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Research paper

Design of fire scenarios for Australian underground hard rock mines – Applying data from full-scale fire experiments

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A R T I C L E I N F O

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A B S T R A C T

One of the most significant tools when designing fire safety in an underground mine is the design fire methodology. This paper presents a number of design fire scenarios which were developed from risk assessments and risk analysis where a deterministic approach was implemented and where the results from earlier full-scale fire experiments in underground mines and analysis were included in the process. The developed scenarios showed that for scenarios, in which ventilation flow was in the same direction as the fuel continuity, continued fire spread to all major components were provided and longer and intermittent periods which resulted in high heat release rates resulted, would present a considerable risk to underground personnel. It was also found that the inclination of the decline has little influence on the resulting heat release rate – despite the flame tilt – and that the design of the mining vehicles was found to effectively delay or even prevent the ignition of adjacent fuel items in a number of cases. The design fire scenarios developed will provide a key tool when evaluating fire protection measures in an underground mine.

1. Introduction

The fire safety design of an underground mine is a challenging task due to its complexity, the ever changing layout of the mine and the introduction of new equipment and risks. One of the key tools when designing fire safety is the design fire methodology. A design fire in an underground mine can be seen as a comparison for fire protection measures and the risk to personnel and mining operations. The design fire scenario describes fire characteristics, both in time and in space, such as the heat release rate and smoke production.

A significant amount of analysis has focused on design fires in tunnels. Ingason (2009) conducted a study which described different expressions to depict the heat release rate of tunnel design fires. Cheong, Spearpoint, and Fleischmann (2008) conducted a study on road tunnel design fires for vehicles which presents an overview of the methodology used when calculating the heat release rate of a vehicle fire in a tunnel; a performance based approach was used, taking parameters, such as ventilation conditions and geometry, into account. Carvel (2008) presented a study on design fires in tunnels where water mist suppression systems are installed. The fire growth rates of a number of tunnel fire experiments were reviewed and design fire scenarios were proposed.

Very few studies have been conducted on design fires in underground mines. Hansen (2010) presented an initial study on design fires in underground mines, where potential parameters were discussed and a number of theoretically derived design fire scenarios were presented. Since the report by Hansen (2010) a number of full-scale fire experiments in underground mines have been conducted (Hansen & Ingason, 2013), which has resulted in an increase in the knowledge of fires in underground mines. The purpose of this paper is to elaborate and take the discussion on design fires further, by utilizing the results of full-scale fire experiments and other recent scientific findings (Hansen, 2015, 2017, 2018a) within the field. The results and findings of the earlier studies and experiments have given a more complete picture on the influencing parameters, which has enabled more focused and comprehensible discussion and analysis on design fire scenarios, as well as giving a fuller picture of the approaches used when developing the scenarios. Taking advantage of full-scale fire experiments will also increase the confidence in the resulting design fire scenarios. The advantages will, for example, consist of the ignition times of the individual fuel items being pinpointed with greater confidence and a focus on parameters which heavily influence fire behaviour. This paper contains a risk assessment and a risk analysis of fires in underground hard rock mines, a discussion on the design fire approach with respect to underground hard rock mines, information on influencing parameters, suggested approaches and the presentation of potential design fire scenarios using input parameters from the Australian mining industry and the deterministic approach.

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Developing and improving the design fire tool for underground mines will improve fire safety in underground mines and provide a safer working environment for mining personnel.

This paper discusses the effects of the presented design fire scenarios on the immediate environment, but does not contain any smoke spread calculations. Smoke spread calculations or simulations for the specific mine in question could be performed based on the output of the scenarios.

2. Design fires – in general and in underground mines

The first step when developing design fire scenarios involves the identification and definition of potential design fire scenarios. The identification of potential design fires could involve tools like historical fire incident data, statistical data for the facility or the equipment in question.

The characteristics of the mine and the personnel should be gathered at an early stage. The mine characteristics would include factors like fire protection systems, smoke partitions, fire barriers, evacuation routes and smoke evacuation. The personnel aspect would include parameters like the number and location of personnel and their level of training.

After selecting the scenarios they are further outlined and quantified, listing a number of associated assumptions.

The scenarios are quantified using either the deterministic or probabilistic approach. The deterministic approach is largely based on physics and chemistry or correlations based on fire experiments. The probabilistic approach rests heavily on statistics, describing the probability of a fire occurring and its outcome. In this analysis, the deterministic approach is implemented due to the small number of actual fires in underground mines.

When quantifying the design fire scenario, a number of parameters will influence the resulting characteristics of the scenario, such as the location of the fire; ventilation conditions; influence of the fire protection system (sprinkler, smoke extraction, fire alarm etc.); the distribution, density and type of combustible materials, etc. The parameters have to be documented along with the scenario.

Typical outputs when quantifying the design fire scenario include heat release rate, smoke production rate, fire size, temperature and heat flux. The heat release rate will represent a key parameter as it dictates, for example, the smoke layer temperature, the descent of the smoke layer and possible fire spread to adjacent items. The heat release rate will therefore significantly determine fire behaviour in an underground mine.

When evaluating the fire safety of an underground mine, several different design fire scenarios should be developed, as a single design fire scenario will rarely present a full picture of fire safety. The different design fires should also be developed by applying a range of criteria when evaluating the outcome of the scenarios, depending on whether life safety, continuity of business, etc. is the focus.

For a further and more thorough discussion on the general theory of design fire scenarios see the report by Hansen (2010).

2.1. Design fires in underground mines

2.1.1. Criteria

When evaluating the output of a design fire scenario and before developing the scenarios, one or several criteria should be decided upon. Given the high costs caused by production stops compared with lower property damage costs, focus should be placed on life safety and business continuity when setting up criteria for the design fire scenarios. Suitable criteria with respect to life safety underground - given the risk of extensive smoke spread – are thresholds with respect to toxicity (toxic effects due to the inhalation of combustion products) and visibility. Both criteria will affect the ability of the miners to safely evacuate the mine or take shelter in a rescue chamber. Continuity of business criteria could, for example, include smoke damage, where smoke containing hydrogen chloride would result in possible secondary damage in the shape of corrosion adversely affecting production.

2.1.2. The fire

As opposed to buildings – where predominantly the pre-flashover phase is of interest – the fully-developed fire and the decaying phase is also of interest in mining. A fully developed fire will have an impact on underground structures, potentially spread the fire to adjacent fuel items and lead to extensive smoke production. The decaying phase with persistent smoke production will influence the possibility of evacuating personnel from refuge chambers. The flashover phenomenon is of significant interest in the building industry, but it has been found to be highly unlikely in underground mines (except for in confined spaces such as underground office complexes, buses etc.) due to the generally open nature of the mining drifts and the limited amount of combustible material.

The fire load of a burning object underground will determine the duration of a fuel controlled fire (excessive access to oxygen). If the fire is ventilation controlled (restricted access to oxygen) the supply of air will largely determine the fire duration. Generally, the air masses available in declines and mine drifts and the existing underground mechanical ventilation decreases the probability of ventilation controlled fires.

The initial fire – ignition source, size, fire growth rate and position with respect to combustible material nearby – will largely dictate the early stage of the fire, a crucial stage when evacuation usually takes place.

