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Keywords

design fire, vehicle fire, underground mine, fire behaviour, fire protection, mine ventilation

Proposed Design Fire Scenarios for Underground Hard Rock Mines

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Abstract

Given the complexity and uniqueness of underground hard rock mines, the application of the design fire scenario approach is recommended when evaluating fire safety in mines. Providing a full set of design fire scenarios – ensuring that several important life safety aspects are covered – for a mine can be challenging. The question is whether a catalogue of potential clusters of design fire scenarios could be developed, covering important aspects found underground? Given the general lack of research into design fires in the mining industry, this paper provides a unique analysis of design fire scenarios in underground hard rock mines. Taking advantage of several different and diverse data sources, a comprehensive analysis with holistic character is provided where several proposed clusters of design fire scenarios and analyses of what criteria to apply when evaluating the scenarios are presented. The analysis of suitable criteria highlights the toxicity of the emitted smoke and decrease in visibility as potential criteria underground. The proposed scenarios focus on influencing parameters such as the fire behaviour, position of fire, fire load, and smoke spread. The proposed clusters of design fire scenarios will provide a key tool when evaluating fire protection measures in an underground mine.

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1. Introduction

The nature and uniqueness of underground hard rock mines will, in many cases, pose a challenge when working on fire safety. Due to the special nature of underground mines – with a high degree of complexity, limited accessibility, heavy reliance on mechanical ventilation, transient nature in both time and space, etc. – an analytical approach would be well suited. When designing or evaluating the fire safety of an underground mine – taking the unique characteristics of the mine into account – the design fire methodology may be an important tool. The design fire methodology has been used extensively throughout the years to evaluate fire protection measures taken in buildings, tunnels, etc. [1,2]. When applying the design fire methodology, the planned or actual fire protection measures are weighed against the risk to personnel and operations caused by the selected design fire scenarios. The selected design fire scenarios will, in turn, describe parameters such as the position of the fire, ventilation conditions, the heat release rate of fire, number of personnel in the vicinity of the fire, etc.

Due to the change from a prescriptive to performance-based approach, the design fire methodology has been highlighted more and more throughout the last years. In the literature, different aspects of design fires are discussed and described. Fitzgerald [3] defines the design fire as the load against which to evaluate the active fire protection and the resultant risk to exposed people, property, and building operations. More specifically, a design fire describes assumed fire characteristics such as the heat release rate, smoke generation, etc. Furthermore, a design fire scenario is a description of a specific fire both in time and in space. Fitzgerald [3] also underlines that one should not think of a design fire as a single option for a fire scenario. The design fire used to evaluate, for example, a sprinkler system is not necessarily the same as that for fire brigade suppression, even within the same building. Perhaps not even the rooms of origin may be the same. In a SFPE publication [1], it is stated that each design fire scenario is part of a so-called scenario group and is meant to be

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representative of that group. The scenario groups must all together include all potential scenarios. Fitzgerald [3] points out that a design fire for an existing building may be easier to define since uses, materials, quantities, and conditions can be inspected and measured. The design fire for a future building is often more complicated because less information is available, and the uncertainties are larger. Klote and Milke [4] discuss the issue regarding combustible materials, namely combustible materials that are not intended to be in space. These combustible materials are referred to as transient fuels. Examples of transient fuels are Christmas decorations, cut up cardboard boxes awaiting removal, etc. Klote and Milke [4] also emphasize that before starting with the work on design fires, performance criteria will have to be established. The following work will then focus on the developing and analyzing design alternatives to meet the earlier established criteria. Several criteria can be addressed – related to established performance criteria – including life safety, protection of property, continuity of business, and environmental protection. A different set of design fire scenarios can be required for each criterion. The Technical Committee ISO/TC 92 [2] points out that when working on a design fire scenario, the design fire characteristics can be modified based upon the analysis's outcome. For example, if flashover in an enclosure is likely, it is necessary to modify the design fire to account for the characteristics of ventilation-controlled or fuel-controlled post-flashover fire.

The number of studies on the design fire methodology in underground hard rock mines is limited, as opposed to tunnels, where several studies have been conducted when applying a performance-based approach [5,6]. The tunnel studies deal with different aspects of the design fire methodology, for example, presenting an overview of the calculation methods applied when calculating the heat release rate of tunnel fires [5], reviewing fire growth rates from tunnel fire experiments, and proposing design tunnel fire scenarios [6].

An initial study on design fire scenarios in underground mines was presented by Hansen [7], where several potential design fire scenarios were presented and discussed based on site inventories of two larger underground mines in Sweden. In a paper from 2019 [8], the design fire methodology was elaborated further, and where design fire scenarios representative for Australian mines were presented. The paper was mainly aimed at the design of various heat release curves where results from earlier full-scale fire experiments and studies were applied. Furthermore, in another study Hansen [9] discussed the use of design fire scenarios when performing pre-incident planning of fires in underground mines.

This paper takes advantage of earlier performed full-scale fire experiments underground, model-scale fire experiments, a site inventory of underground mines, fire and smoke behaviour studies, statistical studies, and design fire studies to analyse, discuss, and elaborate clusters of design fire scenarios. This paper focuses on the description of scenario clusters that are pre-defined to a certain extent to increase the applicability of the scenarios. The clusters of scenarios are aimed at certain risks or aspects with respect to fires underground. The clusters of scenarios are proposed and discussed and could serve as general starting points when performing a design fire analysis of an underground mine. This paper only contains heat release rates and smoke production/spread described in general terms and does not include any specific heat release rate curves, smoke spread calculations, etc. for the proposed scenarios, as these parameters will have to be determined based on the specific fire load, ventilation conditions, dimensions, etc. of the mine in question. This paper is aimed at underground hard rock mines, as it is based on research and studies on hard rock mines, and the proposed clusters of design fire scenarios reflect foremost the risks found in hard rock mines. The risks found in coal mines differ considerably compared to hard rock mines, involving phenomena such as spontaneous heating, gas explosion, etc. [10–12]. Nevertheless, some of the proposed scenarios could very well be applicable or partially applicable to coal mines, depending on the mine layout, present risks, equipment used, etc.

Providing a comprehensive set of design fire scenarios – which could be of potential use when evaluating the fire safety of an underground hard rock mine – would improve the fire safety as well as the egress safety for mining personnel but also improve the safety of fire and rescue personnel responding to a fire underground. With the help of the design fire scenarios fire protection measures could be implemented, preventing fires or mitigating the effects of fires.

2. Design fire scenarios, general theory

The development and evaluation of design fire scenarios involve several different steps (see Fig. 1 for a general flow chart of the process). The initial step would include the decision on what measurable or calculable criteria to apply when evaluating the results from the design fire scenarios and whether design objectives are fulfilled or not.

