the present project. But similar tests with higher HRR should be conducted in the project if possible, as the subject is highly interesting.

7.3 Zone model

In the article *Applied zone model to evaluate the smoke management in an underground structure* /37/ a zone model is used as well as simplified mathematical models to investigate the smoke temperature and accompanying effect in an underground structure with a long corridor. Also, an evacuation assessment and escape time calculation were evaluated in this paper to address the strong relationship between evacuation and smoke control design.
Experimental data collected from a full-scale underground corridor in Japan was used to validate the results from the model predictions.
An alpha t-square curve /38/ was used to describe the HRR.
The mathematical model did not precisely predict the smoke layer height.
The zone model (CFAST /35/) provided quite accurate trend for predicting the average smoke temperature and smoke height.

The conclusions of the article were that two different smoke models coupled with the escape time estimated methods were applied to evaluate the smoke exhaust volumes of an underground corridor structure. The smoke layer heights are calculated using t-squared fire mode and a small fire and ultrafast fire growth coefficients are incorporated into the equation. The simulated results show some discrepancies on predicting smoke layer heights from different models. The data of smoke layer height will result in an important impact on determining the smoke exhaust volumes. Also, experimental data from a full-scale underground structure was adopted to compare with the predicted results. It shows that the zone model can provide quite accurate trend for predicting the average smoke temperature and the smoke height. From the deviation analysis between experimental data and predicted results, it is noted that the smoke temperature predicted by 20-segment case has a better agreement than other cases. In addition, the average discrepancy between experimental data and predicting results by 20-segment case approximately 5.1% that will satisfy for practical engineering design purposes. In short, the smoke temperature distribution and the corresponding smoke lay interface height along the pathway of such underground structures are available, predicted by a zone model with a divided pathway of many equal cross-sectional area segments connected to one another.
The work is of little use in the project as a stable stratified hot layer will most likely only be found at the very near area of the fire. A reason why a zone model was successfully used was due to the fact that the geometry was very simple and the length of the corridor was small (40 m).

In the article *Simulation of tunnel fires using a zone model* /39/ the zone model CFAST (version 2.0) was used. During the simulations an arbitrary tunnel was considered as a single compartment, a two-room structure respectively a three-room structure. Five fires – having a high likelihood of occurring in a tunnel – were considered (burning wood cribs, a passenger train, a subway coach, a truck and a school bus).
Results were compared with another zone model (CCFM.VENTS) and with a self-developed fire field model.
Experimental data from a smaller – abandoned – copper mine in Norway was used to justify the prediction.
The dimensions of the simulated tunnel were: 150x10x8 m (LxWxH).
Peak HRR varied between 10-35 MW for the five fires.
The average values of the smoke temperature and smoke layer interface height calculated for the two-compartment and three-compartment cases agreed well with the values for the single-compartment case, except for the school bus fire.
When comparing the results of CFAST with the results of CCFM.VENTS, it could be seen that the values of maximum smoke temperature are much smaller for CCFM.VENTS than those of CFAST – as much as 50% smaller.
Fairly good agreement was obtained between the results of the self-developed field model with the experimental data and with the results using the field model JASMINE.
The conclusions were that the probable fire environment in a tunnel with cross-section area similar to a typical tunnel found in Hong Kong was simulated using the zone model CFAST. Five types of fires that are believed to have high likelihood of occurring were used. Sensitivity analysis on the predicted smoke temperature and smoke layer interface heights was performed by dividing the tunnel into smaller compartments and varying the length of the tunnel section. The results are also compared with those predicted by another zone model (CCFM.VENTS), and by two fire field models (JASMINE and a self-developed model). Experimental results on a smaller tunnel in an abandoned copper mine in Norway were also used to validate the results. It was found that the zone model CFAST is at least as good as the other models at predicting the average smoke temperature and the smoke layer interface height. To give a "microscopic" description similar to that obtained from a field model, the smoke temperature distribution and the corresponding smoke layer interface height along the tunnel length can be predicted by dividing the tunnel into

more compartments connected to one another by vertical vents with area equal to the cross-sectional area of the tunnel.
The question of whether to use a fire zone model or using a CFD model for simulating the fire environment has been raised on many occasions in the literature. The advantage of using a CFD model is that it can predict the air flow pattern, the temperature and the smoke contours. However, it requires a very long computing time because of the large number of equations to be solved. Floating point errors due to the computer hardware itself is a problem that should not be neglected. Also, there may be hesitation in selecting a turbulence model, the schemes for discretizing the differential equation using the control volume method, and the algorithm for solving the pressure and velocity-linked equations. All of these factors must be clearly understood by the users before applying the CFD model, despite the other problems related to the free boundaries and the relaxation factors.
On the other hand, a zone model is much simpler in nature and includes almost all the physical principles of a compartment fire. Of course, the main assumption is the two-layer picture. This assumption results in many fewer equations to be solved, giving much smaller floating errors, and therefore allows the program to be run on a PC.
The disadvantage of this model is whether a stable stratified hot layer can be found in the tunnel. The conclusions regarding the usefulness of a zone model in a tunnel fire is questionable and definitely in a mine fire, as a stable stratified hot layer will most likely only be found at the very near area of the fire. Also the geometry of the test area in the study was very simple and small, which will most likely not be the case for a mine fire.

7.4 Ventilation network simulation program

In the articles *Transient-state simulation of ventilation systems in fire conditions* /40/ , *Real-time precalculation of the distribution of combustion products and other contaminants in the ventilation system of mines* /41/, *Real-time calculation of products-of-combustion spread in a multilevel mine* /42/, *Study of precalculation of effect of fires on ventilation system of mines* /43/ and *Study of mine fires and mine ventilation, part 1: computer simulation of ventilation systems under the influence of mine fires* /44/ two programs that were developed since 1980 are described. The programs allow the real-time calculation of fume or other contaminant concentration distributions. Both programs were based on 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. Calculated under steady-state conditions are the airflow rates that result from the cooperation of fans, thermal forces and airway resistances. Varying with time are the thermal forces, which are caused by temperature differences of the ventilating air. Changes of the normal air temperature distribution are due to the heat exchange between rock and air (observed only in the immediate vicinity of the heat source and a short distance downwind of it). Changed airflow distributions due to changed temperature distributions are reached almost instantaneously.
The program based on the first assumption is shorter, requires less input data etc. The program based on the second assumption requires detailed information on the ventilation system. Beyond network configuration and airway dimensions, the fan characteristics, the aerodynamic properties of the airways, their elevation changes and the thermal properties of the surrounding rock must be known.
The program based upon the second assumption is worth looking further into and performing simulations integrated with a CFD model.

In the article *Mine fire experiments and simulation with MFIRE* /45/ the work of US Bureau of Mines to validate MFIRE's calculation of temperature distribution in an airway due to a mine fire is

described (as temperatures are the most significant source of ventilation disturbances). The calculations were validated against the results of fire tests conducted at the Waldo mine (fuel used in the two tests were diesel and wood (fir) respectively). From these experiments, temperature profiles were developed as functions of time and distance from the fire and compared with simulations from MFIRE.
The conclusion was that the transient state simulated temperature distributions are reasonably predicted to within a few degrees. With a heat sink added near the soaked timber, even better agreement would result.
The reasonably well predicted temperature distribution makes the model worth looking further into and performing simulations integrated with a CFD model. The heat release rates of the fires in the study are unfortunately not listed.