2.1.3. Fuels

Fire development in an underground mine is largely dependent on the position of nearby combustibles and the ventilation conditions. Fire growth will accelerate as the fire increases in size. If the fire does not spread beyond the initial item, the fire becomes fuel-controlled and eventually decays. If the fire – following the early phase – involves a number of nearby fuel components, the initially local fire transitions into a fire with more extensive combustion which could eventually involve even more fuel components.

The environment in underground hard rock mines typically consists of non-continuous fuel loads and occasional combustible objects with non-combustible hard rock sections in between. Places with continuous fuel loads could for example be larger workshops with several vehicles, storage facilities, parking drifts or declines with a considerable number of vehicles. While the environment typically consists of islands of combustible objects, fuel objects underground can have considerable energy content in the form of large tyres, storage areas with flammable liquids, etc. The maximum heat release rate of fuel components underground can in some cases be tens of megawatts, such as in the case of larger pool fires and fires in larger vehicles which increases risk and causes problems to the personnel underground. The fuel types found underground which cause considerable smoke production include tyres, hoses, cables and flammable liquid. All these fuel types are found in mining vehicles, therefore making mining vehicles an important consideration when selecting underground design fires. Fires involving flammable liquid will, in addition to considerable smoke production, have rapid fire growth, representing a significant effect on underground personnel and the surroundings.

Different types of fuel will result in various convective and radiative fractions of the heat release rate, which in turn will affect the fire spread, depending on the position of nearby fuel items.

The mining industry is distinguished by never ending and numerous changes in mine layout, position of installations, etc. over time. Changes will also include the amount and position of combustible materials, referred to as transient fuels in these cases. Changes could also occur during the same day, where transportation along the decline could vary depending on the shifting of personnel, for example. Regular maintenance stops underground also influence the fuel situation, as a considerable amount of equipment and combustible materials are transported and stored underground.

2.1.4. Position of fire

The position of the fire is highly decisive for parameters like the fire growth rate, smoke spread and fire spread.

The influence of the position on the design fire will be dictated by a number of environmental factors connected to the specific place in question, for example:

- the inclination of the decline or drift,
- the geometrical dimensions of the decline or drift,
- distance to the nearest shaft and ventilation conditions at the position,
- fire protection at the position,
- amount of personnel.

The inclination of the mine drift or decline will affect the fire spread which, in turn, will affect the heat release rate. Increasing inclination will increase the flame tilt, leading to the earlier ignition of combustible items in the flow direction. Earlier ignition will lead to a higher peak heat release rate, severe fire behaviour and a short lasting fire.

The geometry of the decline or mine drift will affect the appearance of the heat release rate curve in numerous ways. A mine drift with a lower ceiling will lead to an increased fire gas temperature, where flames at ceiling level are deflected thereby igniting nearby fuel items at an earlier stage and decreasing the fire duration. A mine drift with limited width will also lead to increased fire gas temperature, increasing the re-radiation from the rock surface to fuel components and igniting nearby fuel items at an earlier stage.

The smoke spread in a mine drift or a decline is primarily dictated by the resulting smoke stratification. The smoke stratification will depend on the ventilation flow, the geometrical dimensions, the inclination of the mine drift or decline, the heat release rate of the fire and the distance to the fire.

An increase in the ventilation flow at the position of the fire will lead to tilting flames, which has the same effect on the fire's behaviour as an increase in inclination. An increase in ventilation flow also increase the effective supply of oxygen to the fire area – increasing the combustion efficiency – as well as decreasing the fire gas temperature.

Any obstacle in the decline or mine drift may interfere with the effects of the ventilation, block the ventilation flow and reduce the flame tilt and supply of air. Any obstacles directly adjacent to any combustible object may also affect the ignition of the object, acting as a heat sink where, for example, extensive metal components could possibly delay or even prevent ignition from taking place.

As distance to intake fans or shafts increases, the combustion efficiency of the fire will decrease as some of the air from fans and shafts will be diverted to other parts of the mine. In these cases the impact of the fire on the air flow may exceed the influence of the ventilation system, potentially reversing the flow of fire gases.

An intake shaft which services numerous areas will pose a serious risk in the case of a nearby fire as it leads to considerable smoke spread.

Any fire protection in the area will influence the resulting design fire scenario. A fire alarm system will alert mining personnel in the area, who in turn could possibly extinguish the fire or limit the fire spread. An automatic suppression system would influence the heat release rate, possibly suppressing the fire or at least limiting the growth of the fire.

The human factor can also have an influence when the possible intervention of nearby mining personnel could potentially lead to the extinguishment of the fire. However, 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 place throughout the day. These factors 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.

2.1.5. Worst credible underground design fire scenarios

The features and nature of an underground hard rock mine lead to a number of undesirable scenarios – with respect to the consequences for the mining personnel (life safety criterion) – such as:

- A fire with a rapid fire growth rate at the very early phase of the fire, possibly affecting the primary evacuation route/s.
- A fire with extensive smoke production over a long time period.
- An extensive or fast growing fire near an area with high density of personnel.
- A fire with continuous fire spread, resulting in a long lasting fire with a considerable heat release rate.
- A fire where the smoke control system fails to activate or function, leading to extensive smoke spread.
- A fire that goes undetected for an extensive time period, growing in size and intensity.

The scenarios listed above contain the potentials for loss of life or injury and have the following common denominators: a fast growing fire during the highly sensitive evacuation phase, a long lasting fire, a fire with high heat release rate complicating a suppression operation or a fire with extensive smoke production. Combining these into a single and highly undesirable scenario: a fire with an initial high growth rate, eventually levelling off or gradually declining but still with a high heat release rate and considerable smoke production and lasting for a long time period. This scenario will pose a risk during the evacuation phase, affecting significant parts of the mine and also poses a risk to personnel who have taken shelter in any refuge chambers.

Implementing the deterministic approach of potential, worst credible fires will lack the probability aspect, which will cause problems when selecting the scenarios for further studies. Taking advantage of statistical material while selecting the potential scenarios for further analysis using the deterministic approach will overcome some of the disadvantages and increase the credibility of the presented scenarios.

3. Method

This paper will not present a full picture of feasible design fire scenarios for underground hard rock mines found in Australia. Instead, a selection of design fire scenarios is developed where different aspects are highlighted with respect to fire behaviour and influencing factors.

3.1. Identification and definition of design fire scenarios

Hansen (2018b) presented a report containing statistical data from the mining industry in Australia, serving as an aid when developing design fire scenarios for the mining industry. The report contains data from various data sources from New South Wales, Queensland and Western Australia. When searching for specific fire objects, emphasis was placed on objects in underground hard rock mines, excluding objects that clearly did not fall into the category.

Table 1 displays some of the characteristics of the most frequent fires in underground mines in New South Wales, Queensland and Western Australia.

The most common fire fuel source in New South Wales is oil or hydraulic oil, which is not surprising given the high frequency of fires in the engine area of heavy vehicles. Diesel as well as electrical wiring is also frequently found to be among the most common fuel sources for fires.

