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Reviewing conditions on a mining vehicle for possible ignition and fire behaviour – flammable and combustible liquids

Rickard Hansen

Contents

Tables

Abstract

With vehicles frequently found in mines and being a dominant fire source, vehicle fires will present a considerable risk in the mining industry. The potential ignition sources, the amount and configuration of combustible components will vary from vehicle to vehicle depending on the vehicle category and the size of the vehicle. This paper presents a study on ignition conditions and fire behaviour on various types of mining vehicles involving flammable or combustible liquids, where data from earlier fire experiments, incident reports and fuel inventories on different vehicle categories are applied. It addresses questions such as: what potential ignition sources can be found on different vehicle categories? What flammable or combustible liquid may pose a severe risk with respect to ignition and the continued fire development? It was found that the most common ignition sources were the exhaust/turbocharger, engine, or any other hot surface in the engine bay, which ignite oil/hydraulic oil, diesel, ethylene glycol, transmission oil or oily rags through hot surface ignition. The common denominator is the ignition taking place within an enclosed structure (engine compartment). The temperature conditions in the engine bay will vary depending on the load condition of the engine, the enclosed nature of the engine bay and the speed of the vehicle. Maximum engine compartment temperatures may occur when shutting down the vehicle – following upon a heavy load sequence – with temperatures of the turbocharger and exhaust system area rising above 700°C. The hot surface ignition of dripping or spraying flammable or combustible liquid will depend on several different parameters, such as the flow conditions, the size and orientation of the hot surface, the droplet size and foremost the degree of enclosure. With an increasing degree of enclosure and hot surfaces, the hot surface ignition temperature will decrease and approach the auto ignition temperature of the fuel. If accounting for the enclosed nature of the engine bay and relating to the auto ignition temperatures, the risk of ignition increases significantly as the ignition temperatures may not necessarily be connected to a heavy load but coming close to engine component temperatures during normal operation. Air and oil mixtures (with droplets and liquid particles of oil) may occur in compressors and air receivers, where a hot surface may suffice to ignite the mixture and cause a flashover. The high pressure of the compressor will lead to a considerably lower autoignition temperature. The high pressure found in compressors will increase the upper flammability limit of the air/oil mixture and thus increase the risk of ignition further. Any porous solid soaked by a flammable or combustible liquid may undergo an oxidative self-heating which will result in ignition taking place at considerably lower temperature at the hot surface compared with the dripping or the spray/aerosol case. A soaked rag or lagging would ignite at considerably lower temperatures than the autoignition temperature. The runaway temperatures would not be considerably higher than the temperatures found normally in the engine compartment and the risk of ignition is evident.

Keywords: Ignition, flammable liquid, combustible liquid, spray, aerosol, mining vehicle, fire behaviour

1. Introduction

Mining vehicles can be found in most parts of a mine, being used in several stages of the mining process. Being frequently found in the mining industry and presenting a considerable fuel load, vehicle fires in the mining industry will present a great fire risk. The different vehicle categories will vary in use, construction, amount of fuel load and configuration of fuel load, and as a result, the risk of ignition and resulting fire behaviour will vary as well. With a considerable risk comes a need for identifying conditions and warning signs of potential ignition and an ensuing fire behaviour for the different vehicle categories. Understanding potential ignition conditions and being able to identify conditions will increase the likelihood of preventing fires or mitigating their effects.

Several studies have been performed on the frequency, fire causes, start positions of fire etc. on mining vehicles. De Rosa [1] conducted an analysis of mobile equipment fires in US mines, examining the mobile equipment fires for all US surface and underground coal and metal/non-metal mining categories. In the analysis ignition sources, methods of fire detection and suppression, and other variables were examined.

Hansen [2] performed an investigation on the fire causes and fire behaviour of vehicle fires in Swedish underground mines, applying incident reports during the years 1988–2010. Hansen [3] studied fire statistical data from the mining industry in Australia, focusing on parameters such as the fire cause, type of fuel involved and position of the fire. It was found that vehicle/mobile equipment fires dominated among the fire statistics and the incident reports, where heavy vehicles were clearly overrepresented. The truck category was found to be the most common vehicle category in the statistics and reports, followed by heavy vehicle categories such as drilling rigs, dozers, and loaders. A clear majority of the vehicle fires was found to occur in the engine area (with the exhaust/turbocharger section being overrepresented), and where the most common fire cause was oil or hydraulic oil onto a hot surface, followed by an electrical cause and diesel onto a hot surface.

Hansen presented several studies [4-7] on the fire behaviour of mining vehicles and in an underground hard rock mine, ranging from fire behaviour in general, heat release rate of mining vehicles to extreme fire behaviour in a mine drift.

This paper focuses on the potential ignition sources and fire hazards – focusing on flammable or combustible liquids - found on mining vehicles. Conditions are reviewed and discussed, serving as an aid in the fire prevention work.

Providing warning signals and increasing the knowledge of potential ignition or severe fire behaviour would improve the fire safety for mining personnel.

This study is limited to cases involving flammable or combustible liquids, as these fuel types are most frequently found in the fire statistics for mining vehicles. This study does not include any preventive measures, mitigating measures or design considerations, nor does it include the aspect of battery powered vehicles. For publications on preventive or mitigating measures on mining vehicles, see publications on passive fire protection [8], pre-ignition or early fire detection [9], or performance requirement [10].

2. Methodology

In the following, earlier research is reviewed and incident reports, data from full-scale fire experiments, fuel inventories and fire behaviour studies are studied and applied when reviewing ignition sources and potential fire behaviour of various types of mining vehicles.

