Overview of fire and smoke spread in underground mines.

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INTRODUCTION
Research regarding fire safety in mines has so far mainly been directed towards coal mines. Thus the need for recommendations, simulation models, engineering tools etc for non-coal underground mines are in great demand. This paper is part of a larger ongoing research project aimed at improving the fire safety in underground 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 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.

This specific paper encompasses a literature survey performed in the project. The main purpose of the literature survey was to investigate and present what has been done in the non-coal underground mine fire field in the past and to give recommendations on the continued work with regard to fire safety in underground non-coal mines.

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 an adjacent 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.

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 and drifts 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 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.

STATISTICS AND FIRE CAUSES
The report by GRAMKO [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: Service vehicles, drilling rigs and loader (diesel and 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].](image)

In the report by De Rosa [2] all types of fires underground in US mines 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.
Most common type of equipment involved in fires was: mobile equipment followed by oxyfuel torches, beltlines, electrical systems, batteries and chargers.
Most common locations of fire were mobile equipment working areas, followed by flame cutting/welding areas, and mine face, section, crosscut and drift 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 and wood.

From another report by De Rosa [3] the mobile equipment fires for all US surface and underground coal and metal/non-metal mining categories are examined.
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.
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.

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 by Thyer [4] who 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, in an article produced by the Department of Primary Industries [5] the statistics on mobile equipment fires together with ignition source statistics are listed.
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] both 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.

**EXPERIMENTAL AND THEORETICAL WORK ON FUEL LOADS**
MSHA, Factory Mutual, HSE etc. have performed an extensive work with respect to the ignitability
and flammability of pressurized hydraulic fluid. In a report by Yuan [6] a study of the ignition of non-fire-resistant hydraulic fluid sprays is described. In the report the effects of the distance between the open flame and the nozzle orifice diameter on the ignitability of the hydraulic fluid sprays, the minimum surface ignition temperature of the hot surface etc. were examined. Finally, the results are compared with those obtained for fire-resistant hydraulic fluids. In figure 2 below, the minimum oil flow rate versus nozzle orifice area is displayed.

![Figure 2 Minimum oil flow rate versus nozzle orifice area][6].

As vehicles are involved in a majority of the fires in underground mines, any material relating to vehicle fires in mines would have been highly interesting. The only report found was a report made by Svenska Gruvföreningen [7] in 1985; unfortunately it contains no HRR curves. In the report 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. One of the conclusions of the report was that 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 thereafter set to 4 hours in Sweden. 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.

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. For example in an article by Yuan and Litton [8] a series of conveyor belt flame spread tests were conducted in a small-scale tunnel using various types of belts. 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. One of the conclusions of the article was that the ventilation velocity and the belt surface-to-roof distance were found to affect each other. 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.

In an article by Lowndes, Silvester, Giddings, Pickering, Hassan and Lester [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. But regarding the proposed model, it was found to not being able to quantitatively replicate the flame spread, thus limiting the use of the model.

Hwang, Litton, Perzak and Lazzara [10] describe in an article the fire development and spread along conveyor belts in ventilated ducts that were investigated experimentally and theoretically. Various types of conveyor belts used in mining applications 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. One of the conclusions of the article was 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 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.

SMOKE SPREAD AND FIRE BEHAVIOUR

Wolski [11] describes 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 an article by Krasnoshtein, Kazakov and Shalimov [12] 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.

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 a report by Linnsén [13] 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 3 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 3: One of the fire experiments performed in the Kiruna mine [13].

Greuer [14] outlines in an article physical principles governing mine ventilation systems and state of
the art ventilation modelling. 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. 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. The article was written in 1985, since then transient state simulations of ventilation systems are a routine tool to work with. This will limit the use of the article.

Klebanov and Romanchenko [15] describe mathematical models 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 questioned. Also, the models presented are mainly for coal mines. The findings of the article are of limited use in the present project.

In an article by Zhou and Wang [16] the backdraft phenomenon in an underground mine is studied through several experiments 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. The backdraft occurred with the reversing process of airflow in the tunnel.

It is stated that a backdraft can occur when the fire itself causes the reversal of the airflow. The conclusions given by the authors were that through the initial experiments in the model tunnels, a specific backdraft in the process of a tunnel fire was illustrated. The backdraft 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 (mine/tunnel) and that of the latter takes place in a closed system (compartment). 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.

CALCULATIONS AND MODELLING
Lea [17] describes three computational models that 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.

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.
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.

In an article by Wu and Li [18] the fundamental strategies adopted in the simulation package “FIRES” developed for ventilation simulation during 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 during mine fires.

The package has been used to simulate an experimental mine fire. A comparison is made between the simulation results and the measured data.

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.

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).

Edwards and Hwang [19] uses a CFD program – CFD2000 - to predict smoke spread from two fires in an entry under zero airflow conditions. In the article 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.

Only small and steady state fires were used in the experiments. Heat loss to rock mass was not included in computer simulations. 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 predicted gas temperature near the roof 30 m from a 296 kW fire was higher than the measured values. When the CFD 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. It was also determined that the measured extensive smoke reversal is more favourably predicted by the Froude model.

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.

Edwards, Franks, Friel and Yuan [20] conducted diesel fuel experiments to determine the critical air velocity for preventing smoke rollback. The fire intensity varied from 50 kW to 300 kW. 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.
See figure 9 below for the plan view of the test area.

![Plan view of the test area](image)

**Figure 4** Plan view of the test area [20].

It was demonstrated with fire smoke reversal experiments that for a range of fire intensities between 50 and 300 kW in a mine entry 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.

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 dramatically different fire behaviour.

In an article by Friel, Yuan, Edwards and Franks [21] 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 5 below for the plan view of the test area.

![Plan view of the test area](image)

**Figure 5** Plan view of the test area [21].

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 conclusions made were for example that:

- 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 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).
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.

Cheng, Ueng and Liu [22] present a fire outbreak and evacuation simulation model, MFIRE. 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.

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 pursued.
- Transient-state simulation: transient-state simulation which follows changes in ventilation step by step to offer a continuous 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.

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 article raises several questions and doubts. What does the 1 kW fire equals to in a full-scale fire? Did the poor correlation really depend upon the reduced physical scale of the laboratory model? The main 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?

In an article by Dzuirzynski, Nawrat, Roszkowski and Trutwin [23] 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

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. 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.

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. 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.

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.

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. For example the article by Wolski [11] contains 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.

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.

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.

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