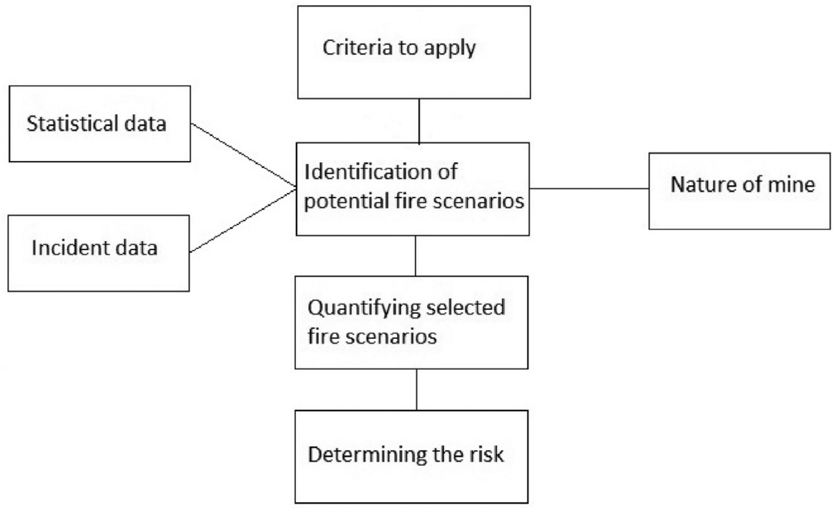

Fig. 1. The process of development and evaluation of design fire scenarios.

Design objectives with respect to the mining personnel, responding fire, and rescue personnel could, for example, be to confine the smoke spread to the involved level, confine the fire spread to the start object or allow for a successful evacuation of the affected level. To facilitate the evaluation, criteria could, for example, be specific thresholds or intervals where the output results should be below, above or within. Depending on the design objective, different criteria will be suitable. Criteria related to the evacuation of a level could, for example, be a visibility threshold or a minimum distance to the smoke layer. The application of several criteria will, in many cases, be the preferable approach to fully evaluate a design fire scenario.

The subsequent step is initiated with gathering data such as the mine layout, equipment used, fire load distribution, personnel density, characteristics of the mine as well as incident data and statistical data. The step aims at identifying potential scenarios based on the gathered data. The potential design fire scenarios would include factors describing:

- The fire: position of the fire, type of fire, type of ignition source, etc.
- Fuels: distribution and type of combustible items, fire load density, etc.
- Ventilation conditions: ventilation flow provided by the ventilation system, doors open or closed, the position of ventilation devices, etc.
- Environmental conditions: geometry of the mine section, distance to portal, etc.
- Fire protection systems: position, type, status, and capacity of existing or planned systems, etc.
- Personnel: number and location of personnel, training level of personnel, etc.
- Response of fire and rescue personnel: capacity, designated attack routes during an intervention, etc.

The incident data and the statistical data will be valuable when identifying possible design fire scenarios. The data may provide input with respect to the frequency and severity of different types of fires in certain areas or on certain objects.

The following step would include the selection, quantification, and further definition of the design fire scenarios. The number of potential design fire scenarios may be considerable – especially for a complex object such as an underground mine – and will have to be reduced and grouped together to allow for a manageable analysis. When filtering the potential scenarios, either a probabilistic or deterministic approach can be used. The probabilistic approach uses the statistical likelihood that a fire occurs – taking advantage of any statistical data – whereas the deterministic approach is based on analysis or judgement – taking advantage of underlying physics and chemistry – to produce the worst credible design fire scenarios. A worst credible design fire scenario is a scenario with a reasonable likelihood of occurrence and representative for the operation or area. Any scenario deemed unrealistically severe or too unlikely to occur should thus be excluded. Even though the deterministic approach of worst credible fires will lack the probability aspect, any existing statistical material can still be analysed in conjunction with the deterministic approach. Taking advantage of statistical material while applying the deterministic approach will increase the credibility of the presented scenarios. Furthermore, the potential design fire scenarios can be divided into clusters of scenarios, where each cluster is composed of scenarios having similar characteristics. By dividing into clusters, the volume of scenarios will become more manageable to analyse. Several parameters will be determined during the quantification of the scenarios, such as the heat release rate, the fire spread to adjacent fuel items, smoke production and smoke spread, visibility, and possible cascading effects. During the quantification, various types of tools and data can be used, such as fire modelling software, empirical correlations, or fire test data.

The final step would include the evaluation of various designs, where different designs and solutions are tested against the developed scenarios, and the risk is determined. The results of the tests are evaluated applying the earlier determined criteria, evaluating whether the design meets the criteria or not.

There is no general guideline on the number of design fire scenarios that should be developed, as it will vary with the size and complexity of the installation. Nevertheless, given the high complexity of underground mines, it is encouraged to include several clusters of scenarios, as a single cluster scenario will not give a full picture.

NFPA 101 [13] presents an interesting approach where eight design fire scenarios are described but not too detailed making them applicable for many installations. The design process is not only limited to the listed design fire scenarios but also other applicable design fire scenarios to the specific situation could be included. Also, if any of the listed design fire scenarios in the codes are found to be inappropriate to the specific situation, it does not have to be evaluated fully. The presented design fire scenarios support the user in the process, ensuring that important aspects with respect to life safety are covered.

3. Methodology

In the following parts of the paper, data and findings from fire experiments, inventories, statistical studies, fire and smoke behaviour studies, and earlier design fire studies are applied during the analysis.

Experimental studies: as vehicle fires are the most frequently occurring fire in underground mines, two fire experiments were conducted in an underground mine involving a loader and a drilling rig. See the report by Hansen and Ingason [14] for a full description of the experiments. Furthermore, fire experiments were conducted in a model-scale mine drift, involving several individual fuel items and a longitudinal ventilation flow. The results were later analysed concerning the mass flow changes occurring due to the fire (i.e., throttle effect) [15].

Site inventory: a site inventory of two underground iron mines was conducted, focusing on the position, frequency and configuration and types of combustible materials and fire protection systems found underground [16].

Statistical studies: available statistical data were analysed in a report to determine the dominating fire objects, fuels involved, and fire causes in the mining industry in New South Wales, Queensland, and Western Australia in Australia [17]. Another statistical study was performed to investigate the fire causes and behaviour of vehicle fires in underground mines in Sweden [18].

Fire and smoke behaviour studies: analysing multiple aspects of the fire behaviour of mining vehicles underground, a study was conducted on the fire and smoke behaviour underground, focusing foremost on the heat release rates [19]. Applying data from full-scale fire experiments underground, the heat losses of the smoke in a mine drift were studied in a paper, which will have a bearing on the smoke spread [20]. A numerical study on the influencing parameters on fires in non-fire resistant conveyor belts was conducted, where several heat release rate curves were presented and discussed [21].

Design fire studies: a study on design fires in Australian underground mines was conducted, using input parameters from the Australian mining industry [8].

4. Results and discussion

In the following chapters, the various factors described and included in a design fire scenario are analysed and discussed, having an underground mine perspective. The different and diverse data from earlier experiments and studies are synthesised, translated, and refined into feasible design fire scenarios. The initial chapter contains an analysis and discussion on suitable criteria for underground hard rock mines. Based on the design fire analysis, clusters of design fire scenarios are proposed and described in the different chapters, covering essential fire risks generally found underground. Points of interest are highlighted for the various clusters of scenarios. The proposed scenarios should not be considered a complete set of scenarios for a specific mine. The design of fire scenarios may give an idea and support regarding what aspects to investigate when weighing the mine's actual or planned fire protection against the fire risks. During the work with design of fire scenarios, it may be challenging to come up with a full set of clusters of scenarios which will cover, for example, the life safety aspect. The proposed clusters of design fire scenarios could be used as a support to ensure that several important aspects are covered.