Hansen [3] performed a study on the cause and behaviour of vehicle fires in Australian mines, where incident reports and statistical data on fires occurring in New South Wales, Queensland and Western Australia were applied. As the data material from Western Australia was extensive and the vehicle category involved in the incidents could be identified in the reports, the ignition source analysis is primarily based on the Western Australian data. The data source for the fire statistics from Western Australia was mining incident summaries presented by the Department of Mines, Industry Regulation and Safety (Government of Western Australia). The time period selected was July 2014 until July 2017 and the material consisted of a total of 2140 incidents during the three-year long period. When searching the data from the database, incidents listed under category “Outbreak of fire above or below ground” for both mining and exploration were extracted. The summaries specify the date of the incident and then continue with briefly describing the incident. The summaries will generally not specify whether the incident took place in a coal mine or a metal mine and only occasionally if it took place above ground or below ground. Thus, when analysing the data material, no distinction was made with respect to the type of mine and only occasionally whether it took place above or below ground. Instead, the starting point for the fire statistics from Western Australia was generally the type of object where the fire started. After extracting the data from the database, the fire incidents involving mining vehicles were divided into the different vehicle categories (see table 1). The fire incidents for each type of vehicle category were then analysed with respect to the fire cause, type of fuel (of the initial fire), part of vehicle, location of the fire in the mine, fire behaviour (if the fire spread beyond the start object), who detected the fire and the fire suppression equipment that was used. In incident summaries where more than one fuel source was listed, the fuel source that was decisive for the initiation of the fire was applied and, in some cases, secondary fuel sources as well.

Table 1. Ten most frequent vehicle categories extracted from incident summaries (Western Australia) [3].

Vehicle category	Number of fires
Truck (dump truck, haul truck etc.)	319
Drilling rig and jumbo	201
Loader and shovel	128
Dozer	122
Light service and passenger vehicle	75
Excavator and digger	74
Road train	68
Water cart	39
Grader and scraper	33
Integrated tool carrier	23

Two full-scale fire experiments were conducted in an underground mine in 2011, where a loader and a drilling rig were used as fire objects. Measured or calculated parameters included for example the mass flow rate, gas concentrations, temperatures, and incident heat fluxes. The main objective of the experiments was to collect data on the fire behaviour of the burning vehicles in the mine drift with longitudinal ventilation flow. The vehicles were ignited using pool fires – circular trays filled with diesel – underneath the fuel tank and adjacent to one tyre. After ignition, the vehicles were allowed to burn freely and engulfing large parts of the vehicles. For a full description of the experiments, see Hansen and Ingason [11]. For an analysis on the fire spread along the vehicles, the heat release rates and the fire behaviour, a study by Hansen [4] is recommended.

Fuel inventories were conducted on the loader and drilling rig involved in the full-scale fire experiments [11] but also during a study on Australian design fire scenarios [12], where inventories were conducted on the vehicle types most frequently found in the Australian fire statistics and incident reports. The fuel inventories resulted in the individual weights, volumes, and energy contents – applying the effective heat of combustion – of the various types of fuel items. In the case of the full-scale fire experiments, the fuel inventory data was applied when reconstructing the fire behaviour and validating the resulting heat release rates of the vehicles.

3. Potential ignition sources found on mining vehicles – results and discussion

When going through and analysing the data material which the report by Hansen [3] is based on, the position of the ignition, the exhaust and turbocharger cases were merged into one group as it was difficult to clearly isolate these two locations (signs of a fire could be seen at the exhaust but the actual fire took place in the turbocharger). When analysing the type of fuel, hydraulic oil and oil were merged into one group as it was difficult in many cases to discern whether it was oil or hydraulic oil that was listed in the summaries. Table 2 contains the number of the various combinations of flammable/combustible liquid, position of ignition source and heat source for the vehicle categories found in table 1. If the incident summary explicitly described an emitted fuel spray or fuel mist, the ignition was classified as a spray or aerosol case. Thus, the actual number of spray or aerosol cases was most likely higher than the numbers found in table 2.

Table 2. The fuel types, positions of ignition, the heat source and number of fires involving a flammable/combustible liquid.

Fuel	Position of ignition	Heat source	Number of fires
Oil/hydraulic oil	Exhaust/turbo	Hot surface	143
	Exhaust/turbo lagging	Hot surface	30
	Exhaust/turbo lagging	Hot exhaust gas	1
	Engine block	Hot surface	19
	Engine bay	Arcing	8
	Brakes	Hot surface	5
	Bearing, failed	Hot surface	3
	Muffler	Hot surface	2
	Starter motor	Hot surface	1
	Universal joint, failed	Hot surface	1
	Hammer barrel	Hot surface	1
Oil/hydraulic oil spray or aerosol	Exhaust/turbo	Hot surface	69
	Exhaust/turbo lagging	Hot surface	1
	Engine block	Hot surface	24
	Park brake assembly	Hot surface	1
Diesel	Exhaust/turbo	Hot surface	32
	Exhaust/turbo lagging	Hot surface	5
	Engine block	Hot surface	2
	Alternator or generator	Hot surface	2
	Fan belt	Hot surface	1
	Starter motor	Hot surface	1
Diesel spray or aerosol	Exhaust/turbo	Hot surface	10
	Engine block	Hot surface	14
	Alternator	Hot surface	1
Transmission oil	Exhaust/turbo	Hot surface	1
Transmission oil spray or aerosol	Exhaust/turbo	Hot surface	2
	Engine block	Hot surface	1
	Muffler	Hot surface	1
Ethylene glycol	Exhaust/turbo	Hot surface	9
Ethylene glycol spray or aerosol	Exhaust/turbo	Hot surface	1