In the article *Design of emergency ventilation system for an underground storage facility* /46/ the design of an emergency ventilation system is examined. Due to the pattern of the underground area and the variety of products stored, numerous fire scenarios should be examined in order to secure escape routes in every case, which significantly complicates the situation. For this reason, a different approach was adopted, matching recent developments in fire safety from tunneling projects and ventilation practices from the mining industry. The ventilation design was based on the critical velocity theory; however, alternative configurations of the underground space were simulated by means of mine ventilation software. These alternatives affect the direction and velocity of the airflows and, consequently, the air quantity and the fan power required, in order to secure escape routes during fire emergency. The analysis not only determines the ventilation system characteristics, but also indicates the most appropriate design of the facility, in order to come up with a solution that is both secure and economically acceptable.
Using a probabilistic approach (95% quantile) when deciding upon the HRR and thus also the resulting critical velocity.
Mine ventilation software that was used, VnetPC, assumes incompressible flow and thus a ventilation network simulation program.
The compartmentalization of the area, by installing stoppings and the partition of the warehouse into parallell corridors, seemed to be the most efficient solution in order to attain the critical velocity (as attaining critical velocity in every airway of the area is proved to be not attainable).
The conclusions were that it examines a special case of an underground warehouse center, which is constructed using a classic mining method, namely room-and-pillar. The analysis tries to bridge the gap in the literature concerning subsurface storage facilities by developing ideas adopted from cases met in both tunnel and mine-fire events. In the case studied, due to the large number of the potential fire scenarios involved, the analysis follows a different approach, dealing not only with the influence of the ventilation system, but also the outline of the underground space. In addition, Monte-Carlo modelling simulation was used to address the uncertainty of the products stored in the warehouse, covering a number of different situations (heat release rates).
The requirement for critical airflow in every airway of the area is proved to be not attainable, since enormous air quantities would be required. Towards this direction, alternative configurations of the underground space are analyzed by means of mine ventilation software. The compartmentalization of the area, by installing stoppings and the partition of the warehouse into three parallel corridors, seems to be the most efficient solution. In addition, the installation of regulators is necessary in order to optimize the ventilation system performance. The analysis proved that the control of smoke flow is achieved at any area of the underground structure and safe evacuation is obtained. Hence, the results not only indicate the proper ventilation system characteristics, but also provide the most suitable design of the facility.
The approach presented is less complicated and can be easily applied compared to CFD simulations. Due to the pattern of the underground area and the variety of products stored, numerous fire scenarios should be examined in order to secure escape routes in every case, a fact

that would significantly have complicated the analysis. Of course, in some cases the approach proposed may be unfeasible, due to the high investment costs required for achieving critical airflow velocities in each corridor.
According to the analysis, the requirements for air supply during normal operation are minimal. This demand could be covered via natural ventilation or the temporary operation of a fan. Nevertheless, the design of the emergency ventilation system is crucial, as fresh air requirements are significant. For this reason, emergency ventilation system should be a part of the overall study of the project, as it interacts with the number and the form of the access works as well as the internal layout of the underground facility.

The decision on not using a CFD model can be discussed as the use of a CFD model can be relatively straightforward and will model the near vicinity of the fire much better than a ventilation network simulation program. A further weakness of the article is that the findings have not been verified against actual fire experiments.
The article also deals with an interesting issue, the problem of achieving critical ventilation velocity. The idea of installing stoppings and partitions does not fully account for the friction losses that will occur when installing stoppings and partitions, thus the conclusions with respect to this issue is a bit oversimplified and misleading.

In the articles *Computer-aided ventilation modelling* /47/ and *A user's manual for MFIRE: a computer simulation program for mine ventilation and fire modelling* /48/ the computer program MFIRE is described in detail and its features are discussed.
The program is distinguished from other network programs in that natural ventilation is calculated from the temperature distribution that exists in the mine or is produced in the airways by a fire.
The conservation of energy in a mesh is a restatement of the first law of thermodynamics (i.e.: *for all adiabatic processes between two specified states of a closed system, the net work done is the same regardless of the nature of the closed system and the details of the process*) as applied to energy losses due to friction, fans and natural ventilation.
By the use of temperature dependent resistances (resistance corrected for temperature induced air density changes), the airflow rates are maintained as volumetric flow rates based upon standard density thermal losses to the airway wall is modelled in a quasi-steady state approximation using a "coefficient of age". Temperature changes in inclined shafts produces natural ventilation, while thermal effects in horizontal passageways produce a throttling of the airflow.
In the network computation a perfect mixing of airflows from different airways is assumed to occur at each junction. Similarly, a perfect mixing of the enthalpy is assumed to occur at each junction.
The conclusions of the article were that the MFIRE program has the predictive capability to determine ventilation flow with thermally generated natural convection. Hazardous events, such as normal methane emission, a fuel-rich or fuel-lean fire, introduction of contaminants into an airway, or a failure of one or more fans, can be simulated with the program. The program user can identify those airways in which critically high methane or smoke concentrations, high temperatures, or small pressure changes exist. This information should be useful in the development of strategies for miner escape and rescue as well as ventilation planning. A recent extension of the program to include a real-time calculation of the contaminant distribution will enable the user to predict both the immediate contaminant concentration as well as the cumulative exposure at any location within the mine.
The model is worth looking further into and performing simulations integrated with a CFD model. Furthermore one could wonder about the accuracy of the assumption that a perfect mixing of airflows from different airways is assumed to occur at each junction. This assumption could be worth investigating further.

In the article *Prediction of smoke movement in mines: Siting of fire detectors and escape considerations* /49/ the MFIRE program was used to study the consequences of fire, and different mitigation strategies, in a complex network of mine roadways at a specific UK coal mine. Results from this work, together with the practicalities of using the program and its transfer into industry, are discussed. Research to develop, validate and apply CFD techniques (using FLOW3D) for the selection and siting of fire detection equipment in mine roadways is also described.
The conclusions were that the network-based mathematical modelling techniques are powerful tools for predicting the gross consequences of mine fires and the effectiveness of different mitigation methods, such as fire door closure or the control of ventilation fans. Their output can be used to give an indication of the relative hazards posed by the combustion products of fire, and so could be utilised in risk assessments for the mining environment. The potential of CFD for helping site fire detection equipment has been demonstrated. Further work to develop and validate the technique specifically for the mining environment is needed.
The results of the article are of limited use for the present project as the study was conducted in a coal mine.

In the article *Simulation of mine fires* /50/ a numerical simulation method – which the program Ventgraph is based upon – is described. The method enables the determination of transients caused by fires. The mathematical model has been based upon a:

- Simple model of combustion of fuel in the airway
- Unsteady exchange of heat between the fire, airflow and surrounding rocks
- Airflow in mine ventilation networks
- The theory of heat flow in the rocks.

This article presents another ventilation network simulation program than MFIRE, thus it would be interesting to include both in the future work when performing simulations integrated with a CFD model and comparing the results of the two programs.
The simplifications and assumptions of the method are listed in the paragraph below.

In the article *Validation study of the mine fire simulation model* /51/ validation studies of the mine-fire simulator (Ventgraph) - using data gathered from an actual coal mine fire that occurred in 1991 – were presented.
The study evaluated the suitability of the computer software package for modelling underground fires.
The Ventgraph is based upon the following simplifications and assumptions:

- Fire has a lump character.
- Rate of fuel consumption is a given function of time.
- Carbon dioxide is the only one combustion product determined due to the combustion process.
- Unidirectional flows.

The purpose of the program is to predict the behaviour of the ventilation system during a fire.
The conclusions were that in order to determine the amount of carbon monoxide generated by the fire, additional theoretical and experimental work is required, leading toward development of a more sophisticated model of an underground fire.
This article reflects the results given in /48/.

In the article *Computer simulation of mine ventilation disturbed by fires and the use of fire extinguishers* /52/ the Ventgraph program is described further in detail. The mathematical model used in the computer simulation program has been based upon mathematical models of the particular phenomena, which accompany the mine ventilation process during a fire fighting action. Phenomena to be taken into account in the model are as follows:

- Combustion of burning materials
- Non-steady heat exchange between the fire, flow and the strata
- Non-steady flows in the network of airways of the mine
- Heat flow in the strata as the result of heat exchange between flow and surrounding rocks
- Generation of inert gas
- Transport and mixing of air and combustion products

The mathematical model considered consists of a very large set of non-linear partial differential equations and ordinary differential equations, algebraic equations, which has been derived from basic physical principles concerning conservation and transport of matter, momentum and energy. Equations of mathematical model fulfil the first and second Kirchoff's law concerning the mine ventilation network.

Simplifying assumption made during the derivation of the mathematical model will restrict the use of the simulation method to certain cases. Assumptions:

- Air and gas flow in branches is regarded as one-dimensional
- Mixing of gas components in junctions is assumed as instantaneous
- Fans, doors, stoppings and other elements (such as the fire) has been assumed as lumped quantities
- The pyrolysis rate is a given function of time
- The fire produces only carbon dioxide.

The conclusions were that computer simulation of transient states and disturbances in mine ventilation networks caused by fires allows carrying out studies and analyses concerning the use of inert gas extinguishers. The simulation method described may facilitate case studies, the working out of effective routines for the management and rescue teams in case when inert gas generators are, or should, be used in order to fight underground fires. Graphical presentation facilities predestinate the presented computer simulation method, especially for planning and teaching. Further work, concerning the subject under consideration, which has to be carried out, is the validation of the simulation method, especially when decision making during fire fighting actions should be supported and assisted by this method.