Obviously, unique fire risks for a certain mine will have to be addressed in additional design fire scenarios and scenarios that are not applicable for the mine in question – if the mine lacks the specific installation, if the mine layout does not include the specific configuration, etc. – should not be included. Instead, the purpose of the design fire scenario should be considered, and the resulting design fire scenario altered accordingly to fit the local conditions.

The proposed clusters of design fire scenarios represent a framework that should be supplemented by characteristics specific to the mine in question. When developing the design fire scenarios in detail, local characteristics such as the number of personnel, the location of personnel, the ventilation conditions at the position, and the type of vehicle burning should be specified.

Some of the proposed clusters of design fire scenarios are related in some respects and can very well be combined or emerged if found suitable.

Several of the proposed clusters of design fire scenarios involve one or several mining vehicles. In these clusters of scenarios, the suppression systems on the vehicles are assumed to be either lacking or not functioning.

4.1. Criteria

Given the general characteristics of an underground mine with:

- an extensive network with declines, mine drifts, etc.,
- very long distances, both horizontally and vertically,
- the presence of both horizontal and vertical ventilation flows,
- the occasional lack of fire or smoke partitions.

Any occurring fire underground may lead to an extensive and rapid smoke spread – both horizontally and vertically – affecting personnel at a long distance from the fire. Given the size and extensive nature of an underground mine, personnel may be thinly spread out in parts of the mine, and any occurring fire underground may often be at a considerable distance from any personnel. The risks associated with the near field of the fire – for example, flame radiation – will most likely affect fewer personnel compared to risks associated with the far field of the fire – i.e., smoke spread.

Suitable criteria with respect to life safety in an underground mine – given the risk of extensive and rapid smoke spread – are thresholds with respect to toxicity (i.e., toxic effects due to the inhalation of combustion products) and visibility. Both criteria will influence the ability of the personnel underground to safely evacuate the mine or take shelter in a refuge chamber. The criteria will also influence the ability of responding fire and rescue personnel or mine rescue personnel to reach the fire site or evacuate mining personnel from refuge chambers.

The ensuing analysis and presentation of design fire scenarios were conducted having foremost the extensive and unwanted smoke spread in mind, with the toxicity of the emitted smoke and decrease in visibility as potential criteria.

Given that smoke stratification can generally be expected to be low underground – with smoke covering more or less the entire cross-section of the mine drift, decline, etc. – evacuation through the smoke layer is expected during a fire and must be addressed when determining toxicity and visibility thresholds.

As escape devices may be used during a fire underground, the toxicity threshold will have to be set, accounting for the possible use of the device. Applying multiple thresholds in the evaluation of the design fire scenarios – whether escape devices are used in the mine or the specific mine section – could be appropriate. The threshold will be different depending on the construction and protection level of the escape device used in the mine – for example a self-contained self-rescue device versus an escape hood (filtering respiratory protective device).

Evacuation may take place by foot or vehicle, where the visibility through smoke will vary depending on the light conditions. Furthermore, vehicle collision risk will have to be accounted for when evacuating by vehicle. The visibility criterion will therefore have to be adjusted according to the evacuation type in the mine section and the light conditions. The use of multiple visibility thresholds could be suitable.

As a fire in an underground mine might be a long-lasting fire, the time aspect will have to be accounted for in the toxicity criterion. Personnel may be trapped or have taken shelter somewhere in the mine – awaiting assistance from the fire and rescue personnel or mine rescue personnel – and may inhale combustion products for a longer time. The exposure time should be addressed as personnel underground might receive permanent damage if exposed to a certain threshold for a certain time.

Other than the mining personnel, other people may also be present underground such as temporary contractors – with limited knowledge of the surroundings – performing, for example, maintenance work or tourists visiting a visitor mine. The setting of the toxicity and visibility thresholds must account for the personnel category or type of people present in the mine section, using lower toxicity thresholds and higher visibility thresholds for mine sections with people with limited knowledge and experience of an underground mine. The same approach – with more conservative threshold values – may be applied in the case of mining personnel that might be required to remain in place to secure a process to allow for a safe evacuation at a later stage.

Another potential life safety criterion could be the minimum distance to the smoke layer, which would affect the possibility of evacuating safely. In earlier full-scale fire experiments in an underground mine, it was found that the cooling of the fire gases was considerable in the mine drift [14]. Fig. 2 displays the fire gas temperatures measured at the ceiling level directly above the boom of a drilling rig and 45 m downstream of the burning drilling rig. Despite the relatively short distance between the two measuring points, the temperature difference was considerable, with a cooling effect of several hundred degrees. Further analyses have shown that the rough rock surface in a mine drift in conjunction with the longitudinal ventilation flow will increase the heat losses of the fire gases compared with, for example, a tunnel with a smooth surface [20]. More rapid cooling of the fire gases in a mine drift can thus be expected, which in turn will lead to a lower degree of smoke stratification and a more rapid descent of the smoke layer level. Therefore, a minimum distance to the smoke layer will only be relevant in the immediate near field and not far field of the fire. Using a minimum distance to the smoke layer as a criterion in an underground mine will therefore be of limited use.

Other than life safety, property damage or business continuity could also be potential criteria. The costs in the mining industry due to interruptions in production will, in many cases, be far exceed the costs due to property damage. Thus, the continuity of business will be highly relevant, where a criterion could include smoke damage due to smoke containing hydrogen chloride causing secondary damage in the shape of corrosion, adversely affecting production.

4.2. Position of fire

The position of the fire will largely influence the fire behaviour as well as the resulting impact on sensitive surroundings. The position of the fire scenarios must be determined for each mine and mine section based on the risks and layout. The fire behaviour may be affected by geometrical dimensions and overall layout at the site, where a lower mine drift or decline ceiling may lead to deflected flames at an early stage, which will result in a rapid fire spread and a fire with higher fire growth rate. The width of the mine drift or decline may influence the fire behaviour by increasing fire gas temperature and re-radiation to fuel items due to decreasing width. An increasing inclination of a mine drift or decline will increase the flame tilt,

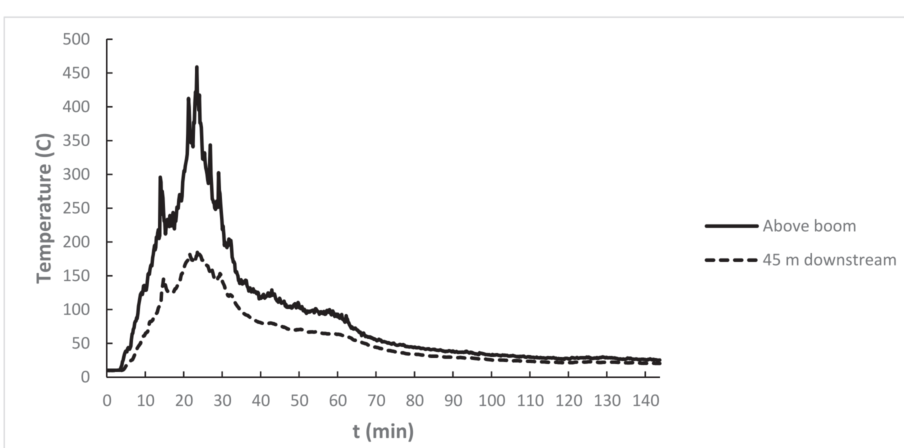

Fig. 2. The fire gas temperature above the boom and 45 m downstream of the fire–fire experiment involving a drilling rig [19].