Flashover	Compressor	Hot surface	10
Oily rag	Exhaust/turbo	Hot surface	3
Contact cleaner	Engine bay	Arcing	1

The most common ignition sources – involving a flammable/combustible liquid - were the exhaust/turbocharger, engine, or any other hot surface in the engine bay, which ignite oil/hydraulic oil, diesel, coolant (ethylene glycol), transmission oil or oily rags through hot surface ignition. The common denominator in these cases is the ignition taking place within an enclosed structure (engine compartment). The number of cases taking place in a non-enclosure environment – brakes, bearing, universal joint, hammer barrel and park brake assembly – was significantly lower than the enclosure cases. Given the overwhelming number of ignitions taking place in enclosed type of structures, the main focus should be on ignition sources found in the engine compartment.

The release of oil, diesel or coolant is generally caused by a failed hose, line or fitting, or an internal failure of the turbocharger in the engine bay. What temperatures and conditions can be expected in the engine bay? The surface temperatures of engine components will vary depending on the load condition of the engine, the enclosed nature of the engine bay and the speed of the vehicle. Travelling up a decline will present a heavy load, with increasing surface temperatures in the engine bay. Under a heavy load the turbocharger and the exhaust system may attain temperatures exceeding 500°C and 600°C [13-15], with even higher temperatures in the case of malfunctioning or failed components. The enclosed nature of the engine bay will decrease the heat losses from the engine components, increasing the temperature of the components compared to a more open configuration. The decreased heat losses will be due to lesser convective heat losses and the increased re-radiation within the boundary of the enclosure. With an increased speed of the vehicle the load on the engine and the component temperature will increase as well, but an increased speed will also cause an increased convective cooling within the engine bay, thus mitigating the temperature increase. The influence of the convective cooling will vary depending on the load vs speed condition, a truck travelling up a decline with low speed and a heavy load will experience less convective cooling compared to a truck travelling with greater speed on an even road. A shut down of the vehicle – following upon a heavy load sequence – will increase the component temperatures and air temperature in the engine bay even further due to the airflow of the fans and ambient air ceasing. During this transient period the engine components will be subjected to higher thermal loads, and the temperatures of the turbocharger and exhaust system area can rise to above 600-700°C [16]. As the muffler is part of the exhaust system, the listed temperatures of the exhaust will be valid for the muffler as well. The temperature of the engine block will typically reach up to 100°C [17], where an overheated engine will attain even higher temperatures. The same temperatures will apply for a starter motor and the other components found in the engine compartment. Given the higher surface temperatures of the exhaust and turbocharger, the frequent ignitions occurring on these components is not surprising.

Merati et al. [17] conducted experiments on a simplified full-scale model of an engine bay, measuring surface temperatures and air temperatures under the bonnet. The highest air temperature during the experiments was measured at 300°C directly above the exhaust system and the period with peak temperatures following a shutdown was found to last approximately five minutes. Besides the hot engine components causing fires, the incident summaries also list fires occurring due to a fracture in the exhaust manifold, allowing hot exhaust gases to ignite for example residual hydrocarbon material on the turbo/exhaust lagging (see table 2). Nolan [18] lists exhaust gas temperatures of 500-700°C at a 100% load from a diesel engine.

The cases of arc ignition of flammable/combustible liquids will involve several mechanisms. The arcing will heat up the liquid, resulting in fuel vapour above the surface. The arc will then act as a pilot ignition source, igniting the flammable atmosphere. Given the high temperatures of the arcing, any droplets in a spray or aerosol will rapidly vaporise and combust. Provided that the fuel vapour or spray in the vicinity of the ignition source is within the flammability limits, ignition will take place.

The compressor and air receiver on support trucks, service trucks, drilling rigs and jumbos was frequently found in the incident summaries, where oil onto a hot surface (due to a failed hose or line), overheating (due to a failed temperature sensor, a faulty discharge air temperature switch, or loss of oil cooling), or short circuit or arcing dominated among the fire causes. The compression of air in combination with lubricating oil may pose a great risk as ignition may occur at lower temperatures. During the compression, high gas velocities occur across the oil film surface, resulting in an increased evaporation from the oil film. The increased oil film evaporation in conjunction with the added heating of the oil film from the hot compressed air results in flammable gas mixtures and an increased ignition risk at lower temperatures [19]. Vibrations may also increase the risk, as an oil mist may result from the vibrations. The flashover cases listed in table 2 predominantly occur in the drilling rig category, which could be expected given the type of use of the drilling rig.

Non-enclosure ignitions sources include foremost brakes and bearings as seen in table 2. Overheating brakes are commonly listed as the ignition source in the incident summaries and may result in temperatures of 500-700°C [20]. The overheating of bearings may result in temperatures approaching and exceeding 200°C [21]. The overheating of non-enclosure components will also result in heat conducted to adjacent components and an increased ignition risk.

4. Flammable and combustible liquids posing a risk – ignition and fire behaviour – results and discussion

The total amount of combustible components and the frequency of various types of combustible material will vary between different sizes and types of mining vehicles. Commonly found combustible components on mining vehicles are diesel, hydraulic oil, motor oil, coolant (for example ethylene glycol), cables, hoses, interior details, and tyres. Prior to full scale fire experiments involving a loader and a drilling rig, Hansen and Ingason [11] conducted fuel inventories on the vehicles. The resulting inventories can be seen in table 3, where the energy content of the individual component types is listed. In table 3 also contains the resulting fuel inventory – focusing on the major fuel components: tyres, diesel, and hydraulic oil - on four mining vehicles most frequently found in the Australian fire statistics and incident reports [12].