Focus on vehicle/mobile equipment fires would be appropriate, as these types of fires are more frequent in underground mines than in open cut mines. In addition, fires in non-coal underground mines are

Table 1
The characteristics of the most frequent fires in New South Wales, Queensland and Western Australia.

State	Types of fire objects	Position of fires	Fire causes
New South Wales	Trucks, loaders and drill rigs.	Engine area (dominated by the exhaust and turbo section).	Oil or hydraulic oil on a hot surface, electrical cause and diesel onto a hot surface.
Queensland	Trucks, dozers and drill rigs.	Engine area (dominated by the exhaust and turbo section).	Oil or hydraulic oil on a hot surface, electrical cause and diesel onto a hot surface.
Western Australia	Trucks, drill rigs, dozers and loaders.	Exhaust or turbo, engine bay (unspecified position) and wheel/tyre/brake area.	Oil or hydraulic oil sprayed or leaked onto a hot surface, short circuit/arcing or an unspecified electrical fault.

more frequent compared to underground coal mines.

When studying weekly incident summaries (NSW Trade & Investment Mine Strategy, 2015–2017) – as other data sources do not indicate the specific vehicle or mobile equipment – a specific vehicle type from one of the three categories above was found, namely the dump truck Atlas Copco MT6020.

For Queensland – given the different nature of underground mines and open cut mines and the associated vehicle fleet – the dozer category was assumed to be the type of vehicle most commonly found in open cut mines. When searching for specific vehicle types in the data sources (Mines Inspectorate, 2008–2017) it was found that the following vehicle types were most frequently found in the statistics:

- CAT AD55 Dump truck,
- CAT 2900 Loader,
- Atlas Copco MT6020 Dump truck,
- CAT 1700 Loader.

The most common types of fuel for vehicle or mobile equipment fires in Western Australia were oil or hydraulic oil, diesel and cable insulation. The most common specific position underground was in an underground decline. When searching for specific vehicle types in the data sources (Resources Safety, 2014–2017) it was found that the vehicle types were identical to those found in Queensland.

Given the results of the statistical report and the data sources above, two types of scenario groups can be distinguished with respect to fuel objects, these being dump trucks and loaders. From the two scenario groups, four specific vehicles can be recognized: the CAT AD55 Dump truck, Atlas Copco MT6020 Dump truck, CAT 2900 Loader and CAT 1700 Loader. The position of the initial fire should be in the engine area, where fire is caused by oil or hydraulic oil making contact with a hot surface, an electrical issue or diesel making contact with a hot surface. Given the fact that an initial high fire growth rate and extensive smoke production represents a highly undesirable fire scenario and the fact that an earlier report by Hansen (2013b) highlighted that vehicle fires which eventually engulf the entire vehicle were commonly caused by diesel spraying on to a hot surface in the engine compartment, which leads to fast fire spread and fire growth, focus should be placed on flammable liquid ignited in the engine area with respect to the initial fire.

Vehicle fires will be unique with respect to the number of fires and the positioning of the fires, as vehicles will be present in most places in a mine and frequently in large numbers. A scenario with a fast growing fire near an area with a high density of personnel, a mine drift or a decline in close proximity to or within a main evacuation route would be of interest when designing the egress safety.

Given the considerable number of potential positions of vehicle fires, the site characteristics of the design fire scenarios could vary considerably without necessarily rendering the scenario improbable. For practical reasons the number of potential design fire scenarios were limited by selecting a few representative values for the ventilation velocity, drift/decline dimensions and inclination. Ventilation velocities were chosen either as 4 m/s or 7 m/s in a decline and 2 m/s or 3 m/s in a drift. The chosen decline ventilation velocities are within the typical ventilation design velocity range for metal mines (The Mine Ventilation Society of South Africa, 1999). The following dimensions of drift/decline were used: width 6 m and height 5 m. The inclination of decline was chosen to be either 6% or 10%. The 10% inclination corresponds to the upper limit for safe climbing for mining vehicles and the 6% inclination was chosen as an intermediate value.

To ensure a high heat release rate after the initial phase of high fire growth rate – possibly involving a fire of flammable liquid – a combustible component with a high total energy content must be involved. One such item with a high total energy content in a mining vehicle would be, for example, one or more of the vehicle's tyres. In addition, to ensure that the high heat release rate persists, the spread of fire from the initial item/s must be guaranteed. The heat transfer – radiative as well as convective – from a larger tyre or the continuous distribution of electrical cables or hydraulic hoses throughout the vehicle construction could fulfil this requirement.

Fuel types emitting a large amount of smoke would include tyres, hoses, cables, diesel and hydraulic oil. A fire in a mining vehicle in which all the listed fuel types are found and where a considerable amount of these fuel types are involved early on in the scenario would be worth analysing.

An example of fire with a considerable heat release rate and lasting for a long period of time is the a situation where the fire involved a larger fuel item early on, but the spread of the fire to other larger items was delayed or the burning time of the items was extended. A delayed ignition could, for example, be a scenario where the fuel item is partly shielded from the adjacent fire, therefore delaying ignition. Extended burning time could, for example, be a scenario where the flames spread along the fuel surface is delayed as the ventilation flow pushes the flames in an opposite direction. A long lasting design fire scenario could furthermore be a fire where the burning mining vehicle ignites a second mining vehicle positioned nearby.

Based upon the reasoning above and the influencing factors deemed to be of interest in the selection process and whilst bearing the consequences in mind, the descriptions of the selected design fire scenarios can be found in Table 2.

The probability aspect has been partially included when selecting the scenarios, as the statistical data indicated that the types of vehicles, initial fires, fuels etc. mentioned above are prioritized.

The influence of any suppression efforts or any other efforts made by the mining personnel or fire and rescue personnel was not included when developing the scenarios, nor were any effects from any fire protection system, e.g. a sprinkler, accounted for, as worst-case scenarios without any mitigating effects were desired.

3.2. *Quantifying the scenarios*

As full-scale fire experiments performed on the selected design fire scenarios would require considerable resources and time, a theoretical methodology was used instead to calculate the overall heat release rate of the individual design fire scenarios. A developed and validated method for developing the total heat release rate of mining vehicles was used (Hansen, 2015) in the analysis. Based upon the findings of Hansen (2015), critical heat fluxes were used as ignition criteria for the individual fuel items, establishing credible ignition times. The various fuel components were regarded as inert until the occurrence of ignition.

Table 2
The characteristics of the selected design fire scenarios.