possibly resulting in earlier ignition of adjacent fuel items (depending on the fuel configuration at the site). An earlier ignition of adjacent fuel items will result in a higher fire growth rate, higher maximum heat release rates and more severe fire behaviour. The fire behaviour will also be affected by the flow conditions at the site, where an increase in the ventilation flow may increase the mixing of hot fire gases with cooler air, decreasing the risk of fire spread caused by convective heating and possibly decreasing the resulting heat release rate. Earlier fire experiments in a model scale mine drift measuring the incident heat flux downstream of the fire resulted in peak values for a full-scale longitudinal ventilation of 2.3 m/s [19]. For the 1.2 m/s and 3.5 m/s cases, the peak incident heat flux was approximately 30% lower. Thus, the flow velocity will have a large impact on the fire spread further downstream. Furthermore, an increase in the flow velocity will also increase the flame tilt and the radiative heating and will therefore not only have a mitigating effect on the fire spread potential. Any sprinkler system will mitigate the fire's effects, decreasing the fire's heat release rate and the fire growth rate. As factors and impacts due to ventilation and fire protection systems are analysed and discussed in later chapters, the focus of the ensuing clusters of design fire scenarios are the factors and impacts due to geometrical dimensions and site layout.

4.2.1. Design fire scenarios with severe fire behaviour due to a fire close to the ceiling

An earlier study on fires involving non-fire resistant conveyor belts found that with decreasing distance between the burning conveyor belt and the ceiling of the conveyor drift, the flame deflection would eventually occur [21]. Initially, the fire behaviour was distinguished by low flame spread velocity and low heat release rate due to a lower radiant heat flux. When flame deflection occurred, flames along the ceiling led to considerably higher flame radiation levels at longer distances from the fire. The higher flame radiation levels led to increasing flame spread velocity and heat release rate. The acceleration phase of a flame deflection scenario was found to be significantly longer, resulting in significantly higher heat release rates. It was found that the occurrence of flame deflection would depend on the distance between the fire and the ceiling and the ventilation flow velocity. With increasing distance between the fire and the ceiling, the flame length would decrease, and the risk of flame deflection would decrease as well. With increasing flow velocity, the flames will tilt closer to the belt surface, and the risk of flame deflection will decrease.

The proposed cluster of design fire scenarios could involve a conveyor belt fire – a non-fire resistant belt – positioned close to the conveyor drift ceiling. The scenario could also consist of a fire on a cable ladder positioned close to the mine drift ceiling, vehicle fire in a mine drift with a low ceiling or a fire in a storage facility with a short distance between the ceiling and the uppermost fuel items. The fire will display a rapid fire growth rate, a high heat release rate and extensive smoke production over an extended time period. The aim of this cluster of scenarios is to investigate the impact of a rapidly spreading fire with considerable heat release rate, potentially continuous fire spread depending on the fuel configuration and considerable smoke production. The close proximity to the ceiling would also increase the risk of falling rocks due to the heating from the fire, which could affect the fire and rescue operation.

The design fire scenario could be further developed also to include the failure of any fire protection system or the ventilation system to either activate or mitigate the effects of the fire.

4.2.2. Design fire scenarios with severe fire behaviour due to inclination causing early ignitions

A previous study on the design of fire scenarios in Australian underground hard rock mines pointed out the increased risk of ignition due to the flame tilt caused by the inclination of the decline or mine drift [8]. The ignition risk of fuel items found in the lower regions would increase as the flames would be tilted towards the floor. As larger flammable or combustible items could typically be found in the lower regions – such as the tyres on a mining vehicle – the risk of early ignition of larger fuel components and a severe fire is increased. The study also pointed out another type of fire spread caused by the inclination, i.e., leaking and burning flammable liquid spreading downwards along the decline, igniting the lower vehicle. The risk of fire spread would be higher for this type of fire scenario.

The proposed cluster of design fire scenarios would include two mining vehicles – positioned close to each other – in a decline (or a mine drift with considerable inclination), where the fire starts on either the lower or the upper vehicle. If the fire starts on the upper vehicle, leaking and burning flammable liquid will spread downwards along the decline towards the lower vehicle. The fire will display early ignition of larger fuel items, resulting in higher fire growth rate, higher maximum heat release rates and more severe fire behaviour at a potentially critical position during evacuation and rescue operations. The aim of this cluster of scenarios is to investigate the impact of fire with a high fire growth rate, high maximum heat release rate, high smoke production, potentially a long-lasting fire, and the smoke behaviour in a decline/mine drift with considerable inclination.

The scenario could be varied by including different types of vehicles found in the mine and by the failure of the ventilation system in the mine section. As mining vehicles can be found in numerous places throughout a mine, the site characteristics of the scenario can be developed further to specifically include positions with a high density of personnel nearby or positions critical with respect to the evacuation or the rescue operation.

4.3. Fire load

The fire behaviour, smoke production and spread are all highly dependent on the fire load density, fuel distribution and type of fuel found underground.

The environment in underground hard rock mines typically consists of non-continuous fire loads and occasional combustible objects with non-combustible hard rock sections in between. While the environment consists of islands of combustible objects, fuel items underground can have considerable energy content in the form of large tyres, storage areas with flammable liquids, etc. [8]. An earlier site inventory of two large underground iron mines found several locations with high fire load densities [16]. The site inventory listed the following locations and types of fuel objects posing a risk underground:

- Storage/fuelling areas with flammable or combustible liquids,
- Storage areas with tyres,
- Conveyor drifts or storage areas with conveyor belts,
- Larger workshops with several larger vehicles, flammable/combustible liquid, etc.
- Cable vault or cable shaft with a high load of cables,
- Larger mining vehicles with larger tyres and containing a considerable amount of diesel, hydraulic oil, hoses, and cables.

Fires in these locations or on these types of objects can easily exceed tens of megawatts in heat release rate, causing severe problems to the personnel underground and the rescue services.

Different fuel types will result in different energy contents and various convective and radiative fractions of the heat release rate, which will affect the fire spread. The fire spread will also depend on the position of nearby fuel items and the ventilation flow velocity. Prior to full-scale fire experiments on mining vehicles in an underground mine, a fuel inventory was performed on the loader and the drilling rig in question. The resulting effective heat of combustion and energy contents of the major fuel items can be found in Table 1. As seen in Table 1, the effective heat of combustion of the flammable/combustible liquids is significantly higher then solid fuel items. For the same amount of fuel, a higher heat release rate can be expected from a fire in a flammable/combustible liquid compared to a solid fire. Furthermore, the fire load on the loader is dominated by the tyres, whereas the hydraulic oil and hydraulic hoses dominate on the drilling rig. Thus, depending on the type of mining vehicle, the fire load will vary, and the fire behaviour can be expected to vary as well. The fire load will also have a bearing on the duration of the fire, with generally longer-lasting fires for higher fire loads.

A statistical study was conducted on fires in the mining industry in New South Wales, Queensland, and Western Australia in Australia [17]. The data from New South Wales and Queensland listed mining vehicles and conveyor belts as the two dominating fuel objects. Mining vehicles will contain several different types of fuel, where the statistics pointed out oil, hydraulic oil, diesel, and

Table 1. The effective heat of combustion and energy contents of fuel items found on a drilling rig and a loader [19].