Table 3. Inventory of combustible components found on various mining vehicles.

Combustible component	Toro 501 DL Loader [11] [MJ]	Rocket Boomer 322 Drilling rig [11] [MJ]	CAT AD55 Dump Truck [12] [MJ]	CAT 2900 Loader [12] [MJ]	Atlas Copco MT6020 Dump Truck [12] [MJ]	CAT 1700 Loader [12] [MJ]
Tyres	42 120	4 185	111 780	61 560	111 780	89 640
Hydraulic oil	18 563	16 283	8 400	4 560	7 750	4 070
Hydraulic hoses	4 905	11 252	-	-	-	-
Water hose	-	1 154	-	-	-	-
Diesel	10 138	3 621	34 760	51 600	30 560	20 640
Driver seat	228	228	-	-	-	-
Electrical cables	21	8 735	-	-	-	-
Rubber covers	270	300	-	-	-	-

As seen in table 3, the differences between the types and sizes of vehicles are significant. The fire load on a drilling rig is dominated by the hydraulic hoses and hydraulic oil, and the fire load of the tyres will be less significant. In the loader case and the dump truck case, the fire load of the tyres and the diesel will clearly dominate. When comparing the fire load of the Toro 501 loader and the CAT 2900 and CAT 1700 loaders, the larger CAT loaders with larger tyres etc. will imply a significantly higher fire load. As the fuel inventories focused on the major fuel components, only diesel and hydraulic oil are listed in table 3 as opposed to table 2 where also motor oil and transmission oil are listed among the incident summaries. The volumes of motor oil and transmission oil are generally significantly lower than the diesel or hydraulic oil volumes for the vehicle categories found in table 1. When studying the data from the incident summaries for the various vehicle categories, it was found that fires involving hydraulic oil or oil dominated for the top three vehicle categories (trucks, drilling rigs and jumbos, and loaders and shovels), but the volume ratios for the different vehicle categories found in table 3 did not correlate with the distribution of the fuels involved in the fires found in table 2. Despite that the volume diesel found on trucks dominate over the volume of hydraulic oil, the hydraulic oil and oil fires were more frequent than the diesel fires. The hydraulic oil and oil fires were approximately seven times more frequent than diesel fires in the truck category, whereas the oil fires were four times more frequent in the drilling rig and jumbo cases and twice as frequent in the loader and shovel cases.

The distribution of the various types of flammable and combustible liquids will vary depending on the vehicle category. The fuel system with diesel is found between the fuel tank and the engine and positioned in the front part of a truck or the rear part of a drilling rig and a loader. The hydraulic system (containing hydraulic oil) will vary depending on the vehicle category. The system on a drilling rig will be extended between the hydraulic oil tank and pump at the rear, and the boom in the front of the vehicle. The hydraulic system on a loader or a dozer will also extend from the rear part or the mid-section of the vehicle to the scoop or the blade in the front. On a truck, the system will often extend from the hydraulic oil tank and pump at the mid-section or the front to the dump box in the rear. Depending on the brake system on the vehicle, hydraulic oil can also be found at the wheel and brake regions. The engine lubrication system (containing motor oil) and the engine cooling system (containing ethylene glycol) are both found in the engine compartments for all vehicle categories. Any compressor – typical of the drilling rigs or jumbos – containing oil will be mounted separately in the rear of the drilling rig or jumbo and will generally not be found in the engine compartment. The transmission system (containing transmission oil) will run from the engine along the lower part of the vehicle to the wheels. Studying table 2, the ignition of hydraulic oil, oil, diesel, ethylene glycol and transmission oil predominantly takes place in the engine compartment and to some degree at the wheel/brake region. Even though the different systems commonly extend beyond the engine compartment, it is at the engine compartment and the wheel/brake region that the ignitions take place. With surface temperatures commonly exceeding 500°C in the engine compartment and at the brakes, the focus should clearly be on the hot surface ignition in these areas.

4.1 Flammable or combustible liquid onto a hot surface – dripping

The ignition of flammable and combustible liquid fuels onto a hot surface is usually termed hot surface ignition. The hot surface ignition is solely due to the temperature of the liquid and with no external ignition source present to force the ignition. When describing the hot surface ignition of a flammable or combustible liquid it is important to remember that the hot surface ignition will be represented by a temperature range, where the percentage of ignition taking place lies between 0% and 100%. Both ignition and non-ignition will take place within the temperature range and the hot surface ignition thus displays a probabilistic behaviour.

The hot surface ignition will depend on several different parameters. Varying forced flow and natural convection will influence the ignition temperature as an increasing forced flow or natural convection will increase the heat losses which in turn will increase the temperature required for ignition. At very high flow velocities the fuel drops will be blown away from the hot surface and ignition does not take place at all. The size and orientation of the hot surface will also influence the hot surface ignition temperature as a greater convective cooling will be attributed to a vertical surface, leading to higher hot surface ignition temperatures compared to a horizontal hot surface. A larger hot surface area will lead to a lower hot surface ignition temperature. Whether the environment is of an enclosed nature or not will also influence the hot surface ignition. With an increasing degree of enclosing hot surfaces, the hot surface ignition temperature required will decrease as the temperature gradient away from the hot surface will decrease less and the radiant heat flux impinging on the fuel will increase. Even with unheated parts the enclosed surrounding will contribute to a lower ignition temperature as it will increase the time that the gaseous fuel is present at the heated area [22]. An engine bay will be distinguished by an enclosed nature with both high temperature surfaces and surfaces at ambient temperature, and where the surfaces will have non-uniform temperatures. The flash point of the fuel will also influence the hot surface ignition temperature, as a fuel with a lower flash point that encounters a hot surface will vaporize to a larger degree and cause a layer closest to the hot surface with a high concentration of fuel vapour, above the upper flammability limit of the fuel vapour. As the concentration at the surface will be above the upper flammability limit, ignition is only possible at a position further away with lower concentration. With increasing distance from the hot surface, the fuel vapour temperature will decrease, and thus to achieve ignition a further increase in the surface temperature is required.