Scenario #	Object	Position and its characteristics	Initial fire and fire growth	Subsequent fire spread
1	CAT AD55 Dump Truck	Decline with 10% inclination. Flow velocity: 4 m/s. Front of vehicle facing ventilation flow.	Spray fire with hydraulic oil in engine compartment evolving into a 2 m^2 pool fire (thick fuel bed). Involving 800 l diesel in total. Rapid fire growth.	Fire spreading from engine compartment to electrical cables and hoses and subsequently to adjacent tyres.
2	CAT 2900 Loader	Drift with no inclination. Flow velocity: 2 m/s. Front of vehicle facing ventilation flow.	Spray fire with diesel in engine compartment evolving into a 2 m^2 pool fire (thick fuel bed). Involving 800 l diesel in total. Rapid fire growth.	Fire spreading from engine compartment to electrical cables and hoses and subsequently to adjacent tyres.
3	Atlas Copco MT6020 Dump Truck	Decline with 6% inclination. Flow velocity: 7 m/s. Front of vehicle facing ventilation flow.	Spray fire with hydraulic oil in engine compartment evolving into a 1 m^2 pool fire (thick fuel bed). Involving 400 l diesel in total. Rapid fire growth.	Fire spreading from engine compartment to electrical cables and hoses and subsequently to adjacent front tyres. Hydraulic hoses burning off mid-distance between front and rear tyres, causing a pool fire and igniting rear tyres.
4	CAT 1700 Loader	Drift with no inclination. Flow velocity: 3 m/s. Rear of vehicle facing ventilation flow.	1 m^2 pool fire (thick fuel bed) with diesel underneath engine compartment. Involving a total of 200 l diesel. Rapid fire growth.	Fire spreading from engine compartment to electrical cables and hoses and subsequently to adjacent tyres.
5	Fire involving two CAT AD55 Dump Trucks	Decline with 6% inclination. Flow velocity: 4 m/s. Front of vehicle facing ventilation flow. Distance between vehicles: 2 m.	Spray fire with hydraulic oil in engine compartment of the lower vehicle, evolving into a 2 m^2 pool fire (thick fuel bed). Involving 800 l diesel in total. Rapid fire growth.	Fire spreading from engine compartment to electrical cables and hoses and subsequently to adjacent front tyres. Hydraulic hoses burning off mid-distance between front and rear tyres, causing a pool fire and igniting rear tyres.
6	CAT 2900 Loader	Drift with no inclination. Flow velocity: 3 m/s. Front of vehicle facing ventilation flow.	Spray fire with diesel in engine compartment evolving into a 2 m^2 pool fire (thick fuel bed). Involving 800 l diesel in total. Rapid fire growth.	Fire spreading from engine compartment to electrical cables and hoses and subsequently to adjacent rear tyres. Hydraulic hoses burning off mid-distance between front and rear tyres, causing a pool fire and igniting front tyres.
7	Fire involving two CAT AD55 Dump Trucks	Decline with 10% inclination. Flow velocity: 4 m/s. Rear of vehicle facing ventilation flow. Distance between vehicles: 2 m.	Spray fire with hydraulic oil in engine compartment of the upper vehicle, evolving into a 2 m^2 pool fire (thick fuel bed). Involving 800 l diesel in total. Burning diesel spreading downwards along the decline. Rapid fire growth.	Fire spreading from engine compartment to electrical cables and hoses and subsequently to adjacent front tyres. Burning diesel spreading the fire to the rear tyres as well as to the tyres, cables and hydraulic hoses of the second vehicle.

A flame radiation term was included in the heat flux calculations, but not the convective and radiative heat loss terms, as they were found to have no influence on the output. The heat flux expression used in the calculations when determining the ignition of adjacent fuel items (Hansen, 2018b):

$$\dot{q}''_{\text{flux}} = h_c(T_{avg} - T_s) + F_{\text{smokelayer}}\varepsilon\sigma(T_{avg}^4 - T_s^4) + F_{\text{flame}}\varepsilon\sigma(T_{\text{flame}}^4 - T_s^4) \tag{1}$$

where $\dot{q}''_{\text{flux}}$ is the external heat flux (kW m^{-2}), h_c is the convective heat loss coefficient (kW m^{-2} K^{-1}), T_{avg} is the average gas temperature (K), T_s is the fuel surface temperature (K), $F_{\text{smokelayer}}$ is the view factor smoke layer to target, ε is the emissivity factor, σ is the Stefan-Boltzmann constant (kW m^{-2} K^{-4}), F_{flame} is the view factor flames to target and T_{flame} is the flame temperature (K).

The convective heat loss coefficient was calculated using an expression by Newman and Tewarson (1983) in accordance with the earlier findings of Hansen (2018a):

$$h_c = 0.026\,\text{Re}_{D_h}^{-0.2}\left(1 + \left(\frac{D_h}{x}\right)^{0.7}\right)\rho\, c_p\, u \tag{2}$$

where Re is the Reynolds number, D_h is the hydraulic diameter of the mine drift or decline (m), x is the position in interest (m), ρ is the density of the fluid (kg/m^3), c_p is the specific heat capacity of the fluid at constant pressure (J/kg K) and u is the average velocity of the fluid (m/s).

The cooling of the fire gases along the rough rock surface was unaccounted for, as the fire gases igniting adjacent fuel items were generally emitted and confined within the near vicinity of the vehicle/s in question and within a short distance. In cases where the flames were pushed in the opposite direction of the fire spread direction, only the flame radiation term was accounted for. The flame spread velocity along the cables and hydraulic hoses were set at the same value even though the ventilation flow direction in relation to the flame spread direction was altered in the different scenarios; the reason for this is the vehicle construction protecting the cables and hoses from the ventilation flow.

The heat release rates of the various fuel components were mathematically represented by a single exponential function (Numajiri & Furukawa, 1998). The exponential function has the advantage of singularly and successfully representing the fire sequence without relying on numerous functions for different time intervals. The exponential function also successfully describes the different phases of a fire in a realistic way. The description of the total heat release rate of a mining vehicle includes the summation of the individual heat release rates. The individual heat release rate of an object is calculated by applying the following equations (Ingason, 2005):

$$\dot{Q} = \dot{Q}_{\max}\, nr(1 - e^{-kt})^{n-1}e^{-kt} \tag{3}$$

$$r = \left(1 - \frac{1}{n}\right)^{1-n} \tag{4}$$

$$k = \frac{\dot{Q}_{\max}}{E_{tot}}r \tag{5}$$

$$t_{\max} = \frac{\ln(n)}{k} \tag{6}$$

where $\dot{Q}_{\max}$ is the maximum heat release rate (kW), n is the retard index of the fuel item, r is the amplitude coefficient, k is the time width coefficient, E_{tot} is the total energy content (MJ) and $t_{\max}$ is the time to maximum heat release rate (s).

The input parameters can be taken from fire experiments, theoretical studies, visual observations, etc. from actual fires.

During the calculations Microsoft Office Excel spreadsheet software was used when employing the theoretical methodology.

A fire in a mine will be distinguished by a transient heat flux over

Table 3
Dimensions and fuel inventory of the designated vehicle models.

Dimension or quantity	CAT AD55 Dump Truck (Caterpillar, 2007a)	CAT 2900 Loader (Caterpillar, 2014)	Atlas Copco MT6020 Dump Truck (Atlas Copco, 2010)	CAT 1700 Loader (Caterpillar, 2007b)
Length (m)	12	11.3	11.2	10.7
Width (m)	3.3	3.2	3.2	2.8
Height (m)	3.3	2.9	3.3	2.6
Weight (kg)	50.000	50.209	43.900	38.500
Hydraulic oil (L)	258	140	238	125
Diesel (L)	960	1425	844	570
Tyre dimensions	35 × 65 R33	29.5 × 29 34 PLY VSMS	35 × 65 R33	26.5 × 25 36 PLY STMS L5S

time from the various fuel components. By calculating the heat flux numerically – using small time steps – the transient condition is fulfilled. A time step of 1 s was used in the calculations.