The use of inert gas generators is a method almost solely used in coal mines, thus making parts of the article not useful in the present project. A question here is how all the rather rough assumptions (listed above) affect the accuracy of the output of the method. As validation studies are apparently missing, the question is still valid.

In the article *Case studies from application of numerical simulation software to examining the effects of fires on mine ventilation systems* /53/ a research project into mine fires study applying the "Ventgraph" simulation software, preplanning of escape scenarios and general interaction with rescue responses was outlined.

The project had assisted the Australian mining industry to attain an improved position in their understanding of mine fires and the use of modern advances to preplan actions to be taken in the advent of mine fires.

It is difficult to predict the pressure imbalance and leakage created by a mine fire due to the complex interrelationships between the mine ventilation system and a mine fire situation. Depending on the rate and direction of dip of the entries (dip or rise), reversal or recirculation of the airflow could occur because of convection currents (buoyancy effect) and constrictions (throttling effect) caused by the fire.

The conclusions were that to understand fire simulation behaviour on the mine ventilation system, it is necessary to understand the possible effects of mine fires on various mine ventilation systems correctly first. Case studies demonstrating the possible effects of fires on some typical Australian coal mine ventilation circuits with diagonal connections were discussed. It is important to identify and understand these potential effects on the mine ventilation network as the airflow through the diagonal connections could reverse or stop due to the changes in the adjoining branches within the ventilation network. Mining companies need to identify the existing and potential diagonal connections in their ventilation system and analyze how these connections will affect their ventilation system especially in the case of fires. Training is necessary to equip mine ventilation personnel how to identify and minimize diagonal connections in their ventilation system.

The same issue on diagonal airways applies to iron mines as well. The diagonal airways will further complicate the spread of smoke at a level. This shows for example the importance of using modelling tools when planning for the ventilation layout.

In the article *Simulation of ventilation and fire in the underground facilities* /54/ the fire outbreak and evacuation simulation model, MFIRE, is presented.

The model provides information for setting up an emergency ventilation scheme, establishing safety procedures and minimizing damage in underground network systems.

MFIRE simulates the interdependence between the ventilation system and its pertinent fans and structures, and the changes in ambient conditions and the heat source. It also takes natural ventilation into consideration.

A laboratory based fire simulation (steady-state fire of 1 kW) was conducted in a small tunnel network to validate the MFIRE. The rates of air flow and temperature distribution in each tunnel were compared with the simulated results obtained by MFIRE. Regarding air flow, the experimental rates correlated with the simulated results very well. Because of the reduced physical scale of the laboratory model, the simulated temperature distribution did not quite correlate with the laboratory data.

The experimental output showed large differences between the tunnels which were located in the vicinity of the fan outlet. The differences could be due to the fact that pressure drop losses may change due to the different angles of the tunnel junctions.

The MFIRE program consists of four parts:

- Network calculation: basic governing equations. Assuming a steady state in the system, the program solves the equations by Hardy Cross method. The solutions can perform basic network balancing without considering heat/mass transfer, and predict the new pattern of updated airflow distribution.
- Temperature calculation: air temperature at a given location behind a fire is determined by the first law of thermodynamics. The heat transfer model in the radial direction of airways considers the temperature of an air current along its source towards the surface, and heat and mass exchange between the air current and its surroundings. The effects of heat transfer and mass diffusion were included in the governing equations, and the analytical solutions were pursed.
- Transient-state simulation: transient-state simulation which follows changes in ventilation step by step to offer a continous snapshot of the ventilation pattern.
- Quasi-equilibrium simulation: quasi-equilibrium simulation predicts the ventilation pattern in more or less steady state conditions after a relatively long period of time has elapsed.

In case reversed air flows occur, the user must actively detect this and change/reorganize the data. Furthermore, it is possible to change fire characteristics during a simulation.

The conclusions of the article were that in order to validate the applicability of the MFIRE, a ventilation system was employed and air flow and temperature distributions within the various tunnels of the designed system was measured. Both the numerical simulation and the physical experimental results indicated that the heat produced by a fire without ventilation could not discharge from the system quickly, thus creating a high temperature environment. However, if a fan was activated timely to provide ventilation, the hot gases could quickly discharge and the tunnel temperature fell to an equilibrium value gradually. If mechanical ventilation was applied immediately after the outbreak of fire, both the experimental and simulation results had indicated

that stability could be achieved once an equilibrium temperature was reached, and the temperature stopped to rising. However, the simulated temperature distribution does not correlate with the laboratory data very well because of the reduced physical scale of the laboratory model.
The air flows in the ventilation system obtained through both the experimental and the numerical simulations, in contrast to temperature simulation, were practically coincident.
MFIRE simulated a hypothetical fire incident. The simulation results of airflow confirmed that the flow rate of fire and evacuation tunnel is adequate for the safe evacuation of people. On the other hand, the simulation results of temperature showed that the temperature of the fire node rises immediately to near the highest temperature. At the same time, the hot gas in the "push-pull" ventilation model gradually expands into the downstream part of the tunnel where the temperature rises slowly. On the contrary, the other tunnels without "push-pull" ventilation model maintain almost normal temperature. The current "push-pull" ventilation method can extract the high temperature air and smoke out of the underground facilities efficiently.
The article raises several questions and doubts. What does the 1 kW fire equals to in a full-scale fire? Did the bad correlation really depend upon the reduced physical scale of the laboratory model?
But the big question with respect to this article is how well does the results correlate with the results of a real fire? Most likely the MFIRE will not be able to reproduce the fire dynamics at the region near the fire. How will that affect the results of the smoke spread further away from the fire? The article was found to be of limited use in the present project.

In the article *Simulation of thermal and aerodynamic effects of a fire in a complex underground ventilation network* /55/ a program developed by the Lorraine Basin Coal Mines in France is described. The program – named FEUMIN - calculates the smoke temperature over the mine network using the Hardy Cross method. To be more precise the program supplies the following parameters: the temperature at each point (for calculating the density), the modified value of resistance in each branch and the flow rate in each branch. In the program the walls are progressively heated by the smoke from the fire.
Further developments of the program is described in the article *Development of ventilation software on personal computers in France and the application to the simulation of mine fires* /56/. At this stage the program was renamed as the PC FIRE program and being an additional module to PC VENT. The program starts with a standard PC VENT calculation, as though there was no fire. It then calculates pressure drop and temperatures along the fire branch. After this it follows the circulation of the air from its ending node downstream, taking the temperature as an unknown and calculating it as well as the new ventilation pressures. At the end of this first stage, a new calculation is started, initialized with the new values of airflows etc.The calculation is stopped if the network is stable. The required inputs of the program are (besides the required input of PC VENT):

- The length of each branch
- The location of the fire
- The time since the fire broke out
- The dry bulb temperature of the air flowing through the fire.

The conclusions of the articles were that with the program it is possible to analyze specific steps to be employed rapidly in the case of a fire to stabilize the ventilation and to prevent dangerous fluid inversions.
The input data (i.e. the dry bulb temperature of the air flowing through the fire) seems a bit unpractical to use. Furthermore, if the program is still available it could be included in the future study when performing simulations integrated with a CFD model.

In the article *Unsteady-state processes during an open fire in a ventilation network* /57/ a method and computer program (named VENT-4) is described. The method and the program were developed in order to solve the complex simulation of a mine ventilation network during an open fire (an open fire is a fire that occurs in airways, faces and other openings that form part of the active ventilation system of the mine and, hence, affect the quality of the mine airflows quickly and directly). Unsteady-state conditions in the system have resulted from the following factors:

- Temperature changes in the fire zone
- Gradual filling of the ventilation network with combustion gases
- The local heat transfer between these gases and the rock surfaces.

The method is illustrated with calculations for a small ventilation network.
The transient character of the temperatures of combustion gas-air mixtures gives rise to an unsteady-state condition for the density of the gas-air mixture, which results in the formation of time-dependent contours of the thermally induced draught and corresponding changes in the airflows and fan performance. These factors provoke a complicated condition for the mine ventilation system during the first 30-60 minutes after starting of an open fire in a mine. The network problem is reduced to an iterative solution of the system of equations, which takes into account the following parameters at each branch, junction and mesh in the network:

- Airflow quantity
- Aerodynamic resistance of the mine workings
- Air pressure
- Air temperature
- Air density
- Temperature of the rock walls
- Fan pressure
- Natural ventilation pressure.