Standard diesel dripping onto a stainless steel sample resulted in 0% ignition at temperatures below 445°C, and 100% ignition above 500°C. Standard diesel on stainless steel heat shield resulted in 0% ignition at temperatures below 400°C, and 100% ignition above 550°C [23]. The hot surface ignition temperatures measured by Shaw et al [23] were obtained through experiments on an open test rig. Thus, the degree of enclosure was negligible and the application of the resulting temperatures for engine bays limited. Severy et al [24] conducted hot surface ignition experiments using a test rig which was enclosed on five sides and with an open front, thus resembling an engine bay to a larger degree. The resulting hot surface ignition temperatures were presented as a temperature range, with marginal ignition as the lower end and consistent ignition as the upper end. The presented temperature range would thus have a probabilistic character. The marginal ignition temperature of diesel was measured at 521°C and the consistent ignition temperature at 549°C [24], which partially coincides with the temperature range presented by Shaw et al [23]. The corresponding values for motor oil was approximately 320°C and 420°C respectively, the lower ignition temperature range of motor oil could partially explain the higher frequency of motor oil compared to diesel in the fire statistics for engine bays. The autoignition temperature of diesel was measured at 257°C and for motor oil within the range 260-371°C [24]. When studying the data on the frequency of diesel fires – the dripping cases found in table 2 – for the various vehicle categories it was found that the relative frequency was unusually high for the grader and scraper category. The position of the ignition was foremost the exhaust/turbo area, and a possible explanation could be positioning of the fuel system versus the exhaust/turbo surfaces. The cases in table 2 involving an alternator or a generator as ignition position, solely involve diesel as fuel for the dripping case as well as spray/aerosol case. A possible explanation could be positioning of the fuel system versus the alternator or generator.

Colwell and Reza [25] performed drop ignition experiments using a test rig which was enclosed on four sides (thus not fully enclosed). The 0% ignition of ethylene glycol was measured at temperatures below 565°C and the 100% ignition at temperatures above 705°C [25]. The autoignition temperature of ethylene glycol was measured at 238°C [26]. When studying the underlying data of table 2, it was found that the dripping cases involving ethylene glycol were unusually frequent in the case of integrated tool carriers. A possible explanation could be the positioning of the engine cooling system versus the turbo surfaces, where most of the ignitions take place.

Deleanu et al [27] conducted drop ignition tests using a fire resistant mineral hydraulic oil (MHE-40) on a hot manifold structure in a test rig enclosed on four sides. A single hot surface ignition temperature of 450°C was presented in the paper [27]. The autoignition of a hydraulic oil (ISO VG 10, mineral oil) was measured at 320°C [28]. The cases involving brakes as ignition position in table 2, were found to predominantly involve oil or hydraulic oil as fuel and be presented as dripping cases. The dominance of hydraulic oil as fuel is expected as the brake system may contain hydraulic oil.

It is important to apply tabulated values from experiments or tests conducted at similar conditions as the scenario in question, where the degree of enclosure and hot surfaces will be key factors for an engine bay. With an increasing degree of enclosure and hot surfaces, the hot surface ignition temperature will decrease and approach the auto ignition temperature of the fuel as the auto ignition temperature measurements are conducted with the fuel surrounded by heated surfaces.

All the above listed hot surface ignition temperatures of the flammable or combustible liquids will be well within the earlier listed possible temperature range of a turbocharger and exhaust system. If accounting for the enclosed nature of the engine bay and relating to the auto ignition temperatures, the risk of ignition increases significantly as the ignition temperatures may not necessarily be connected to a heavy load but coming close to engine component temperatures during normal operation. Non-enclosure type of ignition sources such as the exhaust also presents surface temperatures which may exceed the above listed hot surface ignition temperatures for diesel. Studying table 2, the non-enclosure cases were predominantly dripping cases and thus the non-enclosure ignition temperatures listed earlier may have bearing on the dripping cases.

The fuel inventories found in table 3 indicate large amount of diesel for the truck and loader categories and large amount of hydraulic oil for the drilling rig category. Ignition in the engine compartment may involve the fuel system with diesel and/or the hydraulic system with hydraulic oil. Any fire occurring in the engine compartment has the potential to spread beyond the compartment via hoses or cables and to other fuel items. Any dripping scenario may also result in pool fires, with burning pools of diesel or oil along the underside of the vehicle. As pools may be formed further away from the fuel or hydraulic systems – due to an inclined surface – fuel items which should otherwise not have ignited or at least not early due to longer distance from the fuel or hydraulic systems now run the risk of being ignited at an early stage. An early ignition of large fuel items may lead to a severe fire with a high heat release rate, considerable smoke production and extended smoke spread. Drilling rigs – containing large amount of hydraulic oil and hydraulic hoses as seen in table 3 – may also result in fires where the hydraulic hoses and the hydraulic oil inside the hose will act as a line fire along the vehicle and provide a fire spread bridge to fuel items.