Based upon the findings of Hansen (2017), the radiative fraction of the heat release rate was set to 0.17 for the vehicle tyres. The radiative fraction of the remaining fuel items was set to 0.33.

The fire gas emissivity varied as a function of the fire gas temperature, in accordance with Hansen (2018a).

The dimensions and fuel inventory of the selected vehicle models can be found in Table 3. The characteristics of the various fuel items, such as the energy content per unit mass and critical heat flux, can be found in a paper by Hansen (2015).

The fuel load contribution of each vehicle's cab would be very low compared with the other fuel components and this was, therefore, unaccounted for in the calculations.

The total length and average diameter of the cables and hydraulic hoses could be very difficult to obtain, as this is generally not readily available data. If it is assumed that the total length and average diameter of the cables and hoses correlates roughly with the weight of the vehicle, then data from an earlier fire experiment with a similar type of vehicle – a Toro 501 DL loader – could be applied (Hansen, 2015). The calculated and assumed lengths and diameters can be found in Table 4.

4. Results

The fire of scenario #1 consisted of a large pool fire at the front right tyre which ignited both front tyres more or less simultaneously due to the extensive pool area. The fire in the front left tyre resulted in slower fire growth as the pool fire was not in the direct vicinity of the tyre. The rear tyres did not ignite as the distance between the front and rear tyres was too large for the flame radiation to attain sufficiently high incident heat flux at the rear tyres. The radiative and convective heat transfer from the fire gases did not suffice for ignition as the longitudinal ventilation would cool the fire gases. The overall heat release rate curve (see Fig. 1, where the acronym HRR stands for the heat release rate) displays an initially rapidly growing fire–peak value at ~18 MW – as the pool fire and the front right tyre attain a maximum value early. The peak value is followed by a declining phase, which is interrupted by a second peak value after approximately 2 h, as the fire in the front left tyre attains a maximum value. The inclination of 10% will tilt the flames closer to the rear tyres, but not enough to achieve ignition.

The spray fire in the engine compartment and the large pool fire at the rear tyres of scenario #2 eventually ignites the rear right tyre first and at a later stage the rear left tyre. Both tyre fires display a slow fire growth as the ventilation direction is pushing the flames and the fire gases away from the tyres. The flame spread along the tyre surfaces will therefore be low. The rear right tyre peaked after ~2 h and the rear left tyre after ~3 h and 20 min. The front tyres did not ignite due to the distance between the front and rear tyres as well as the ventilation direction which pushed the flames and fire gases in an unfavourable direction. The overall heat release rate curve (see Fig. 2) displays an initially rapidly growing fire-peak value at ~14 MW – caused by the pool fire and hydraulic hose fire. A declining phase followed the peak value and was interrupted by the peak periods of the rear tyres.

After the initiation of the pool fire of scenario #3, the front right tyre ignites early on. The heat release rate of the tyre showed a rapidly growing fire due to favourable ventilation direction. The front left tyre ignites at a later stage as the flames and fire gases are pushed in a parallel direction and at a longer perpendicular distance from the tyre (the peak value after ~2 h is attributed the front, left tyre).

Despite the favourable ventilation flow direction, the rear tyres were not ignited by the pool fire or the front tyre fires due to their distance from the fire and the cooling of the fire gases. Instead, the burned off hydraulic hose and a second pool fire midway between the front and rear tyres ignited the rear tyres. The rear tyres – positioned in the flow direction of the flames and fire gases of adjacent fires – displayed a significant flame spread and a fast growing heat release rate. The fire initially peaks at ~25 MW – see Fig. 3 – involving primarily the pool fire, front, right and rear tyres and the hydraulic hose fire.

Scenario #4 was similar to scenario #3, except that no pool fire occurred in between the front and rear tyres and the front tyres were therefore not ignited. There was a lower maximum heat release rate in scenario #4 (see Fig. 4) – ~12 MW – compared with the ~25 MW of scenario #3.

Scenario #5 was similar to scenario #1, except that the occurring pool fire in between the front and rear tyres ignited the rear tyres in scenario #5. This resulted in a peak value of ~25 MW in scenario #5 (see Fig. 5) compared with ~18 MW in scenario #1. The initial peak value after approximately 15 min was primarily caused by the fires in the front right tyre and the hydraulic hoses (the same peak value occurred in scenario #1). The second peak value after approximately 20 min can be mainly attributed to the fires in the rear tyres. This second peak value will not be found in Fig. 1 as the rear tyres were not ignited in scenario #1. Despite the fire completely involving the lower vehicle, the fire would not spread to the upper vehicle. The radiative and convective heat transfer of the lower vehicle were insufficient to ignite the upper vehicle.

Table 4
Assumed lengths and diameters of hydraulic hoses and electrical cables.

Dimension	CAT AD55 Dump Truck	CAT 2900 Loader	Atlas Copco MT6020 Dump Truck	CAT 1700 Loader
Length of hydraulic hoses (m)	320	320	280	240
Average diameter of hydraulic hoses (mm)	29	29	26	22
Length of electrical cables (m)	290	290	250	220
Average diameter of electrical cables (mm)	1.9	1.9	1.7	1.5

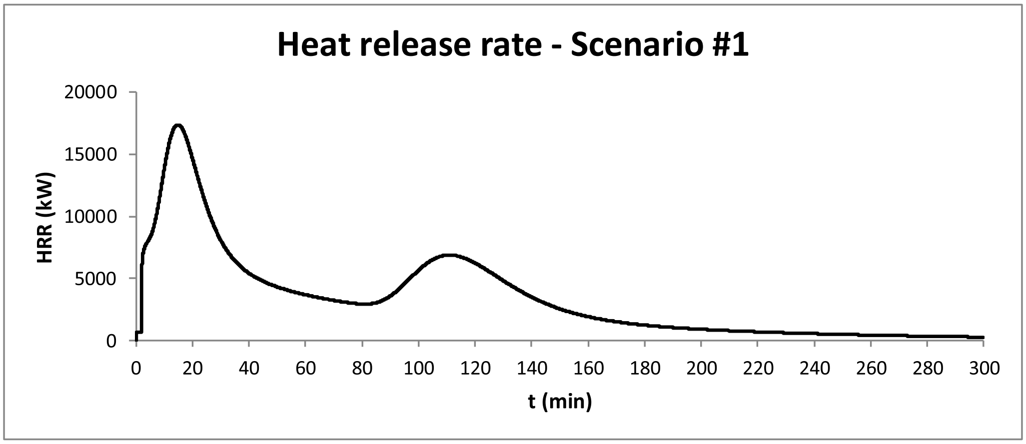

Fig. 1. The heat release rate of scenario #1.