The fire is assigned to a junction of the network and may have a constant or variable temperature.
The conclusions of the article were that the precise prediction of the thermal energy transfer of the fire in the ventilation network is of great significance for the correct description of these processes. An extension of the experimental and theoretical studies in this direction is recommended.
The theory has had limited spread around the world and seems to have been limited to Bulgaria. Thus it is doubtful whether the computer systems are presently available.

7.5 Genetic algorithm

In the article *Airflow optimizing control research based on genetic algorithm during mine fire period* /58/ a qualitative tool is briefly described for achieving the appropriate air flow during a mine fire. The tool is not suitable for complex ventilation networks. In this case a quantitative method is required.
The article describes how the ventilation should be arranged depending on the position of the fire. In order to quantitatively compute the airflow control scheme, it is necessary to describe these requirements using mathematical model.
The model used genetic algorithm to solve the problem of airflow quantitative optimization control during a mine fire, instead of using nonlinear programming.
The model can for example provide suggestions on safe escape routes for miners during a fire. It can also be used for optimization design of ventilation system when designing, reforming or expanding the mine tunnels.

The article is of little use in the project, as for example no physics is involved in the described tool. This is purely a mathematical model. Also – as stated above – the tool is not suitable for complex ventilation networks, which drastically limits its use.

Summary:

The idea of using a CFD model in conjunction with a ventilation network simulation program is very much worthwhile to investigate as the benefits of a successful method would be most rewarding to the mining industry during for example the design process of a new mine section. The results should of course be compared with and validated against corresponding fire experiments.

The ongoing work on CFD modelling has been extensive but there are still some gaps that need to be investigated (and compared with and validated against corresponding fire experiments). The following factors should be looked into:

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

The investigation should also include the actual implementation of CFD models and suggestions on improvements should be made.

Zone models are found not found to be applicable to modelling in underground mines as a stable stratified hot layer – typical of a zone model - is only applicable in the near field region of the fire. Using a CFD model in that region would be a better choice.

With respect to ventilation network simulation programs it would be most interesting in the future to:

- Validate them for non-coal mines.
- Validate the results of several ventilation network simulation programs and comparing the results of the different programs with each other.

8. Fire protection systems

8.1 Flammability testing

In the book *Flammability testing of materials used in construction, transport and mining* /59/ materials found in mines are described.
The book also lists the flammability test methods (in USA) for various materials in mines:

- Brattice and ventilation tubing
- Conveyor belt
- Cable and splice kit
- Signal cable
- Hydraulic fluid
- Coatings/sealant
- Stoppings and other ventilation controls

The material could be used as a reference material during the project when looking into design fires in underground mines.

8.2 Sprinkler systems

In the article *The performance of automatic sprinkler systems in the extinguishment of incipient conveyor belt fires under ventilated conditions* /60/ a study by US Bureau of Mines to evaluate the effectiveness of automatic water sprinkler systems in the extinguishment of incipient conveyor belt fires under ventilated conditions is described.
Large-scale experiments were conducted using a double strand conveyor belt configuration. Various types of sprinkler heads with different activation temperatures were tested at different air flows.
The conclusions were that the results indicated that each type of sprinkler installation was able to control and extinguish the incipient fires. In tests using 100ºC standard response sprinklers in both system configurations, the results showed an increased effectiveness at the lower airflows in terms of when the first sprinkler activated and the peak heat release rate observed. When 74ºC fast response directional sprinklers were installed according to the Federal standards, the sprinkler system showed a slightly improved performance at the lower airflow.
The result of the article is not of interest to the present project as conveyor belt fires are not a common type of fire in Swedish underground mines and that in vehicle fires (which are the dominating type of fire) the fuel is not continuous.

In the article *Effectiveness of various concentrations of an inert gas mixture for preventing and suppressing mining equipment cab fires: development of a dual cab fire inerting system* /61/ a series of large-scale experiments were conducted to evaluate the effectiveness and safety of various concentrations of an inert gas mixture (i.e. Inergen) for preventing and suppressing cab fires. See figure 13 below for the experimental setup.
Comparison of concentrations effectiveness in yielding safe times led to the choice of an optimum gas mixture concentration, discharged in the cab through a muffled nozzle system, for the development of a dual cab fire inerting system.
Cab fires are caused by the ignition of flammable vapors and mists that penetrate the cab during prolonged hydraulic fluid and fuel fires, and electrical malfunctions involving other cab combustible materials. Often, these fires force the operator to exit the cab under hazardous conditions during a time needed to perform emergency tasks. Hence, it is important to provide the operator, not only with an engine fire suppression system (dry chemical powder), but also

with a cab fire protection system, effective both in preventing the ignition of flammable vapors in the cab, and suppressing cab material fires.
The conclusions were that for the prevention of flammable vapours and mists experiments, the 51%, 45% and 41% gas mixture concentrations, respectively, were effective in preventing the ignition of flammable vapours and mists in the cab while maintaining breathable atmospheres. Based upon the results the 45% gas mixture concentration discharged into the cab through a muffled discharge nozzle system, was chosen as the optimum concentration for the development of a dual cab fire inerting system. For the cab fire suppression experiments, results show that the 45% gas mixture concentration discharged through a muffled nozzle system at closed cab vents, was effective in suppressing the cab fires (~32 kW) within the first 20 s of gas mixture discharge-start while maintaining safe cab atmospheres. Finally, results of fire parameters obtained during the 30 s fuel preburn time such as oxygen depletion, and possible evolution of toxic gases at flame temperatures of ~400ºC, imply that any cab fire protection system should be accompanied by a rapid cab fire detection system. Similar rapid detection systems may also be installed within the engine compartment for the rapid detection of incipient hydraulic fluid/fuel fires before large concentrations of flammable vapours penetrate the cab.
The tests demonstrate the rapid fire behaviour of spray fires and the hazard to operators in a cab. The fire suppression system and rapid fire detection system should be considered for Swedish cabs that are manned in underground mines.

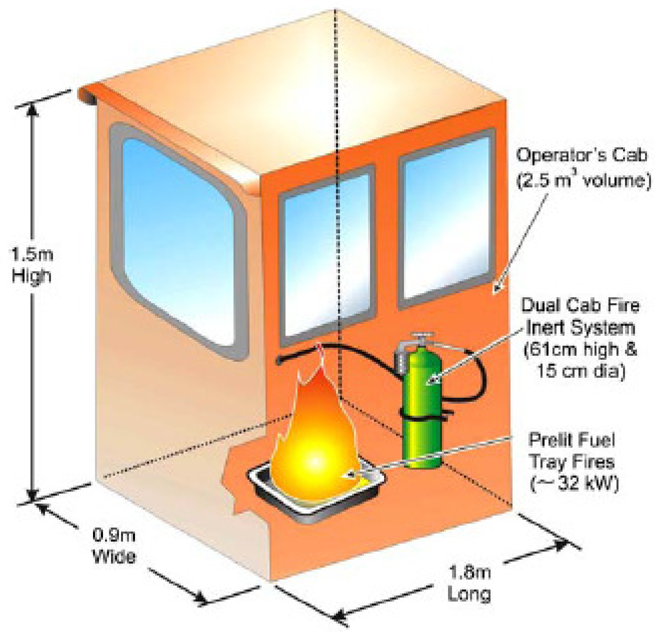

Figure 13. The experimental setup for the cab fire suppression tests /59/.

8.3 Detection systems

In the article *Early detection of mine fire in underground by using smell detectors* /62/ a new detection system using smell detectors is described to detect the spontaneous combustion of coal and the combustion of other materials used underground.
The conclusions of the article were that spontaneous combustion of coal can be detected earlier by this new detecting system using smell sensors than by conventional CO detection systems. There is no difference in the results for different kinds of coal. There are significant differences between the shapes of graph for the coal, rubber, machine oil and wood samples (charts enable us to discern the source of combustion gases). Combustion of other materials can also be detected earlier by this system than by conventional detectors for gas and smoke.

The article does not specifically apply to the present project and mostly applies to coal mines. Thus it is not of any specific use in the project.