Prior to the full-scale fire experiments in an underground mine, an earlier investigation on mining vehicle fires in Sweden showed that in any fire involving a larger mining vehicle, the initial fire would have to be a diesel fire – possibly a pool fire – positioned close to a larger fuel item to achieve a fire which eventually engulf large parts of the vehicle [2]. From the full-scale fire experiments, it was observed that if the tyres – especially the large loader tyres – were ignited, the fire would generally head in an undesired direction with high heat release rates, a long lasting fire, extensive smoke production and smoke spread, and a fire difficult to extinguish [11]. Thus, any adjacent pool fires or bridging types of fires increase the risk of severe fire behaviour and are highly undesired.

Table 4 lists ignition temperatures of common fuel items on mining vehicles. With enclosed compartments and with an operating mining vehicle with elevated temperatures, the surface temperatures of the fuel items will be elevated as well, which will increase the risk of rapid ignition from a nearby fire source.

An earlier study investigated and highlighted a fire scenario where burning diesel spread downwards along a decline, igniting a second vehicle [12]. The distance between the vehicles which normally would have functioned as a fire safety measure, was evaded by the spreading diesel, and resulted in a highly intensive fire involving multiple mining vehicles. The ability of a pool fire to spread beyond the vehicle in question could contribute to a severe and unforeseen fire behaviour and fire spread.

The pool surface area will dictate the heat release rate and the smoke production from the pool fire. A large pool surface area at an early stage will be highly undesirable due to the higher risk of fire spread but also the risk of overwhelming smoke production during evacuation and low visibility due to the potentially high soot content in the diesel and oil smoke. The construction of the mining vehicle and any longitudinal ventilation flow may add further to the severity of any pool fire occurring along the underside of the vehicle. The vehicle construction and ventilation flow will deflect and tilt the flames, which may result in an even earlier ignition of adjacent fuel items and a more severe fire behaviour and smoke behaviour.

Table 4. The ignition temperatures of common fuel items on mining vehicles.

Material	Ignition temperature (°C)
Tyre	297 [29]
Hydraulic hose (Nitrile-Butadiene Rubber)	335 [30]
Electrical cable (flame retardant polyurethane)	308 [26]

4.2 Flammable or combustible liquid onto a hot surface – spray and aerosol

A spray is generated at the discharge point with significantly high discharge velocities and with large droplets. Further away from the discharge point the large droplets of the spray will undergo a breakup process, where the droplets are fragmented into liquid particles (aerosol) which will be small enough to stay suspended in air for some time. The larger droplets of a spray will typically be within 20 μm to 200 μm in diameter.

The ignition of a spray or an aerosol on a hot surface is similar with the drop ignition case – i.e., a sufficiently high amount of spray droplets or aerosol particles on the hot surface needs to be vapourised to achieve flammable vapour concentrations. Furthermore, the temperature of the hot surface – and the flammable vapour - will have to be sufficiently high to achieve ignition before the vapours flows out of the environment. The minimum hot surface ignition temperature will thus depend on parameters such as the size, extent and orientation of the hot surface, and the droplet size.

The minimum hot surface ignition temperatures findings from drop ignition will thus also apply for sprays or aerosols, i.e., for unconfined conditions the required surface temperature will be significantly higher than the auto ignition temperature of the fuel. For enclosures the required minimum hot surface ignition temperature will approach the auto ignition temperature.

Jagger et al [31] conducted experiments with fire resistant hydraulic fluids (with droplet sizes in the range 50 μm to 60 μm), where the spray was contained within a chamber and ignition taking place against a vertical surface perpendicular or at an angle to the flow direction of the spray. The minimum hot surface ignition temperature of a mineral oil based fluid was measured at 400°C (with an auto ignition temperature of 341°C) and a polyol ester based fluid at 490°C (with an auto ignition temperature of 400°C). Yuan [32] conducted hot surface ignition tests with various types of hydraulic fluids (four fire resistant and eight non-fire resistant fluids) and diesel. The hydraulic fluids and the diesel were sprayed – with droplet sizes between 30 μm to 150 μm - onto a horizontally positioned stainless steel surface as well as a vertically positioned steel surface (non-enclosure configurations). The obtained minimum hot surface ignition temperatures (i.e., the oil spray was ignited at least once) ranged from 350°C (ATF and compressor oil) and 390°C (AW 32 and AW 46) to temperatures at or slightly above 400°C (AW 68, Premium 46, THF, and AW68) [33]. The minimum temperature for diesel was measured at 330-370°C [32]. Yuan also found that a too small orifice would generate smaller droplets, which may be unable to overcome the convective flows from the surface and would thus not reach the hot surface and ignite. With increasing pressure and thus also increasing amount of oil onto the hot surface, the cooling effect of the oil would increase and in some cases the ignition did not take place until the spray ceased and thus also the cooling. For a vertically, downwards applied spray onto a hot surface the minimum hot surface ignition temperature increased for the hydraulic fluids and could be found within the range 500-530°C. The direction of the spray will thus influence the hot surface ignition due to changing flow field and air entrainment diluting the flammable mixture.

In table 2 it can also be seen that the engine block is more frequent as ignition position for oil/hydraulic oil spray as well as diesel spray cases compared with the dripping cases. A possible explanation could be the alignment of the lines and hoses of the fuel systems and hydraulic systems, limiting the ignition to spray/aerosol cases with longer range. The same explanation could possibly also apply to the transmission oil as well – dominated by the spray/aerosol cases – with the spray or aerosol reaching ignition surfaces further away.