Fuel item	Effective heat of combustion [MJ/kg]	Energy contents: loader − Toro 501 DL [MJ]	Energy contents: drilling rig − Rocket Boomer 322 [MJ]
Tyres	27	42,120	4185
Hydraulic oil	42.85	16,283	16,283
Hydraulic hoses	28.85	4905	11,252
Diesel	42.6	10,138	3621
Electrical cables	19.41	21	8735

cable insulation as the most frequent fuel sources in fires. The resulting data from Western Australia was similar, pointing out mining vehicles, electrical devices, and conveyor belts as the most frequent fuel objects. The most frequent fuel sources for mining vehicles were similar to the results from New South Wales and Queensland. Common for all three states was the dominance of heavy vehicles among the fire statistics for mining vehicles. Specifically, the truck, drilling rig, dozer, and loader category were most frequently found in the fire statistics. Given the severity, the frequency of fires in mining vehicles and that vehicles can be found throughout most parts of a mine, the majority of the design fire scenarios underground should include a mining vehicle.

Having the very high fire load at storage or fuelling areas and the higher effective heat of combustion of flammable/combustible liquids, a proposed cluster of design fire scenarios would include a pool fire which takes place at a storage or a fuelling area, involving large amounts of a flammable or combustible liquid. The pool fire will display a rapid fire growth rate, a high heat release rate and extensive smoke production over a long time period. The aim of the scenario is to look into the impact of a long-lasting fire with considerable heat release rate and smoke production. The scenario would also investigate the aspect of falling rocks due to the heating from the fire, hampering the fire and rescue operation.

The scenarios at a fuelling area could be further developed also to include a burning mining vehicle, which ignited during the fuelling process. By adding a mining vehicle, the total fire load and resulting heat release rates and fire duration will increase even further.

4.4. Fire behaviour

The fire behaviour will play a central role with respect to the design fire scenario, dictating the appearance of the heat release rate curve, which is a decisive item during the continued work. The fire behaviour contains several different parameters, influencing the output results in various ways.

The parameters of the initial fire – i.e., the type and intensity of ignition source, size of initial fire, fire growth rate and position with respect to combustible items nearby – will largely dictate the early stages of the fire. The early stage of the fire is a crucial part when evacuation usually takes place. An ignition source with a high heat release rate will pre-heat larger surface areas at an early stage, leading to a rapid flame spread and fire growth at an early stage. A rapid fire growth at an early stage may affect the evacuation of the mine or mine section negatively as conditions may become untenable at an early stage. The fire characteristics of the item which is first ignited will also have an impact on the ensuing fire behaviour. An item with, for example, flashy characteristics will result in rapid fire growth and possibly involve adjacent fuel items at an early stage. An earlier study on fire causes in mining vehicles found that vehicle fires eventually engulfing the entire vehicle were often caused by a spray fire involving diesel [18]. The spraying diesel would encounter and ignite onto a hot surface in the engine compartment, leading to a rapid fire spread and fire growth at the very start of the fire. Fires involving flammable or combustible liquid will – whether it is a pool fire or a spray fire – display rapid fire growth and considerable smoke production. Fig. 3 displays the heat release rates of earlier conducted full-scale fire experiments on a loader

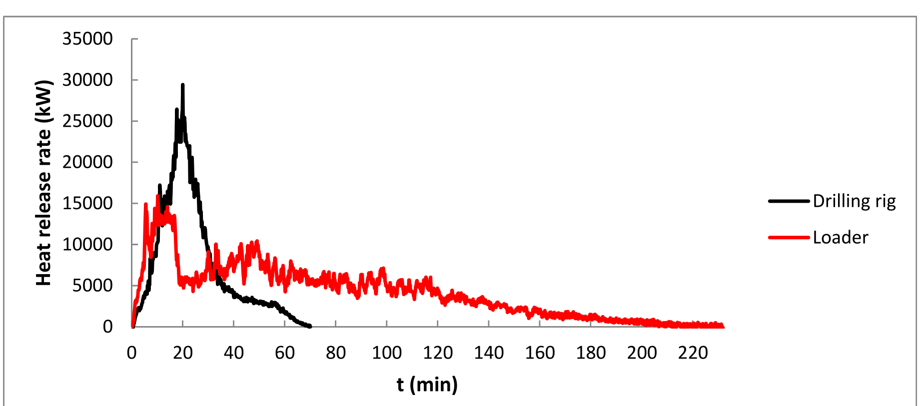

Fig. 3. The heat release rates of the full-scale fire experiments involving a loader and a drilling rig, respectively [19].

and a drilling rig [19]. The heat release rate of the loader displays an initial increase due to a diesel pool fire and the engulfment of the right rear tyre. The rapid decrease approximately 20 min after the ignition is due to the diesel running out. The subsequent intermediate peak of the heat release rate is due to the ignition and flame spread along the surface of the left rear tyre. The heat release rate of the drilling rig is also distinguished by the initial rapid increase due to the diesel pool fire and an adjacent tyre. As opposed to the loader fire, almost all the combustible items of the drilling rig were ignited during the initial stages of the fire, resulting in a higher maximum heat release rate and a more short-lived fire.

The continued fire spread will be highly dependent on the fuel distribution, the type of fuel found close to the initial fire and the ventilation flow direction. A mining vehicle will present an object with a continuous fuel distribution in the form of hydraulic hoses and electrical cables along the vehicle and larger fuel items – for example, tyres – as discrete fuel items positioned at a distance from other items. The hoses and cables could have a bridging function during the fire spread to the outer fuel items. If the fire spreads to one of the major fuel items with high total energy content, the characteristics of the fire will change. The heat release rate would increase, and the increased radiative and convective heat transfer would increase the risk of further fire spread and a persisting high heat release rate. The ventilation flow direction could potentially assist the fire spread by pushing the flames toward adjacent fuel items. The influence of the ventilation flow direction on the fire spread was further studied in an analysis of heat release rates of mining vehicles [19].

The duration of a fire underground will have a large impact on fire safety, as the smoke production and smoke spread may be extensive, which in turn may force some of the personnel to remain underground for the duration of the fire. Even the decaying phase of the fire may significantly impact on the fire safety and the possibility of evacuating personnel, with persistent smoke production and the risk of falling rocks after significant heat exposure. Fig.3 displays a loader fire with a considerable fire duration and decaying phase, despite that rear tyres of the loader never took part in the fire [14]. Any fire in a larger mining vehicle can be expected to last for a considerable time. Furthermore, with larger items igniting at a later stage of the fire – for example, a fire where the burning mining vehicle ignites a second mining vehicle positioned nearby – the risk of an extended fire duration and additional and delayed peak heat release rates will increase. Multiple and delayed peak heat release rates may cause problems for the fire and rescue personnel and the smoke ventilation operation. The delayed ignition could, for example, be due to a fuel item partly shielded from the adjacent fire, reducing the incident heat flux and delaying ignition.

Battery-powered vehicles are becoming more and more frequent in underground mines. Adding a new type of mining vehicle with a different source of propulsion will potentially result in different fire behaviour and risks. No full-scale fire experiments have been conducted on battery-powered mining vehicles to date. Still, fires have occurred, and fire experiments have been conducted on larger Lithium-ion batteries, allowing for some conclusions to be drawn on potential fire behaviour underground [22,23]. The characteristics of a burning Lithium-ion battery include phenomena such as the possible occurrence of jet flames, which may lead to an earlier ignition of adjacent fuel items and the ignition of fuel items found at lower positions (which would have been harder to ignite by an adjacent buoyant flame). An occurring jet flame would also increase the risk of igniting adjacent mining vehicles, developing into a severe fire involving multiple vehicles. The total fire load of a battery-powered mining vehicle may not necessarily differ much compared to a mining vehicle with a different source of propulsion, but a more rapid fire growth and increased risk of multiple vehicles on fire should be accounted for when developing the heat release rate curves.