In the article *Rapid detection and suppression of mining equipment cab fires* /63/ a series of large-scale experiments were conducted to evaluate the effectiveness of optical flame detectors, photoelectric smoke detectors and combined ionization and photoelectric smoke detectors for rapidly detecting mining equipment cab fires. The detector alarm time were then used to trigger the discharge of a fire inerting system inside the cab to suppress cab material fires.
The article discussed the types of fire detectors that were tested, the experiments that were conducted and the results obtained.
Conclusions were that rapid detection of equipment cab fires can be achieved to trigger the discharge of a fire inerting system inside the cab to protect the operator in the cab.
The extinguishing agent used during the tests was Inergen.
HRR of the various fires: 32, 0.5, 0.05 and 0.005 kW.
The conclusions of the article were that the data indicate that the optical flame detector, installed within the operator's cab, provide the operator with sufficiently early warning of early flaming fires and the combined ionization and photoelectric smoke detector provide sufficiently early warning of smouldering fires to activate a cab fire suppression system, to perform safe parking of the vehicle and engine shutoff, and exit the cab. Of note is that the combined ionization and photoelectric smoke detector offers additional qualities such as manageable size and cost effectiveness.
The article could serve as a basis for recommendations regarding supplying the cab with additional fire protection with respect to the obvious hazards of spray fires underground.

In the article *A fresh approach to mine fire detection* /64/ the detection of fires in coal mines (mostly) is described.
Traditionally mine fire detection systems in coal mines rely on the detection of changes in the levels of CO in the mine atmosphere. Experiment shows that other gases, products-of-combustion, are evolved from coal at much lower temperatures and therefore earlier in the heating/fire life cycle than CO. Tin oxide sensors are both cheap and very sensitive to POC's. They are in fact sensitive to a very wide range of gases and this has always been considered a disadvantage. This high sensitivity and broad spectrum response has often been interpreted as base line instability but experiments has shown that their response is both predictable and stable. Using a multi-sensor array of heated tin oxide sensors it was found possible to analyze gas mixtures using a neural network to deconvolve the results.
Based on these results a mine fire detection system using tin oxide sensors to detect POC's is proposed.
The conclusions were that the present methods for detecting heatings are based on monitoring carbon monoxide levels. The disadvantage of this method is that relatively high coal temperatures are required before detection is possible. The article shows that by using products of combustion concentration together with NO_x, water, carbon monoxide and Sulphur compound levels, a much earlier detection is possible. Reliable detection, however, requires the use of neural networks to correct the products of combustion levels for drift due to the presence of water vapour and shot firing fumes. Finally, the article describes how the results of the work can be used to develop an Intelligent Monitoring System (IMS) based on existing multi sensor arrays to provide early detection of heatings and mine fires.
The article mostly applies to coal mines and is thus of limited use in the present project.

The article *In-mine evaluation of underground fire and smoke detectors* /65/ the current state of fire and smoke detection technology is reviewed from the standpoint of suitability for use in underground metal and non-metal mines. Detection modes, fire signatures and environmental considerations

are included in the review. Preliminary results of long-term, in-mine tests are presented in the article.
The article provided some discussion on nuisance alarm discrimination.
Little is known about optimum detector positioning and spacing in mines. NFPA standards do not offer any criteria directly useful in a mine. Mines vary so widely in distribution of combustibles, ventilation patterns and roof support systems that an installation code may not be feasible or even desirable. Complicated ventilation patterns, random ceiling obstructions and a variety of tunnel shapes would not allow general applicability of such a code.
The intensive fire detection activity tends to make the contents of the article old and not very useful, as the fire detection technology has evolved a lot since this article. Also the contents of the article do not directly apply to the present project.

In the report *In-mine evaluation of smoke detectors* /66/ an evaluation of smoke detectors placed in conveyor belt entries of underground coal mines is presented.
Principal concerns are early detection and warning of fires, reliability of operation, frequency of maintenance, and adaptability of detectors to monitoring systems and the mining environment.
The data in the report provided comparisons between smoke detectors and CO sensors, specifically in the areas of early detection of fires and susceptibility to nuisance alarms due to diesel exhaust contaminants.
The conclusions were that several instances were noted where the detectors discovered heatings along the belt in some form or other. Aside from the diesel alarms, the primary sources of false alarms were rock dusting, dust accumulation, and cutting and welding. The fact that alarms occurred during rock dusting implies that some method should be found to eliminate or reduce the dust transported to the detector. Further, routine maintenance and cleaning of the detector head at intervals of about 8 to 10 weeks should eliminate alarms due to dust accumulations, and are recommended for future smoke detector installations. The HRD-2A smoke detector experienced several alarms due to diesel-powered equipment emissions. Although alarms did occur, the frequency of alarms was less than that of CO sensors. The alarm rate of the VESDA detector to diesel exhaust contaminants was much lower, which is most likely due to the principle of operation of this device. Diesel particles have small diameters and their scattering efficiency is significantly less than that of smoke particles. Photoelectric-type smoke detectors may have significant potential for use in mines with diesel-powered equipment, because these detectors are less sensitive to diesel particulates matter, but this aspect of fire detection needs to be further validated.
As the contents of the article mostly applies to coal mines, it is deemed to be not directly applicable to the present project.

In the article *Comparative in-mine evaluation of carbon monoxide and smoke detectors* /67/ a series of liquid fuel fire experiments evaluated the comparative responses of five types of available smoke detectors and a diffusion-mode CO detector under normal and reduced airflow conditions based upon the alarm times of the detectors.
A correlation was developed of the travel time of 5 ppm CO between pairs of CO detectors with the travel time calculated from entry and crosscut volumes and measured airflow. Based upon the relative performance of smoke detectors in this limited study, smoke detectors can be as effective as CO detectors for mine fire detection once identifiable alarm values are defined.
Implementation of smoke detectors as part of an atmospheric mine monitoring system will improve mine safety.
It is recommended that smoke detectors that have a continuous analogue output signal be used whenever possible as part of a mine atmospheric monitoring system. These sensors would give greater flexibility for setting alarm values for fire detection at low smoke levels. Smoke detectors that require relatively low maintenance, such as diffusion-mode detectors, have a reasonable

expectation of being at least as effective as CO detectors. Based upon results from experiments with one pair of ionization-type, diffusion-mode smoke detectors, the effect of crosscuts on smoke travel time would be minimal for a particular smoke detector alarm level under normal airflow conditions. This aspect would be incorporated in a mine fire location strategy. Smoke detectors, when incorporated into a mine atmospheric monitoring system, will complement CO detectors and thereby improve mine safety.
The technology presented is clearly not the technology of today, which limits the use of this article in the present project.

In the report *Fire detection for conveyor belt entries* /68/ the results of a series of large-scale experiments where small coal fires were used to ignite the conveyor belt at air velocities ranging from 0.76 to 6.1 m/s are described.
In the tests, electrical strip heaters imbedded within a pile of coal were used to heat the coal to a point of flaming ignition. The flaming coal subsequently ignited the conveyor belt located approximately 5 to 10 cm above the coal pile.
During the tests, temperature, CO and smoke levels were continuously measured in order to determine both alarm time and level as the fire intensity progressed through the stages of smouldering coal, flaming coal and flaming coal plus flaming belt.
Analysis of the data leads to certain conditions of air velocity and sensor alarm levels that are required for early detection of conveyor belt entry fires. Two nomographs are presented, which define sensor alarm levels and sensor spacings as a function of belt entry cross-sectional area and belt entry air velocity.
The conclusions were that the data have provided significant insight into the phenomena of fires that develop within conveyor belt entries. In general, both coal fires and subsequent belt fires before the onset of belt flame spread were found to grow at rates that increase with increasing air velocities. The rates of CO and smoke production were found to decrease as the air velocity increases. For smouldering coal fires, the duration of the smouldering stage decreases as the air velocity increases, while the length of time from ignition of the coal until ignition of the belt increases as the air velocity increases. Once the rubber belt ignites, the time to reach a stage of sustained flame spread decreases gradually as the air velocity increases. For the PVC belt, flame spread did not occur.
A constraint was proposed that may be used to define the conditions for use of proposed CO and smoke fire detection systems. For CO or smoke fire sensors, this constraint defines the sensor spacing and alarm thresholds for a range of air velocities and entry cross-sectional areas. This constraint, derived from the data presented in this report and designed to approximate worst-case conditions for ignition of conveyor belting by a small precursor coal fire, defines the condition for sensor usage so that fire detection and alarm occurs just prior to ignition of conveyor belting. It is extremely important to realize that if these data and subsequent constraints can be accepted as approximate worst-case conditions, then fires that develop via some other scenario will generally be detected earlier in their stage of development, thus providing more time for subsequent evacuations and control. It is also extremely important to realize that this worst-case scenario can happen and that evacuation of personnel should be as rapid as possible owing to the short periods of time that may be available until belt flame spread begins along with the untenable levels of combustion gases and smoke that result.
The article mostly applies to coal mines and is thus of limited interest.