When studying the underlying data of table 2, it was found that the spray/aerosol cases involving oil or hydraulic oil were unusually high for the grader and scraper vehicle category, with more than twice as many cases compared with the dripping cases. The reason for this is unclear.

Air and oil mixtures (with droplets and liquid particles of oil) may occur in compressors and air receivers, where a hot surface may suffice to ignite the mixture and cause a flashover. Given the enclosed nature of the compressor, the autoignition temperature of the compressed air/oil mixture is highly relevant when investigating the hot surface ignition temperature. The high pressure of the compressor will lead to a considerably lower autoignition temperature. Ignition experiments involving an air/oil mixture with a pressure of up to 30 atm resulted in an autoignition temperature interval of 215-255°C [33]. The required temperatures will thus be significantly low for the ignition in a compressor or air receiver. The high pressure found in compressors will increase the upper flammability limit of the air/oil mixture and thus increase the risk of ignition further. Due to the flashover occurring in a small enclosure, it will cause large over pressures and possible fire spread due to rupturing of equipment. A flashover in a compressor or an air receiver may lead to secondary fires due to jet flames or hot gases emitted from safety relief valves or the rupture of hoses – resulting in for example spray fires – positioned in the path of the pressure wave.

As opposed to the dripping scenario, spray and aerosol scenarios will be highly variable with respect to the droplet or liquid particle size which in turn will affect the ignition probability. Depending on the diameter of the discharge point and the discharge velocity, the droplet or liquid particle diameter of the spray/aerosol will vary. With increasing distance from the discharge point – with occurring droplet breakup – the droplet diameter will change. Furthermore, with time the discharge velocity will vary – with changes in pressure – and thus also the droplet and liquid particle size. Thus, the ignition of a spray or an aerosol will be highly transient, and focus should be on the path of the droplet or liquid particle – from discharge point to the possible ignition source – and the impact of influencing parameters. The impact of ventilation and wind will also have a larger impact compared with the dripping scenario, where the ventilation or wind may steer the droplet or liquid particle in a certain direction, cause droplet breakup or dilute the cloud of droplets or liquid particles. Given the complexity of the spray and aerosol ignition, pre-modelling of possible scenarios could be warranted to identify possible risk spots and to take preventive or mitigating measures.

For the hydraulic fluids and the diesel, the above listed hot surface ignition temperatures are well within the earlier listed temperature ranges of a turbocharger and exhaust system. The risk of ignition will increase even further if accounting for the enclosed nature of the engine bay, where the ignition temperatures approach the engine component temperatures during normal operation. Thus, the engine bay is distinguished by a more or less omnipresent ignitable environment with respect to ignition sources. Table 2 contains no spray or aerosol cases in non-enclosure environment, indicating that the spray and aerosol ignition is predominantly an enclosure phenomenon on mining vehicles.

An ignition in the engine compartment may result in a spray fire with a rapid increase of temperature due to continuous release of flammable/combustible liquid and the enclosure limiting the heat losses. As opposed to the pool fire scenario, a spray fire may be highly transient and more localized. The rapidly increasing temperature together with a long flame length and the lack of partitions within the engine bay will lead to early ignition of adjacent fuel items, higher fire growth rates and higher heat release rates [5]. The ignition may be more or less instantaneous for fuel items in the direction of the resulting flame (the ignition temperatures seen in table 4 will be rapidly surpassed). The heat release rate and the intensity of the spray fire will vary depending on the heat of combustion of the fuel and the mass flow rate of the spray. An increased velocity of the spray will thus result in a higher mass flow rate and heat release rate. The heat of combustion will vary depending on the type of fuel. Same as for the dripping case, a spray fire may ignite hydraulic hoses and electrical cables, resulting in a line fire along the vehicle which will provide a fire spread bridge to adjacent fuel items.

4.3 Flammable or combustible liquid ignited by arcing

In the arcing cases, the arc will act as a pilot ignition source and ignite the flammable atmosphere above the fuel surface. In the case of pilot ignition, the flashpoint and the flammability limits of the involved flammable/combustible liquid will act as benchmarks when analysing the risk of ignition. The flashpoints of the liquids will be significantly lower than the autoignition temperature, increasing the risk of ignition. The flashpoint of motor oil and hydraulic oil may be in the region of 210°C [26] and for a contact cleaner as low as -18°C [34], which are temperatures normally found in at least parts of the engine bay. Furthermore, the lower flammability limit of oil/hydraulic oil as well as a contact cleaner is very low (1 vol% [35] and 1.7 vol% [34]), which means that the required amount of vapourised fuel is low, will be attained at an early stage and increase the risk of ignition. The arcing cases predominantly occur in the engine bay according to table 2, which is not surprising as the enclosed structure will attain the lower flammability limit earlier and retain a higher concentration of the vapourised fuel compared to a non-enclosure case. The lower flammability limits of other flammable/combustible liquids found in the engine bay - such as diesel and transmission oil – are also found in the lowest region of the flammability range. Thus, any arcing occurring in an engine bay with combustible/flammable liquid in the near region will have a high probability of ignition even under normal operating conditions.