4.4.1. Design fire scenarios occurring in one of the main evacuation routes or any other position sensitive with respect to evacuation, with the fire potentially spreading to adjacent fuel objects

The proposed cluster of scenarios includes a vehicle fire in one of the main evacuation routes, a vehicle fire at a critical junction, or any other position critical to the evacuation. The vehicle fire displays a rapid fire growth rate, involving flammable/combustible liquid at an early stage and with extensive smoke production. The scenario is aimed at looking into the impact of a fire with severe fire behaviour positioned at a critical position with respect to evacuation and the safety of the mining personnel.

As opposed to the earlier proposed cluster of scenarios positioned at a storage or a fuelling area, this set of scenarios could be positioned at any location where mining vehicles are found. The design fire does not necessarily have to be positioned in the immediate surroundings of an evacuation route or junction. The fire could also be found at a position where the ventilation flows are critical with respect to evacuation.

The scenarios could be further developed also to include the fire spread to an adjacent mining vehicle, extending the duration of the fire, and potentially increasing the maximum heat release rate.

4.4.2. Design fire scenarios with a fire with longer and intermittent periods with high heat release rates and sudden increases of heat release rates

The sets of scenarios would include vehicle fires with longer and intermittent periods with high heat release rates occurring long after the initiation of the fire. The fire will be long-lasting and display sudden increases of heat release rates. The aim of the scenario is to investigate the impact of a fire behaviour which may hamper the fire and rescue operation and smoke ventilation.

The scenarios could be further developed by including several vehicles with delayed ignition of the different vehicles. Further variations could also include the type of vehicles as well as the position of the initial fire with respect to the ventilation flow direction.

The position of the scenarios could include any position deemed critical with respect to smoke ventilation or any position at or near a designated attack route for the fire and rescue service or the mine rescue.

4.5. Smoke production and smoke spread

The smoke production from a fire will depend on several factors, such as the type of fuel involved, the heat release rate and the ventilation conditions. Fuels typically associated with severe smoke production would include tyres, hoses, cables, cab interior, diesel, oil, hydraulic oil, and conveyor belts. Several of these fuel types are typically found on mining vehicles and in large quantities (see Table 1). In earlier performed cone calorimeter experiments involving solid material typically found on mining vehicles − low voltage cable sheathing, hydraulic hose and cab interior material − the peak smoke production rate was almost twice as high for the cab interior material compared with the low voltage cable sheathing (with the hydraulic hose found in the intermediate region) [19]. Whereas for the total smoke production, the low voltage cable sheathing displayed the highest result, and the cab interior material displaying the lowest result. Thus, when looking into the smoke production of materials and substances found underground, the time aspect will have to be considered (i.e., studying the entire duration of the fire and/or specific intervals with peak values). Locations underground with a potentially high smoke production would include locations with several larger mining vehicles, conveyor drifts, warehouses or storage areas, and workshops containing vehicles, tyres, and flammable/combustible liquids. An extensive smoke production underground is highly undesirable as it will affect the evacuation and rescue operation negatively with lowering visibility and increased amount of toxic substances.

The smoke emitted from the fire will spread throughout parts of the mine, depending on factors such as the existing ventilation flows underground, the heat release rate of the fire, the temperature of the smoke and the position of the fire. As opposed to buildings above ground where the smoke spread may often be limited to the room of origin, the smoke spread underground can be spatially extensive, and the smoke movement paths numerous. The smoke spread in a mine drift or a decline, is largely determined by the occurring smoke stratification, which in turn depends upon the air velocity, the dimensions of the mine drift or decline, the heat release rate as well as the distance to the fire. The position of the fire with respect to any ventilation shaft or fan has been pointed out in an earlier study as playing an important part [19]. A fire close to an intake shaft will result in a rapid and extensive smoke spread and increase the risk to the personnel underground. The reasons for this are that the ventilation velocity has not yet been affected by the friction losses and thus remaining at a higher level, as well as the fact that an intake shaft will service several areas and thus increase the extension of the smoke spread. A fire close to an exhaust shaft will, in many cases, result in a limited smoke spread and minor impact to the personnel as the affected area will be limited [19].

4.5.1. Design fire scenarios occurring at a short distance from an intake fan or shaft and burning with a considerable smoke production

The proposed set of scenarios involves a vehicle fire taking place close to either an intake fan or an intake shaft. The fire should include burning combustible/flammable liquid at an early stage, leading to extensive smoke production. The scenarios aim is to investigate the impact of a fire which will lead to an extensive smoke spread and affect large areas, investigating the impact of scenarios where initially the ventilation system may aid the smoke spread.

The scenarios could be varied by including several mining vehicles in the fire and where the vehicle categories are varied as well.

4.5.2. Design fire scenarios involving a conveyor belt and one or several mining vehicles

The proposed cluster of scenarios involve a burning mining vehicle that has ignited a nearby conveyor belt. In the case of a fire-resistant conveyor belt, the fire may involve multiple mining vehicles for continued smoke production from the conveyor belt. This cluster of scenarios differ from the earlier proposed cluster involving a conveyor belt by not necessarily requiring a short distance between the belt and the ceiling. The position of the scenarios would include a conveyor drift, loading area or distribution level. The scenarios could be further varied by assuming that the smoke ventilation system at the site fails. The scenarios aim is to investigate the impact of a fire with considerable smoke production, potentially affecting larger areas through the smoke spread.

For heat release rates, ignition time, energy released, mass loss rates, etc., of fire-resistant conveyor belts, data from full-scale fire experiments and cone calorimeter experiments can be found in papers by Wachowicz [24,25].

4.6. Fire protection

Fire protection systems in an underground mine would, for example, consist of automatic fire alarm systems, automatic suppression systems, smoke ventilation systems, and fire and smoke partitions. Any fire protection system in a mine section will affect the fire behaviour, smoke behaviour and the impact of the fire. A fire alarm system will alert mining personnel in the affected mine section, which in turn could extinguish the fire, limit the fire spread, or initiate an evacuation. Upon initiating of a fire alarm, fire and smoke partitions could be closed, and smoke ventilation be initiated. An automatic suppression system would influence the heat release rate, possibly suppressing the fire or at least limiting the growth and the spread of the fire. With decreasing heat release rate, the smoke production would decrease as well and potentially the duration of the fire. A discussion on the impact of the suppression system on the resulting heat release rate curve can be found in a publication by Klote and Milke [4]. A smoke ventilation system could steer the smoke spread in the desired direction, limiting the affected mine sections, facilitating the evacuation and the fire and rescue operations. A smoke ventilation system could also overcome or mitigate any backlayering, which would aid the fire and rescue operation. An earlier study on pre-incident planning of fires in underground mines identified mine ventilation as a key function during the evacuation phase as well as the fire suppression and recovery phases [9]. It was proposed that any design fire scenarios should be tested against the management of the mine ventilation system. Fire and smoke partitions would block the fire spread and the smoke spread, limiting the heat release rate and the extension of the smoke spread. Fire and smoke partitions would also aid the smoke ventilation of the mine section.