In the article *Overview of mine fire detection* /69/ several experiments are described that were conducted to investigate the level of mine fire detection and alarm capability possible using state-of-the-art technology. Comparing the response and alarm time of optical and ionization type smoke sensors to smouldering and flaming coal combustion in a smoke chamber.

A series of 30 and 330 kW diesel fuel fire intensity experiments were conducted under zero airflow conditions.
It was determined that thermal sensors are inadequate at a distance of 30 m from a 300 kW fire.
A diffusion mode ionization smoke sensor could be more effective for mine fire detection than a diffusion mode CO sensor.
Recommendations can be made for sensor spacing in a mine entry based upon the measured CO buoyancy induced spread rates along the mine roof and the time for a developing coal fire to ignite a conveyor belt.
The early mine fire detection can be best accomplished with CO or smoke sensors. The equivalency of CO concentration of 5 ppm above ambient to a smoke optical density of 0.022 m^{-1} was demonstrated for smouldering and flaming coal combustion. It was determined that smoke sensors can be reliable indicators of smouldering and flaming coal combustion for an optical density less than 0.011 m^{-1}. From an operational point of view in terms of sensor alarm definition, smoke sensors with a continuous analogue output have an advantage over those with preset alarm levels. For diesel fuel mine fire experiments it was demonstrated that a diffusion mode ionization type smoke sensor alarmed earlier than a diffusion mode CO sensor under normal ventilation conditions. A similar result was found for 30 and 330 kW average intensity diesel fuel fire experiments under zero airflow conditions. Thermal detection was shown to be inadequate at a 30 m distance from a 300 kW fire under zero airflow conditions. For imposed mine fire ventilation conditions, sensor spacing in a mine fire detection system can be evaluated from the known ventilation conditions. In the absence of imposed mine ventilation, the buoyancy generated flow produced by the fire defines the sensor spacing criteria. It was determined that for the 14.25 min required for a developing coal fire to ignite a conveyor belt, a sensor spacing of 183 m and 105 m would be required for average 330 kW and 30 kW fires respectively under zero airflow conditions.
The same conclusions ca be drawn as for the other articles regarding fire detection, i.e. that it mostly applies to coal mines and is thus of limited interest.

In the article *Mine fire detection under zero airflow conditions* /70/ a series of diesel fuel fire experiments that were conducted to determine products-of-combustion (POC) spread rates along a single entry under zero imposed airflow conditions are described. Six fires with HRR of 330 kW and three fires with HRR of 30 kW were conducted in a 180 m long entry which had an average 2 m height and 4 m width. POC spread rates were measured by the response time of diffusion type CO detectors, positioned at 30 m intervals, to CO concentrations 5 ppm above ambient.
For the 330 kW fires, average POC spread rates of 0.22, 0.13 and 0.06 m/s were determined at 30, 60 and 90 m distances from the fire.
For the 30 kW fires these average values were reduced to 0.08, 0.04 and 0.04 m/s.
The measured maximum roof layer temperature 30 m from two of the 330 kW fires was 30 and 36ºC, which is less than the 57ºC alarm point of a typical mine thermal sensor.
The conclusions were that the results of the research can be used to make recommendations for sensor spacing in a zero or low air low section of a mine. Interpolation of fire sizes between 30 and 330 kW could be used to estimate detector spacing as part of an atmospheric mine monitoring system in a mine section in which low airflow is expected. The recommended detectors would be CO, or smoke detectors with alarm values identifiable from a continuous analogue output signal. Implementation of these measures can be expected to improve miners' safety.
The geometry used in the fire experiments is mostly applicable to coal mines, thus limiting the use of the article in the present project.

In the report *A comparison of mine fire sensors* /71/ the results of research tests at Lake Lynn laboratory are discussed, to determine the alarm times of smoke and carbon monoxide sensors,

and a point type heat sensor to slowly developing coal-conveyor belt fires. The tests were conducted at air velocities of 0.44 and 0.97 m/s.
The conclusions were that data clearly indicated that smoke sensors provided earlier warning of fire than 10 ppm CO-sensors, and that 10 ppm CO-sensors provided earlier warning than point type heat sensors.
A success rate of 1.0 was obtained for both smoke and CO-sensors for the point type heat-sensors, the success rate was 0.57 at the lower air velocity, decreasing to 0 at the higher air velocity.
The data also indicated that at the lower air velocity, 10 ppm of CO was produced prior to flaming, demonstrating that the detection of fires in their incipient, smouldering stages is a viable possibility in many instances. The use of smoke sensors enhances this possibility. The data also allow for estimates of CO and smoke optical density levels that would be present if detection was via point type heat sensors spaced at intervals of 15.2 and 38.1 m. These levels are significantly greater than the recommended alarm thresholds for CO and smoke sensors. The data clearly indicate the effects of air velocity on the detection times that were realized for each type of sensor. Air velocity also impacts the relative sequence of events observed during the stages of fire development. These results clearly indicate that the likelihood of miners escaping from mine fires will improve with earlier detection.
These results mostly applies to coal mines and is thus of limited interest.

In the article *Mine fire source discrimination using fire sensors and neural network analysis* /72/ fire experiments that were conducted with coal, diesel-fuel, electrical cable, conveyor belt and metal cutting fire sources to determine the response of fire sensors to products-of-combustion are described.
MOS and smoke fire sensors demonstrated an earlier fire detection capability than a CO sensor. This capability was of particular significance for a conveyor-belt fire in which the optical visibility was reduced to 1.52 m with an increase in CO of less than 2 ppm at a distance of 148 m from the fire.
The conclusions were that the role for mine fire smoke sensors and MOS sensors was shown to be enhanced by their earlier alarm times relative to a CO sensor. The low optical visibility in the absence of significant CO for flammable material further supports the role of smoke sensors for early mine fire detection. Data, recorded from an optical path smoke, a CO and MOS sensors placed in a multiple sensor arrangement and inserted into a back propagation neural network program, enabled the program to correctly classify coal, diesel fuel, electrical cable, and conveyor belt test fires and a metal-cutting procedure based upon a training set similar to the testing set. This correct mine fire combustible source classification is based upon an average 96% correct classification of seven tests of the test data with the worst case probability of a correct prediction being 86%. The article mostly applies to coal mines and is thus of limited interest.

In the article *Multiple type discriminating mine fire sensors* /73/ it was determined that a selection of different types of fire sensors could be used to discriminate mine fires from nuisance emissions produced by diesel equipment.
A neural network was developed for application to coal, wood and conveyor belt fires in the prescence of diesel emissions and evaluated with the successful prediction of 22 out of 23 mine fires based upon a fire probability determination.
The optimum sensor selection for the neural network was comprised of a CO sensor, two different types of metal oxide semiconductor (MOS) sensors and an optical path smoke sensor.
The conclusions were that the research conducted with multiple fire sensor types supports their use with a neural network program for mine monitoring to provide a mine-fire nuisance-emissions discrimination capability. Incorporation of a trained neural network into a mine

monitoring system which included these sensors could provide the coal mining industry a reliable mine fire detection and nuisance emissions elimination method.
The article mostly applies to coal mines and is thus of limited interest.

In the article *Summary of combustion products from mine materials: their relevance to mine fire detection* /74/ an investigation on the characteristics of combustible materials used in typical coal mining operations in a series of experiments conducted in an intermediate-scale fire tunnel is presented. The materials examined included wood cribs, transformer fluid, coal, conveyor belting, brattice cloth and ventilation ducting.
Results showed that smoke was the product-of-combustion most readily detected from the smouldering materials tested.
The goal was to develop more reliable and sensitive mine fire sensors.
The conclusions were that because of the unique nature of underground mining, fire detection is of utmost importance. For the materials tested, smoke sensors are most effective for fire detection because their alarm thresholds are reached before that of the CO sensors.
The article *Smoke, carbon monoxide, and hydrogen chloride production from the pyrolysis of conveyor belting and brattice cloth* /75/ is similar to the one above.
The sensors apply mostly to coal mines and are thus of limited interest in the present project. But parts of it (results with respect to conveyor belting and ventilation ducting) could be used when evaluating the risks and appropriate protective measures.