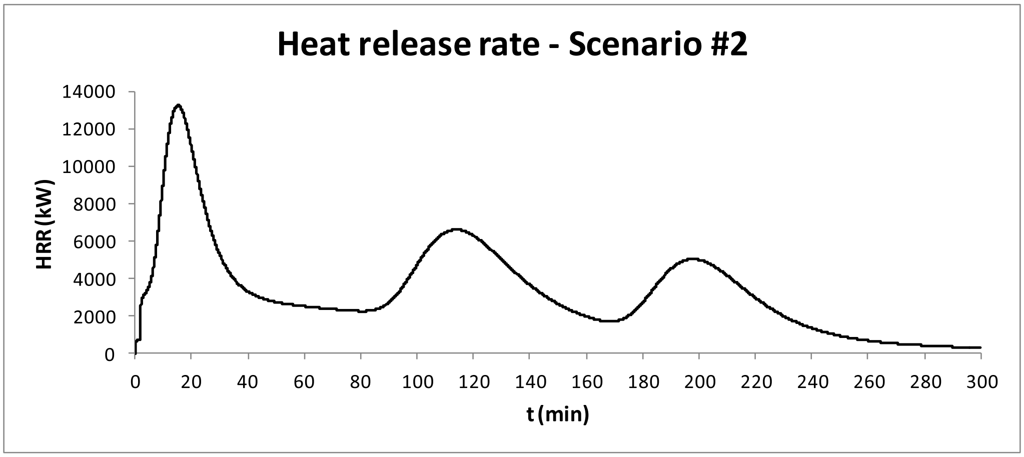

Fig. 2. The heat release rate of scenario #2.

The characteristics of scenario #6 were initially similar to those of scenario #2. The pool fire eventually ignited the nearest tyre and at a later stage the radiative heat transfer from the pool fire and the burning tyre ignited the second rear tyre. The second pool fire which occurred between the front and rear tyres eventually caused the ignition of the front tyres.

The ventilation flow working against the flame spread direction results in a slowly increasing heat release rate of the tyres on the left hand side and the front right tyre. This slowly increasing heat release rate can be detected in the later occurring peak values after ~2 h and ~3 h and 20 min (see Fig. 6).

The characteristics of scenario #7 were initially similar to scenario #1, as it involved a pool fire, both front tyres of the upper vehicle and attained a peak value of ~18 MW (see Fig. 7). The burning diesel along the decline ignited the rear tyres as well as the tyres, cables and hoses of the second vehicle. The second peak value at ~15 MW is largely contributed by the hose fire on the second vehicle.

Due to the ventilation flow working against the flame spread, the heat release rate of the rear tyres of the first vehicle and all tyres of the second vehicle progressed slowly. The third peak at ~30 MW is

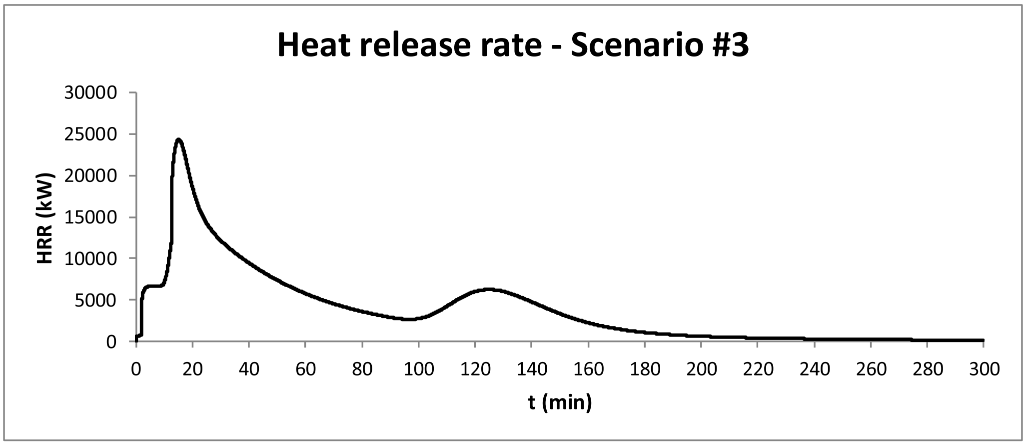

Fig. 3. The heat release rate of scenario #3.

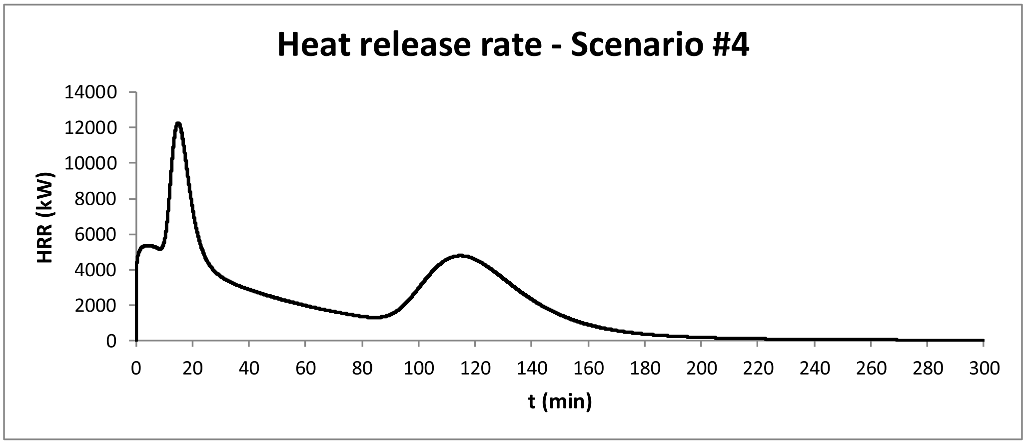

Fig. 4. The heat release rate of scenario #4.

attributed to the aforementioned tyres.

5. Discussion

The design fire scenarios with the most rapid initial fire growth rate were scenarios #3 and #5, where the heat release rate reached 25 MW after approximately 20 min. Both cases involved one or two dump trucks, where the ventilation flow faced the front of the vehicle (i.e. in the direction of the fuel continuity) and the rupturing of hydraulic hoses causing a pool fire in between the front and rear tyres. These factors all contributed towards a fire scenario involving numerous, large fuel items at the early stage of the fire.

After 5 h all the resulting heat release rate curves indicate a heat release rate of less than 1 MW. Two of the scenarios (#2 and #6) display a considerably higher heat release rate after 4 h compared with the other scenarios. The common denominator for these two scenarios is a loader in a drift where the ventilation direction is facing the front of the vehicle, therefore pushing the flames in the opposite direction to the fuel continuity.

The inclination of the decline was found to have little effect on the resulting heat release rate curve. Even though the flames would be tilted towards adjacent fuel items – increasing the incident heat flux at the fuel surface – the decrease in distance between the flames and the fuel surface will not be enough to cause ignition. When comparing the heat release rate curves of scenarios #1 and #5 (similar scenarios but where the inclination varied), the key difference between the two curves at the early phase is the ignition of the rear tyres in scenario #5. This was caused by the burned off hydraulic hoses and was not attributed to a variation in the inclination, as the distance between the front and rear tyres is too large. The inclination would have to be considerably greater than the 6% and 10% applied in the analysis to have any significant influence on the ignition process.