In the case of arcing igniting a spray or aerosol of flammable or combustible liquid, the ignition may take place at significantly lower temperatures than the flash point of the liquid [36]. Thus, the flash point temperature will be a poor benchmark in these cases. With very small droplets – diameter smaller than 10 µm – the flammability limits of the aerosol will be similar to the corresponding air/vapour mixture [37]. For sprays with droplets larger than 20 µm in diameter, the lower flammability limit is lower than the corresponding air/vapour mixture [38]. The minimum ignition energy of a spray or aerosol will depend on the droplet diameter, where a diameter of 10-30 µm will require the least energy [26]. Furthermore, the minimum ignition temperature will also depend on the ambient temperature where the minimum ignition energy will decrease with increasing ambient temperature. Given the environment in the engine compartment – with elevated temperatures in an enclosure – and the expanded flammability limits of a spray or aerosol, the risk of arcing ignition in the engine compartment is significant.

4.4 Porous solid soaked by flammable or combustible liquid

Table 2 contains several ignition cases, where a lagging or a rag have been soaked – predominantly through dripping - by a flammable or combustible liquid. The lagging or the rag is then ignited by a hot surface or hot exhaust gases.

As opposed to dripping and spray/aerosol cases involving only a flammable/combustible liquid as fuel, the soaked lagging or rag may also undergo an oxidative self-heating which will result in ignition taking place at considerably lower temperature at the hot surface or in the exhaust gas. Jagger et al [31] conducted experiments on manifolds soaked in different flammable or combustible liquids, to measure the runaway temperature for oxidative self-heating. With an initiated oxidative self-heating and where the heat released exceeds the heat lost, ignition may eventually occur. Jagger et al [31] measured the temperature of initiated runaway self-heating of lagging soaked by ethylene glycol and water mixture at 132.5°C and lagging soaked by mineral oil at 200°C. Thus, a soaked rag or lagging would ignite at considerably lower temperatures than the autoignition temperature. The runaway temperatures would be close to the temperatures normally found in the engine compartment and the risk of ignition is evident.

5. Conclusions

The ignition of flammable or combustible liquids and the ensuing fire behaviour on mining vehicles was reviewed and analysed, applying earlier research, data from full-scale fire experiments, fuel inventories and fire behaviour studies. The focus of the study was to investigate potential ignition sources and fire hazards found on mining vehicles, where flammable or combustible liquids constituted the fuel source. It was found that:

(1) The most common ignition sources were the exhaust/turbocharger, engine, or any other hot surface in the engine bay, which ignite oil/hydraulic oil, diesel, ethylene glycol, transmission oil or oily rags through hot surface ignition. The common denominator is the ignition taking place within an enclosed structure (engine compartment). The number of cases taking place in a non-enclosure environment – brakes, bearing, universal joint, hammer barrel and park brake assembly – was significantly lower than the enclosure cases. Given the overwhelming number of ignitions taking place in enclosed type of structures, the main focus should be on ignition sources found in the engine compartment.

(2) The temperature conditions in the engine bay will vary depending on the load condition of the engine, the enclosed nature of the engine bay and the speed of the vehicle. Travelling up a decline will present a heavy load, with surface temperatures possibly exceeding 600°C. A shut down of the vehicle – following upon a heavy load sequence – will increase the component temperatures and air temperature in the engine bay even further, where the temperatures of the turbocharger and exhaust system area can rise to above 700°C.

(3) In the cases of arc ignition of flammable/combustible liquids, the arc will act as a pilot ignition source and ignite the flammable atmosphere. Given the high temperatures of the arcing, any droplets in a spray or aerosol will rapidly vaporise and combust. Provided that the fuel vapour or spray in the vicinity of the ignition source is within the flammability limits, ignition will take place.

(4) The hot surface ignition of dripping flammable or combustible liquid will depend on several different parameters, such as the flow conditions, the size and orientation of the hot surface and foremost the degree of enclosure. With an increasing degree of enclosing hot surfaces, the hot surface ignition temperature required will decrease as the temperature gradient away from the hot surface will decrease less and the radiant heat flux impinging on the fuel will increase. With an increasing degree of enclosure and hot surfaces, the hot surface ignition temperature will decrease and approach the auto ignition temperature of the fuel. The hot surface ignition temperatures of the flammable or combustible liquids found in the engine compartment will be well within the possible temperature range of a turbocharger and exhaust system. If accounting for the enclosed nature of the engine bay and relating to the auto ignition temperatures, the risk of ignition increases significantly as the ignition temperatures may not necessarily be connected to a heavy load but coming close to engine component temperatures during normal operation.

(5) For the spray and aerosol case the minimum hot surface ignition temperature will depend on parameters such as the size, extent and orientation of the hot surface, and the droplet size.

The minimum hot surface ignition temperatures findings from drop ignition will thus also apply for sprays or aerosols, i.e., for enclosures the required minimum hot surface ignition temperature will approach the auto ignition temperature.

(6) Air and oil mixtures (with droplets and liquid particles of oil) may occur in compressors and air receivers, where a hot surface may suffice to ignite the mixture and cause a flashover. Given the enclosed nature of the compressor, the autoignition temperature of the compressed air/oil mixture is highly relevant when investigating the hot surface ignition temperature. The high pressure of the compressor will lead to a considerably lower autoignition temperature. The high pressure found in compressors will increase the upper flammability limit of the air/oil mixture and thus increase the risk of ignition further.

(7) Any porous solid soaked by a flammable or combustible liquid may undergo an oxidative self-heating which will result in ignition taking place at considerably lower temperature at the hot surface compared with the dripping or the spray/aerosol case. A soaked rag or lagging would ignite at considerably lower temperatures than the autoignition temperature. The runaway temperatures would not be considerably higher than the temperatures found normally in the engine compartment and the risk of ignition is evident.

The study will increase the knowledge of potential ignition or severe fire behaviour which would improve the fire safety for mining personnel.

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