In the article R*esearch of fire hazard critical guidelines of mine use belt conveyor and automatic fighting fire system* /76/ methods on detecting fires in conveyor belts (coal mines) are described and the article also describes tests that have been performed. One of those tests is the belt skid friction test.
The article describes tests on sprinkler systems on conveyor belt fires.
The conclusions were that cooperation of differential speed sensor and temperature sensor is effective to detect incipient belt conveyor fires. Carbon monoxide does not generate until flaming occurred, so CO sensor is unsuitable for early conveyor belt fire detection. Water spray protection is an economical and practical method to fight belt conveyor fires. As to belt conveyor fires, which are not caused by friction, the system still works well. The system can detect working status of belt conveyor, preventing belt fire or extinguishing fire at an early stage.
The article does not apply to the present project and is thus of limited use.

In the article *Product-of-combustion fire detection in mines* /77/ the relationships that exists between the developing fire, the products of combustion that are liberated, and the sensitivity levels of various detectors are discussed.
The article also discussed how these factors can be utilized for determining the optimum distribution of candidate sensors.
The article assumed wood to be the primary combustible.
The conclusions were that in the article the detection system is defined in terms of a developing fire hazard. If such systems are to be used to provide protection at some specified level, then it is essential that the system be directly related to the hazard. Certainly, the fire growth rates discussed here represent only a fraction of those that might be encountered in underground mines. Other factors can confuse the problem, such as high backgrounds from diesels, or ventilating flows that intersect and mix, reducing combustion product concentrations.
As wood is not a common material in the Swedish underground mines, the contents of the article is of limited use in the present project.

8.4 Rescue equipment

In the article *US Bureau of Mines technology applicable to disaster response, urban search and rescue* /78/ three US Bureau of Mines research areas are discussed: closed-circuit breathing apparatus, trapped miner location and mine fire diagnostics.
Mine fire diagnostics deals with developing practical techniques for remotely monitoring how the atmosphere inside a mine changes during a fire, in order to estimate the spread and severity of an underground fire (this applies mostly to coal mine fires).
The work does not directly apply to the present project.

In the article *Mine rescue training simulations and technology* /79/ a positive-pressure inflatable escape device (IED) is described that was used to isolate the hazardous environment from fresh air and allow rescue personnel to traverse through.
The article also describes an inflatable feed-tube partition that can rapidly block large openings and simultaneously provide a feed-tube for high-expansion foam generators.
The work described does not directly apply to the present project.

The article *Mine safety recommendations* /80/ provides a summary and description of self-rescuers, emergency shelters, communications, and tracking along with recommendations regarding implementation, compliance and enforcement.
In 2001 NIOSH reported that out of 214 miners surveyed, 38% had been notified to evacuate a mine because of fire or explosion during their career.
The work can provide some background information and other point of views with respect to protective equipment such as emergency shelters.

<u>Summary:</u>

An investigation is recommended with respect to the material brought down into the Swedish underground mines, as only parts of the material is regulated with respect to their flammability (conveyor belts, cables etc.) but others are not (hydraulic fluid etc.). The investigation would result in a description of the deficiencies and listing recommendations on how to improve the fire safety in underground mines with respect to flammability of materials.

Implementing a fire suppression system and rapid fire detection system for Swedish cabs that are manned in underground mines, should be considered due to the hazards of spray fires.
When considering additional fire protection for cabs with respect to the hazards of spray fires underground, the material found during the search could very well be used.

No further work is identified with respect to fire suppression of fires in engine compartments, as earlier work on the issue has been quite extensive.

An enormous amount of work has been spent on detecting fires in mines and conveyor belts. Thus no further work is identified at the moment.

The material regarding rescue equipment is deemed not applicable to the project at this stage.

9. Other types of mines

9.1 Spontaneous combustion

In the article *Spontaneous combustion fire detection for deep metal mines* /81/ a possible system that warns of spontaneous combustion fires in metal mines is described.
The system detects low levels of combustion products believed to indicate the pre-flaming stage of spontaneous combustion in metal mines.
Spontaneous combustion fires in non-coal mines only account for about 2% of all fires. Most often they start in abandoned, backfilled, and/or caved mine areas where access for fire fighting operations is difficult or impossible.
Fires on discrete pieces of equipment are generally of short duration because they self-extinguish when the available fuel is consumed. However, the large quantity of support timber (often in old mines) can provide fuel sufficient for fires of many months duration.
The work does not directly apply to the present project, as the Swedish mines are not particularly deep and wood is scarce in the mines.

9.2 Dust explosions

In the article *Secondary explosion hazards during blasting in oil shale and sulfide ore mines* /82/ dust explosions in Sulfide ore dust is discussed.
Sulfide ore dusts can be ignited given the proper predispersed dust concentration, particle size and sulfide content.
With the help of tests, low-incendive explosives – coupled with good blasting procedures – show promise in reducing dust ignitions associated with blasting operations in sulphide ore mining applications.
Sulfide mines provide several metallic ores, particularly of the nonferrous metals such as lead, zinc and copper. Sulfide ore mines are also called base metal mines. In addition to the base metals, some sulfide ore mines produce small amounts of precious metals, such as silver and gold.
The fatalities associated with these ignitions have been minimal due to the practice of evacuating mines before stope blasts. But many operators report extensive damage during many of the dust ignitions.
The article *Safety management of underground combustible sulphide dust* /83/ also discusses the dust explosion issue in sulphide ore mines.
The work based on these two articles is not directly applicable to the present project.

9.3 Flammable gas explosions

In the article *Lessons learnt from recent flammable gas explosions in South African hard rock mines* /84/ is discussed.
Flammable gas is widely reported in gold, platinum, chrome, diamond and coal mines, and has resulted in 78 accidents during 1988 to 2005 with a total of 89 fatalities and 144 injuries.
The article describes three case studies.
Several recommendations are given on how to handle this risk.
Flammable gases encountered in gold mining industry are: methane, ethane, propane, butane and hydrogen.
These two articles do not directly apply to the present project.

9.4 Visitor mines

No material was found in the literature survey on fire safety research in visitor mines, i.e. old mines that have been converted to museum etc.

<u>Summary:</u>

The risk of spontaneous combustion could be applicable to tourist mines as abandoned, backfilled parts of the mines where organic material is stored (wood, refuse etc.) could exist.

In the LKAB mines and the tourist mines, dust explosions and flammable gas explosions are deemed as not applicable and probable.

During the literature survey, no material about visitor mines with respect to fires was found.

10. Current research activities

During a search on the internet, the following two research projects – with respect to fire and smoke spread in underground non-coal mines - were the only ones found. Both projects are run by NIOSH (USA):

- Fire hazard reduction in the metal and non-metal mining industry (through a comprehensive program of education, training, and basic and applied research). Contact person: C.D. Litton
- Smoke management and fire modelling for underground mines. Develop a real-time mine fire simulator with mine ventilation and smoke control decision making capability based on mine fire sensor data to determine the most effective smoke management methods to provide safe mine egress and safe access for fire-fighters. Contact person: J.C. Edwards

11. Analysis and discussion

Based upon the statistical material, the dominating fire cause in underground mines is found to be flammable liquid sprayed onto hot surface, followed by electrical shorting/arcing and hot works. Further down the list conveyor belt and conveyor belt equipment is found.
A conclusion would thus be to focus on spray fires, fire caused by flammable liquid ignited by hot surface, vehicles (including drilling riggs) fires (including rubber tires) and cable fires.
A fair amount of work has been spent on conveyor belts, a reason why so much effort has been spent on this issue could be due to the high risk in coal mines, as the goods transported on the conveyor belt is combustible. This high risk is not applicable to for example iron ore mines.
Furthermore, the most interesting places in underground mines, mobile equipment working areas would be first priority due to the high risk of fires in mobile equipment.
The types of mobile equipment with the highest fire risk are: service vehicles, drilling rigs and loaders.
The following suggestions are examples taken from the US mine safety research – but still highly applicable to Swedish mines - that can be used in order to prevent, reduce or suppress equipment fires in underground mines:

- Schedule more frequent and more thorough inspections of hydraulic, fuel, and electrical systems.
- Develop new technologies for emergency engine shutoff system and line drainage system.
- Develop cab fire detection and fire prevention/suppression systems.
- Develop effective and rapid local fire-fighting response capabilities.
- Schedule more frequent fire emergency preparedness training for equipment operators.

Organisations such as MSHA, Factory Mutual, HSE etc. have conducted an extensive work with respect to the ignitability and flammability of pressurized hydraulic fluids, due to this there is at the moment no need for any extensive research within this field. But a relatively easy task would be an inventory with respect to the type of hydraulic fluid being used also fire-resistant hydraulic fluid should be recommended being used whenever possible.
With respect to examining hydraulic fluid/fuel sprayed onto a hot surface the results from the article can be used in the further work, i.e. examining the equipment that is used containing hydraulic fluid , what type of hydraulic fluid being used and what actions that can be taken to minimize the risk of a spray fire.