The design fire scenarios with increasing ventilation velocity in the opposite direction to the fuel continuity resulted in slower fire spread or even a complete stop. In these cases the flame spread would decrease, flames tilted away from nearby fuel components, convection and smoke layer radiation would be negligible and the fire would perhaps merely include the start object. A slower fire spread can be seen when comparing the heat release rates of scenarios #5 and #7; two similar scenarios but the direction of the ventilation flow with respect to the fuel continuity varied. Scenario #5 consisted of a fire with initially higher fire growth rate and higher heat release rates (24 MW compared to 17 MW).

Any design fire scenario where the fire spread was in the opposite direction to the fuel continuity displayed a heat release rate with a slower initial fire growth.

The design of the mining vehicles was also found to significantly influence the ignition of adjacent fuel items and the heat release rate. Either the rear tyres, the front tyres or all tyres were shielded and protected by the vehicle construction, limiting the flame area exposed to adjacent fuel items. This limitation in the exposed flame area together with the greater distances will delay or even prevent the ignition of adjacent fuel items.

Scenarios #5 and #7 contained the longest periods with high heat release rates (> 10 MW), which could provide a significant test to fire protection systems as well as the miners and fire and rescue personnel. In particular, the heat release rate curve of scenario #7 presents a scenario which could present a considerable risk. The high heat release

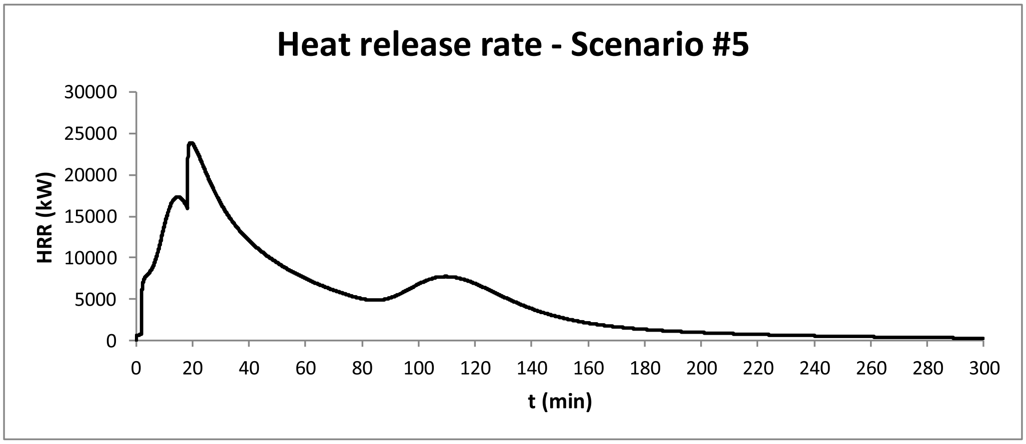

Fig. 5. The heat release rate of scenario #5.

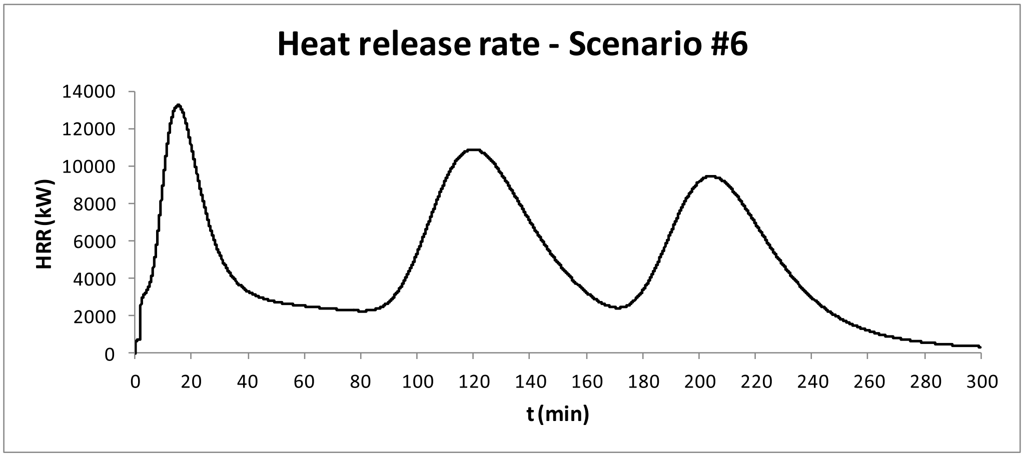

Fig. 6. The heat release rate of scenario #6.

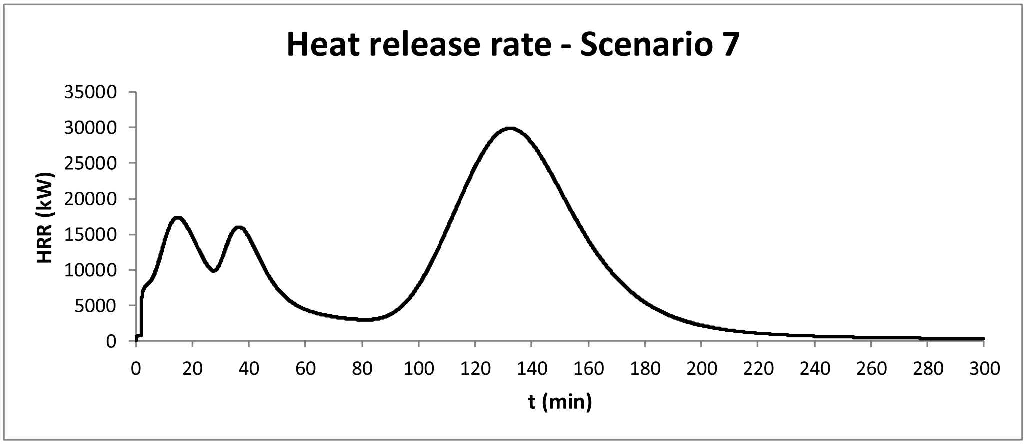

Fig. 7. The heat release rate of scenario #7.

rate, which was distinctly higher than the initial peak periods, occurring after more than 2 h could cause problems during the smoke extraction operation as well as posing a challenge to the fire and rescue personnel during their work.

Scenario #7 presents another fire spread opportunity, through the leaking of flammable liquid. The hydraulic hoses and electrical cables in a mining vehicle will provide the fire spread tool within the vehicle in question and leaking flammable liquid – spreading downwards, along a decline with considerable inclination – will lead to a fire spread opportunity between vehicles.

A sensitivity analysis was conducted on scenario #4 where the amount of hydraulic hoses and cables were varied by ± 20%. The analysis was conducted to investigate the variations in the resulting heat release rate, given that the amount of hydraulic hoses and electrical cables were assumed. As can be seen in Fig. 8 variation in the amount of hoses and cables had very little effect on the resulting heat release rate and they primarily affected the peak period. Given the fire load on loaders and dump trucks, the focus for these types of vehicles should generally be on tyres.

The influence of any fire protection system was not included in any of the design fire scenarios. The successful activation and implementation of a fire protection system will influence the fire scenario, but when analysing the influence, the likelihood of a successful activation and implementation must be considered. A manually activated fire protection system will decrease the likelihood that the system is actually activated during a fire when compared to an automatic system. In addition, wear and tear in a harsh environment could decrease the likelihood of successful implementation. These considerations are especially applicable for mining vehicles equipped with extinguishing systems. Furthermore, an extinguishing system in a mine may not be designed to fully extinguish the fire but only to stop the fire spread and limit the fire to the start object. This will also affect the appearance of the heat release rate curve.