The environment of an underground mine is sometimes distinguished by a harsh environment and heavy tear, which may affect the reliability of a fire protection system. Will it actually activate and function properly during a fire? The reliability of any existing or planned fire protection system will have to be addressed when developing design fire scenarios.

The failure of a fire protection system to either activate, suppress the fire, direct the smoke flow, or mitigate the effects of the fire may have a serious impact as the fire protection system has most likely been installed to reduce a certain risk. The risks will be considerable in the case of mine sections where a large number of personnel works, as a fundamental assumption on the expected fire behaviour and its impact will change. A fire alarm system which fails to activate may lead to delayed evacuation − putting the evacuating personnel at risk − or delayed suppression efforts which would decrease the chance of extinguishment as the fire will grow in size and intensity, or a delayed initiation of the smoke ventilation system which may affect the efficiency of the action. A suppression system that fails to activate will lead to a continued fire growth and spread, resulting in higher heat release rates, smoke production, and a longer lasting fire. A smoke ventilation system that fails to activate − for example, an individual fan − may lead to difficulties in directing the smoke in a desired direction or providing the required flow velocity, endangering the evacuation and rescue operation. Fire and smoke partitions which fail to close may result in smoke spread and fire spread in an undesired direction, potentially affecting larger parts of the mine and the safety of the mining personnel.

The fire conditions and the surroundings may also affect the efficiency of the activated fire protection systems. A fire occurring on a mining vehicle may be difficult for an external suppression system to extinguish or limit the fire growth as the construction of the vehicle could block the fire suppression agent from reaching the fire. The reduced amount of fire suppression agent reaching the fire should be addressed when developing the heat release rate curve, accounting for an increase in the resulting heat release rate of the burning mining vehicle. A similar problem is faced in rack-storage commodities, where the concept of Actual Delivered Density (ADD) is used when studying the water density from a sprinkler system which actually penetrates the fire plume and delivers to the top surface of a burning rack-storage commodity [26]. A severe fire with high heat release rates and a rapid fire growth rate may cause problems for the smoke ventilation system. Occurring phenomena include the buoyancy effect, the throttle effect, and backlayering [19]. The buoyancy effect may occur in declining drifts where the decrease in density — caused by the fire — will cause disturbances and even reversal of the ventilation flow. The throttle effect occurs underground during a fire with a considerable heat release rate or fire growth rate, where the heated air masses passing the fire causes reduced mass flow rates downstream of the fire. The throttle effect in underground mines has been investigated in several studies and is a well-known phenomenon underground [15,27,28]. Fig. 4 displays the reduced mass flow rate caused by the throttle effect during model-scale fire experiments (ignition took place 2 min into the experiment) [15]. The backlayering phenomenon — i.e., smoke travelling in the opposite direction with respect to the ventilation flow — will foremost pose a challenge and a risk to the fire and rescue operation. A severe backlayering will hamper the fire suppressing and rescue operation when trying to reach the fire site or reach a refuge chamber from the upstream side, as the visibility may be poor, and the heat from the smoke may have affected the rock ceiling upstream of the fire. Backlayering usually occurs when the ventilation velocity is in the low or moderate range, depending on the heat release rate of the fire and the geometrical aspects of the mine drift or decline. Numerous studies have been conducted on the backlayering phenomenon in an underground mine [29–31].

In any design fire scenario with a high heat release rate, a rapid fire growth rate, a low/moderate ventilation velocity, or an inclined surface, the issue of buoyancy effect, throttle effect, and backlayering will have to be looked into and investigated. This would include earlier proposed clusters of design fire scenarios containing for example several burning mining vehicles, pool fires with rapid fire growth, and declines and mine drifts with significant inclination.

4.6.1. Design fire scenarios occurring in an area with high personnel density and where the existing fire suppression system or fire alarm system fails to activate

The sets of fire scenarios take place in an area equipped with a fire alarm system and/or a sprinkler system involving one or several mining vehicles. One or both fire protection systems fail to activate. The vehicle fire displays an extensive and fast-growing fire behaviour. Adjacent to fire site is an area where personnel are frequently found. The scenario is aimed at analysing the impact of a fire which should be suppressed or detected but is not due to the failure of the fire protection systems. The position of the fire could, for example, be a workshop or a parking drift. The scenarios could be

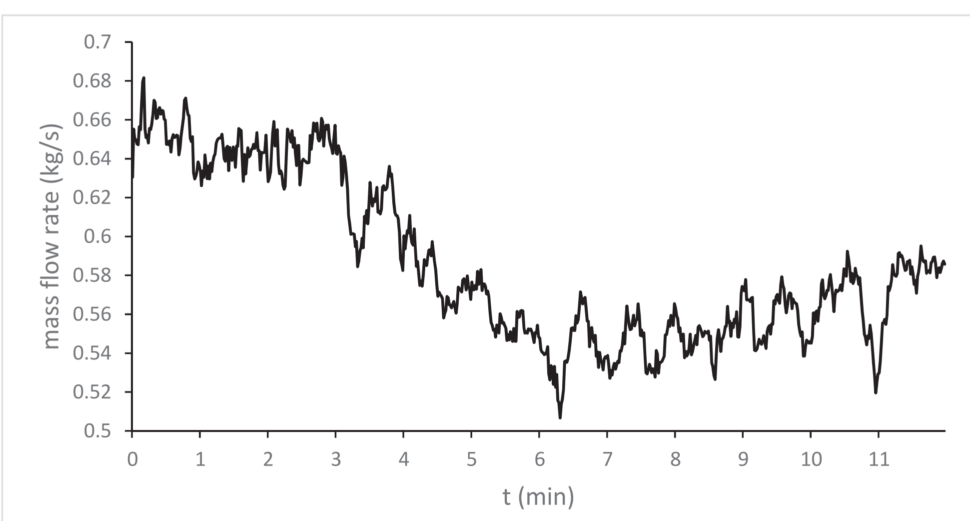

Fig. 4. The mass flow rate of a fire experiment in a model-scale mine drift, experiencing the throttle effect.

varied by including several mining vehicles in the fire and where the vehicle categories are varied as well.

4.6.2. Design fire scenarios occurring at a position where the smoke ventilation system fails to function or underperforms

The cluster of scenarios involving a failed system could encompass a vehicle fire which burns off the power supply to fans in the vicinity. The scenarios involving an underperforming smoke ventilation system could, for example, be caused by fire or smoke partitions that fail to open or close, leading to smoke spread in undesired directions. The fires would involve a large amount of diesel and tyres, emitting large amounts of smoke. The cluster of scenarios is aimed at investigating the impact of a fire, where a crucial fire protection system – i.e., the smoke ventilation – fails or underperforms, leading to an extensive smoke spread.

Interesting positions to investigate could be where multiple mine drifts, declines, etc., intersect, with a possible smoke spread in several directions.

4.7. Personnel

The operation underground will be distinguished by personnel unevenly distributed throughout the mine, with mine sections containing a lot of personnel and other mine sections where personnel are seldom present. The personnel density underground will also vary with time, i.e., rotation of shifts, larger maintenance stops underground, etc. Any undesired fire development with respect to the mining personnel would include some mining personnel found in the vicinity of a fire with severe fire behaviour or found at a distance from the fire site but in danger due to the smoke spread and blockage of an evacuation route.