Due to the fact that a majority of the fires in underground mines involve vehicles/mobile equipment, the lack of documented fire experiments in vehicles/mobile equipment is quite serious. The main focus has so far been cab fire detection and suppression. There is thus a great need for HRR curves.

A majority of the articles dealing with conveyor belts investigate the ignitability and flammability of the belt conveyors, HRR curves, mass loss rate, flame propagation speed and fire modelling of conveyor belt fires. The focus should not be on this type of design fire during the project, as the conveyor belt fire is by far not a dominating fire cause in non-coal mines. Nevertheless a relatively easy and effortless task would be to investigate and document the principal causes of belt conveyor fires in underground non-coal mines.
As the belt surface-to-roof distances is greater than 0.22 m in the LKAB mines, it would be interesting to investigate the minimum ventilation velocity for these cases as earlier studies have dealt with distances equal to or less than 0.22 m.

Due to the fact that the statistics put cable fires high on the list, efforts ought to be made with respect to cable fires in underground mines.

Fire experiments and studies using wood as the primary fuel source applies mostly to coal mines, but not to for example the Swedish iron ore mines. These studies are thus of limited value for this specific project.

Not all CFD models will be able to take friction losses of fire gases in a mine drift into account, there is a demand for investigation in this field.
The article *Fire tests in a blasted rock tunnel* /16/ contains data about a blasted rock tunnel resembling the roughness of a mine, thus the output data could be used when investigating and validating for mine conditions.

Natural ventilating pressure has been investigated in earlier works, but there seems to be a lack of material with respect to the non-steady state case. Further work could be needed with respect to this field.

There exist an extensive theoretical material concerning heat exchange between fire/fire gases and rock, but nevertheless there seems to be a lack of full scale experiment validating the theoretical models/equations. When performing future fire experiments the articles *Simplified method to calculate the heat transfer between mine air and mine rock* /18/ and *Modelling of heat exchange between flowing air and tunnel walls* /19/ contain methods for calculating the heat exchange that could be used during the work.

Fire experiments with more complicated and varying geometry (opening area, inclination, aspect ratio), larger test area, reversing/increasing the ventilation, and larger, non-steady state fires are needed in order to get a better picture of movement of fire gases in a mine ventilation network. Also the results should be examined against the results of corresponding CFD/ventilation network simulation program.
As no fire barriers are possible in production areas (due to practical reasons, i.e. the blasting taking place every day would destroy the fire barriers), the problem of smoke spreading from a fire affected production area will have to be looked into. Other methods will most likely have to be developed.

The use of a CFD model together with a ventilation network simulation program would be very interesting to investigate due to the potential use of the findings in future designs of underground mine sections. The results should be compared with corresponding fire experiments.

The work on CFD modelling 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 fires with larger HRR are examined.
- Friction losses/obstacles are investigated.
- Heat losses to surrounding rock are included.
- Changes in ventilation (non-steady state ventilation).

The CFD investigation should also include the actual implementation of the CFD models and also suggestions on what improvements that could be made.

Zone models are clearly not applicable to modelling in underground mines as a stable stratified hot layer is only applicable in the near field region of the fire. CFD models are in that specific region a better choice.

A clear majority of earlier work regarding the validation of ventilation network simulation programs has mainly been for coal mines, clearly it would be most interesting to also validate them for non-coal mines.

It would be most interesting in the future to validate the results of several ventilation network simulation programs with respect to the results of performed fire experiments and also comparing the results of the programs with each other.

As not all the material brought down into the Swedish underground mines are regulated with respect to their flammability, a full investigation is recommended be performed in order to find out the deficiencies and list recommendations on how to improve the fire safety in underground mines with respect to flammability of materials.

Material relating to the rapid fire behaviour of spray fires and the hazard to operators in a cab could be used when investigating the possibility of fire suppression systems and rapid fire detection systems for Swedish cabs that are manned in underground mines, and as a basis for general recommendations regarding supplying the cab with additional fire protection.

No further work is identified at the moment with respect to fire suppression systems for fires in engine compartments, as the earlier work has been quite extensive.

Several number of articles have dealt with the issue of detecting fires in mines and conveyor belts. No further work is identified at the moment.

The material regarding rescue equipment is deemed not applicable to the project at this stage.

For tourist mines the issue with spontaneous combustion could be applicable due to abandoned, backfilled parts of the mines where organic material is stored (wood, refuse etc.).

As the risk of dust explosions and flammable gas explosions is negligible for the LKAB mines and the tourist mines, this issue is deemed as not applicable to the present project.

During the search, no material about visitor mines with respect to fires was found.

12. Conclusions

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

There is at the moment no need for any extensive research with respect to the ignitability and flammability of pressurized hydraulic fluids, as an extensive work has already been conducted. Still the type of hydraulic fluid being used in the Swedish mines should be investigated and fire-resistant hydraulic fluid should be recommended being used whenever possible.
But when examining the equipment that is used containing hydraulic fluid (i.e. what potential ignition sources can be found on the equipment), what type of hydraulic fluid being used and what actions that can be taken to minimize the risk of a spray fire. The results from the articles can be used in the work.

A major concern is the lack of documented fire experiments in vehicles/mobile equipment. This is essential knowledge when designing new mine sections and overlooking existing sections. Thus there is a great need for HRR curves, also due to for example the fact that a majority of the fires in underground mines involve vehicles/mobile equipment.

Taking into account that conveyor belt fires are not a dominating fire cause in non-coal mines and the fact that a very intensive work has dealt with for example ignitability and flammability, HRR curves etc. The focus should not be on this type of design fire during the project. Nevertheless a relatively easy and effortless task would be to investigate and list the principal causes of belt conveyor fires in underground non-coal mines and another interesting issue would be to investigate the minimum ventilation velocity for belt surface-to-roof distances much greater than 0.22 m, which is applicable for the LKAB mines.
Research material so far has mainly dealt with cases where the surface-to-roof distances are equal to or less than 0.22 m.

Taking into account the enormous volume of cables present in an underground mine and the fact that the statistics put cable fires high on the list, some efforts should be made with respect to this type of fire.

Generally there is a demand for investigation of the friction losses fire gases in a mine drift (as not all CFD models will be able to take this into account). Further work is needed within this discipline.

When performing full scale experiments in an underground mine, models and equations describing the heat exchange between fire/fire gases and rock should be validated at the same time. The articles *Simplified method to calculate the heat transfer between mine air and mine rock* /18/ and *Modelling of heat exchange between flowing air and tunnel walls* /19/ contain methods for calculating the heat exchange that could be worth looking further into and validating during the future fire experiments.

Regarding the movement of fire gases in a mine ventilation network, the earlier work will have to be supplemented with fire experiments with more complicated and varying geometry (opening area, inclination, aspect ratio), larger test area, reversing/increasing the ventilation, and larger, non-steady state fires are needed. Besides performing the fire experiments the results should also be examined against the results of corresponding CFD/ventilation network simulation program. A practical issue that would greatly affect the fire safety in production areas is the difficulty in preventing smoke spreading from a fire affected production area, as no fire barriers are possible (the blasting taking place every day would destroy the fire barriers), other methods will have to be looked into.

The use of a CFD model together with a ventilation network simulation program would be very interesting to investigate. The results should be compared with corresponding fire experiments. Ventilation network simulation program could at the same time be validated for a non-coal mine.

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).

Besides the investigation of the above factors the investigation should also include the implementation of CFD models and suggestions on improvements should be made.

Conveyor belts, cables etc. are regulated with respect to their flammability but others are not. In order to get a good picture of the fire risk in Swedish underground an investigation should be performed.

The use of fire suppression systems and rapid fire detection systems should be considered for manned cabs in Swedish mines. The reason for this is the rapid fire behaviour of spray fires.

A large part of the earlier mine safety research has been conducted with respect to detecting fires in mines and conveyor belts. No further work is identified at the moment.

As organic material stored in abandoned, backfilled parts of mines could be applicable to tourist mines, the risk of spontaneous combustion is a subject in these cases.

During the search no material related to tourist mines was found.

Finally, the three activities with the highest priority are:

- Conducting fire experiments with respect to cab/vehicle fires, resulting in HRR curves.
- Conducting an extensive work on CFD modelling (validating the results with corresponding fire experiments), 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).

- Investigating the use of a CFD model together with a ventilation network simulation program. The results should be compared with corresponding fire experiments.

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