When developing the design fire scenarios, the ventilation velocity was set to a fixed value and direction throughout the entire scenario. Any changes in the ventilation velocity or ventilation direction during the fire would have altered the appearance of the resulting heat release rate curve. A change in the ventilation direction would have altered the speed and direction of fire spread, depending on the continuity of combustible items. This could be a field for further study when developing and refining design fire scenarios for underground mines.

The presented design fire scenarios contained several sequences of rapid fire spread and high heat release rates. The design fire scenarios also included sequences with lower heat release rates and smouldering fire, which can be seen in the final decaying phase of the scenarios. The relatively low temperatures generated from smouldering fires mean that there is little buoyancy in the emitted fire gases, decreasing the likelihood of smoke stratification under the mining roof compared with fires with high heat release rates. This could represent a hazard to fire and rescue personnel and may hamper their work during the decaying phase of the fire and must be included when evaluating the resulting scenarios.

When comparing the resulting heat release rate of loader scenario #2 with the resulting heat release rate curve of a loader in the report by Hansen (2010), the differences were found to be considerable. Even though scenario #2 only involved two tyres, the peak heat release rate

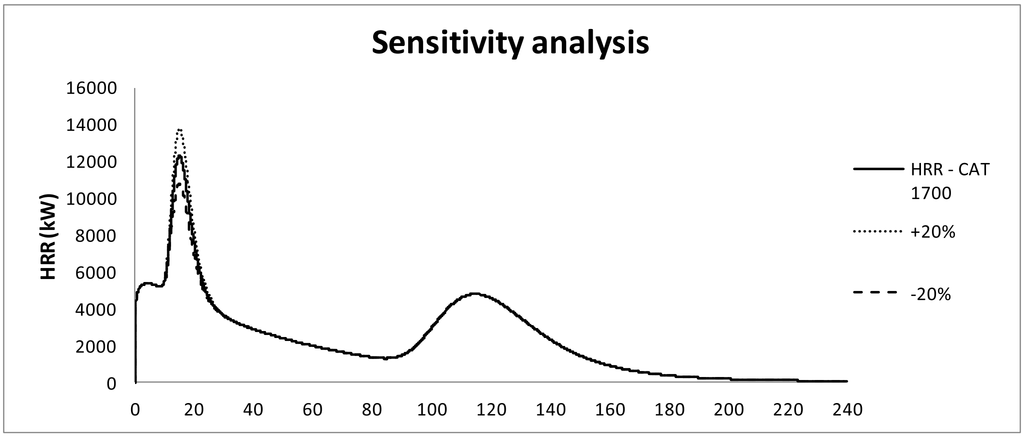

Fig. 8. Sensitivity analysis of scenario #4.

of scenario #2 was almost twice as high compared with the loader scenario in Hansen (2010). In the report by Hansen (2010) the heat release rate of the hydraulic hose fire as well as the fires in the individual tyres were underestimated compared with the findings from the full-scale fire experiments involving a loader (Hansen & Ingason, 2013a). Additionally, the overall appearances of the two design fire scenario curves differ considerably which is due to the fact that in Hansen (2010) all four tyres are assumed to display the same type of fire behaviour. During the full scale fire experiments (Hansen & Ingason, 2013a) it was found that the flame spread and fire behaviour of the individual tyres varied and were highly dependent on, for example, the flow direction. The differences in the tyre fire behaviour were accounted for in this paper.

When comparing the heat release rate of loader scenario #2 with the heat release rate curve from the loader experiment (Hansen & Ingason, 2013a), the similarities are considerable: the level and occurrence of the peak heat release rate as well as the overall appearance of the heat release rates (with subsequent periods with higher heat release rates). The similarities are not surprising as the development of the design fire scenarios in this paper was based on the findings from the full scale fire experiments.

The resulting heat release rate curves can be used for calculating several key parameters. The heat release rate will, for example, give the fire gas temperature, heat flux, smoke production and visibility. The smoke production and visibility parameters will be valuable if applying the life safety criterion.

Furthermore, the appearance of the heat release rate curves – maximum heat release rate, fire growth rate, etc. – will be valuable when evaluating the smoke evacuation system and the egress safety in a mine.

The resulting design fire curves can also be used as input data for fire modelling software, such as FDS or Ventsim.

The continuation of the fire safety evaluation work – using the data from the design fire scenarios as a starting point – would be to determine the impact of the fire. One of the key parameters would be the site of the fire. The positioning of the fire will have an impact on any nearby sensitive surroundings. In a mine sensitive surroundings could, for example, be a section with a high density of personnel, a drift with a refuge chamber or a drift with electrical cables powering fans vital during smoke evacuation. A further developed design fire scenario could, for example, involve an underground mine with a limited number of evacuation routes, where a fire with a high fire growth rate and at a sensitive position incapacitates the main evacuation route at an early stage.

A further developed design fire scenario would also include the smoke spread from the design fire. Besides being a key parameter when determining the smoke production rate, the heat release rate of the design fire scenario may also be an indicator as to when the fire may affect the ventilation flow. High heat release rate fires could lead to two different types of phenomenon: the throttle effect and the buoyancy effect (Banerjee, 2000).

Even though the presented design fire scenarios are based on Australian statistical data and environmental conditions underground, the output can also be used elsewhere providing the conditions are similar.

6. Conclusions

A number of design fire scenarios for underground hard rock mines are presented and the development of the design fire scenarios are described and discussed. The design fire scenarios were developed through a risk assessment and risk analysis, and a deterministic approach was implemented. The results from a number of earlier full-scale fire experiments in underground mines and analysis were included in the process.

It was found that the design fire scenarios with the most rapid initial fire growth rate - presenting a considerable risk to the miners during the initial evacuation phase - were scenarios where the ventilation flow was in the same direction as the fuel continuity and where the rupturing of hydraulic hoses caused a pool fire in between the front and rear tyres and thus also a bridge for further fire spread.

It was also found that the inclination of the decline has little effect on the resulting heat release rate curve, despite the tilting of flames. The inclination would have to be much larger than normally found in a decline to have any significant influence on the ignition process.

Design fire scenarios with a slower fire spread and a longer lasting fire at higher heat release rates were cases where an increasing ventilation flow in the opposite direction to the fuel continuity caused slower fire behaviour.

The design of the mining vehicles was found to limit the visible flame area which together with the long distances between the fuel items would delay or even prevent the ignition of adjacent fuel items.

A number of scenarios contained longer and intermittent periods with high heat release rates and where the sudden increase of heat release rate took place after a longer time span from ignition. These scenarios could present problems during smoke extraction as well as during the fire and rescue operation.

The developed design fire scenarios for underground mines will provide a tool for evaluating the fire protection measures in a mine. Therefore, improving fire safety in underground mines and providing a safer working environment for mining personnel.

Conflicts of interest

None declared.

Ethical statement

Authors state that the research was conducted according to ethical standards.

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Declarations of interest

None.

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