Some mining personnel in a mine sector may increase the likelihood of early and successful intervention. However, as mentioned before, the personnel working underground at any one time could be limited, and there may be just a few miners who are located at the same mine section throughout the day. This factor would decrease the likelihood of a possible successful intervention. In addition, the time it takes for the fire and rescue personnel to arrive at the fire could be lengthy, decreasing the likelihood of an intervention during the early phases of the fire [8]. If using a conservative approach during the development of design fire scenarios, it may be warranted to assume that no personnel manage to extinguish any occurring fire.

4.7.1. Design fire scenarios occurring at a position or nearby a position where the personnel or people density is high

The proposed design fire scenarios involve one or several mining vehicles and take place at or nearby a site with high personnel or people density. A potential position could be the main level with a high frequency of vehicles. The position could also be in the vicinity of, for example, a visitor museum. When assigning the position, parameters such as the number of personnel or people in the vicinity, the level of familiarity with the mining conditions, the level of training and the responsiveness of the personnel and people, the ventilation conditions, the fuel continuity, and the risk of fire spread to an adjacent object should be considered and possibly varied.

The set of design fire scenarios aims to investigate the impact of a fire occurring at one of the levels or mine sections with presumably frequent activities and with a higher personnel or people density.

4.8. Cascading effects

Besides an extensive smoke spread or a fire spread to other mining vehicles or fuel items, a fire underground may also cause other risks, having a cascading and escalating nature. The mine may include areas with certain risks that may be triggered during a fire and could negatively affect the evacuation and the fire and rescue operation. One example could be a fire in a workshop where oxy-fuel welding equipment is stored. Acetylene cylinders may have been affected by the heat, and the content has started to decompose, and where the decomposition process may cause the cylinder to explode hours after being heated up. This time period – before it is considered safe to approach the cylinders – will have an impact on any personnel taking shelter in a refuge chamber or the fire and rescue operation. A fire affecting other types of pressurized containers in a workshop could also trigger similar cascading effects. Yet another example could be a scenario with a burning larger mining vehicle with an ensuing risk of tyre explosion or a severe vehicle fire where the rock ceiling is affected by the heat, resulting in a risk for falling rocks. These types of scenarios could take place in numerous places underground.

A proposed cluster of scenarios would be design fire scenarios causing cascading effects and occurring at positions sensitive for the evacuation or the fire and rescue operation. The scenarios would include fires occurring in a position where additional risks are triggered by the fire. The purpose of the scenario is to investigate the impact of a fire having a cascading effect, for example, explosion or falling rocks. The cascading effect will affect the evacuation process as well as the fire and rescue operation, possibly putting mining personnel – seeking refuge underground – at risk during the time period. As the above-listed characteristics would imply numerous positions underground, the positions of the design fire scenarios should be selected based on the possible severe impact on the evacuation (for example, close to any larger refuge chamber) or fire and rescue operation (for example along an attack route).

4.9. Transient risks

An underground mine will, in many ways, have a transient nature, where the layout, operations and risks will change over time. An earlier site inventory pointed out the following risks with transient characteristics [16]:

- maintenance stops with hot works conducted and a large amount of combustible material transported and stored, and where the number of personnel underground increases considerably,
- intermittent transports with explosives and flammable liquid in declines and mine drifts.

The underground mine is distinguished by never-ending and numerous changes in mine layout, the position of installations, etc., over time. Besides the construction of newer parts, older parts may be abandoned as the mining operation moves on. Abandoned parts of a mine may contain combustible material, and fire protection systems may have been removed. A fire occurring in an abandoned section may go on for a long time before being detected, and the fire size may become considerable. This can affect evacuation, smoke ventilation and fire suppression activities [9]. The changing characteristics of mine sections could be defined as a transient risk.

Another transient risk underground would be the movement of mobile refuge chambers, changing the risk situation in the area. Due to the temporary positioning, the fire protection systems at the mine section may be limited.

A proposed cluster of scenarios would be design fire scenarios including a transient risk and having an impact on the evacuation or the fire and rescue operation. The following scenarios are suggested when investigating the impact of transient risks:

- A fire taking place during a maintenance stop involving either a mining vehicle or a larger amount of stored, combustible material. Potential positions would include any levels with high personnel density during the stop. Contractors with limited knowledge and experience of underground mining should be accounted for.
- A vehicle fire in a decline or a mine drift, where the involved vehicle is either a transport with flammable liquid, combustible liquid, or explosives. Potential positions would include in or nearby any evacuation or attack routes.
- A fire taking place in an abandoned part of the mine where no fire protection systems can be found. The fire grows in size and intensity before it is detected. The fuel involved would include any combustible material left at the mine section. The size and fire growth rate of the initial fire could be varied, developing both a scenario with a small initial fire and low fire growth rate as well as a scenario with a large initial fire and severe fire growth rate.
- A vehicle fire taking place in the vicinity of a refuge chamber containing mining personnel which has taken refuge there. The fire could be varied by also including a second vehicle, extending the fire duration.

4.10. External conditions and incidents

The earlier proposed clusters of design fire scenarios have entirely been defined by the conditions and incidents occurring underground, while some design fire scenarios could be heavily influenced by external conditions and incidents. External conditions could, for example, be weather conditions that may influence the smoke spread in mine sections close to the surface. External incidents could influence the conditions underground through the ventilation system or any access routes from the surface.

A proposed cluster of scenarios could be design fire scenarios influenced by conditions or incidents outside the underground mine. This proposed cluster of design fire scenarios could, for example, contain scenarios with the following characteristics:

- A fire is positioned at the intake of the main airway above ground, and where the smoke from the fire is spreading downwards into the mine. This scenario aims to investigate the impact of a fire scenario occurring outside the underground mine, but which may have a serious impact due to extensive smoke spread from the intake and where fire protection systems may be absent (i.e., the area around the intake). The fire could result in an extensive

smoke spread which would increase the areas affected and decrease the time available for evacuation. As opposed to the earlier proposed scenario in the smoke production and spread chapter, this scenario takes place both above and below ground.
- A vehicle fire taking place close to a portal and where weather conditions could possibly affect the smoke spread from the fire and interfere with the smoke ventilation.

5. Conclusions

Design fire scenarios are an important tool when designing the fire safety in an underground mine. The work with design fire scenarios may be challenging when attempting to provide a full set of scenarios covering the life safety aspect. Given the general lack of research into design fires in the mining industry, this paper provides a unique analysis of design fire scenarios in underground hard rock mines. Taking advantage of several different and diverse data sources, a comprehensive analysis with a holistic character is provided. This paper presents several proposed clusters of design fire scenarios which could be used as a support to ensure that several important aspects are covered. The paper also contains an analysis of suitable criteria when evaluating the results from the design fire scenarios, highlighting the toxicity of the emitted smoke and decrease in visibility as potential criteria underground. The proposed clusters of scenarios account for the diverse and influencing parameters such assmoke production, smoke spread, personnel density, cascading effects, fire load and fire behaviour. The proposed clusters of design fire scenarios should be regarded as a framework to be supplemented by characteristics of the mine (the types of vehicles, smoke ventilation system, number of personnel, etc.). Providing design fire scenarios would improve fire safety as well as the egress safety for mining personnel.

Ethical statement

The authors state that the research was conducted according to ethical standards.

Funding body

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Conflict of interest

The authors declare no conflict of interest.

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