Fire safety: hydraulic systems used in underground work

Prepared by researchers at the
Health and Safety Executive

RR1206 (2024)

Research Report

Prepared 2023
First published 2024

Present day mining and tunnelling in GB have different risk profiles to the coal mining that dominated underground work in the 20th century, but fire remains a significant hazard. In any underground work, a fire can be particularly hazardous. Using fire-resistant hydraulic fluids can reduce the risk of fires occurring.

To gain understanding of present-day fire risks due to hydraulic systems used underground, HSE scientists reviewed fire incidents, potential fire scenarios and the controls available to manage fire hazards, and visited 4 mineral mines and 1 tunnelling site. The hydraulic fluids most used at the sites visited were HFDUs. Compared with the hydraulic fluids typically used above-ground, HFDUs need to reach a higher temperature to catch fire, but some fire risks remain. Other fluids are available that are even more fire-resistant, but these are harder to work with.

One concern was that changes in HDFU fluids during use might reduce their fire resistance, but tests carried out on samples taken from working machinery did not find this. HFDU's fire retardant properties were maintained throughout the useful life of the fluid.

The visits did find that the remaining fire risks were not always fully recognised by workers and dutyholders. Further controls are still needed to effectively manage the risk of harm from fire.

Findings from this report will be of interest to the users and managers of hydraulic systems underground.

DOI: https://doi.org/10.69730/hse.24rr1206

This report and the work it describes were funded by the Health and Safety Executive. Its contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.

Fire safety: hydraulic systems used in underground work

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Key Messages

During the 20th century, the majority of the mining in Great Britain was for coal extraction. As this involved a combustible product, flammable coal dust and potential release of methane gas, a very tightly controlled safety regime, particularly for fire safety, was appropriate. In current time, coal is a small fraction of mining in Great Britain and most mines now have a very different risk profile, although fire will still be a significant hazard in any underground situation.

To gain understanding of current day risk due to hydraulic systems and the fluids used in them, HSE scientists visited 4 non-coal sites and 1 tunnelling site, as well as carry out a review of recent fires, different fire scenarios and controls available. During the visits the range of equipment and hydraulic fluid types currently used was assessed. Samples of the different hydraulic fluids found were analysed through a range of standard tests to assess fire performance both for the different types of fluid found, as well as potential degradation of fire-retardant properties over time and use.

Despite the change in risk profile in today’s mining and tunnelling industry, fire remains a significant risk and major hazard. Findings from the study include:

- A wide range of hydraulic machines are in use underground, in different activities, of physical sizes and system complexity.
- The most commonly utilised hydraulic fluid was HFDU, a fire-resistant fluid developed within the tunnelling industry in response to a number of serious incidents. Only a few machines used mineral oil-based hydraulic fluid typical of above ground systems or the HFA, HFB and HFC fluids which were often utilised in coal mines (these have a high water content to reduce flammability).
- The number of fires involving hydraulic machinery is low but increasing.
- From the fire performance test of the different hydraulic fluids found in use, mineral oil performed the worst. The most commonly used hydraulic fluid, HFDU fluids, performed better, but the best results were seen from HFA, HFB and HFC fluids.
- The fire-retardant properties and performance of HFDU fluids did not decline with increased use.
- Test results confirmed that commonly used HFDU fluids have a lower risk of igniting but can still produce significant fires if they do catch light.
- During the site visits, the general perception from workers/dutyholders was that the use of HFDU fluids removed almost all the fire risk associated with hydraulic systems. As a result, little or no thought was given to the use of HFB/HFC fluids, and other controls were seen as less critical. Increased understanding of the strengths and weaknesses of HFDU fluids would lead to more informed decision making and safety improvements.

Findings from this report will be of interest to the users and managers of hydraulic systems underground.

Executive Summary

Background

Fire is a significant hazard in underground workings because heat, smoke and harmful gases produced by a fire are confined in the same enclosed areas occupied by people.

During the 20th century, most of the mining in Great Britain was carried out for coal extraction. Handling a combustible product and managing the risk from methane gas trapped in the coal-bearing seams led to a very tightly controlled safety regime, particularly for fire safety. This often required the use of procedures, equipment and materials that were unique to coal mining, even when equipment performing similar tasks was available from other industries.

One area where this was particularly noticeable was in the fluids used in hydraulic machinery. Most hydraulic systems in use above-ground use mineral oil-based hydraulic fluids, which are combustible and can be ignited relatively easily. Hydraulic systems used in coal mines were specifically built to use fluids that were an emulsion containing a high proportion of water to reduce their flammability (ie HFA, HFB, and HFC fluids). This does result in increased costs however, due to specialist components, higher maintenance and shortened working life for the fluids and the machinery.

Today, coal forms a minute fraction of mining in Great Britain and most mines now have a very different risk profile. As a result, specialist underground equipment has been based on standard hydraulic system designs that use either mineral or HFDU hydraulic fluids. HFDU fluids are based on fatty acid esters and were developed to provide a more fire-resistant alternative to mineral oil following a number of serious underground incidents.

Aims

The aim of this work was to obtain a fuller understanding of current day risks of fire underground due to hydraulic power transmission systems and the fluid used in them.

Methods

Five site visits were carried out between 2017 and 2019 to gather information on the range of equipment being used underground in non-coal mines. Samples of the range of hydraulic fluids in use in equipment at the sites were analysed for fire retardant properties using a series of standard tests. These were carried out on both new, unused fluids as well as those that have previously been used to look for a potential decline in fire performance over time.

A review of fire incidents in GB mines over the last 30 years was carried out with a focus on those that may have related to the use of hydraulic fluids.

The causes of potential fires relating to hydraulic fluid systems were reviewed under a range of failure scenarios, and the consequences of these estimated. Finally, the controls for hydraulic fluid mine fires were considered.

Findings

There are many hydraulic machines currently in use underground, covering a wide range of activities, physical sizes and system complexity.

There have been relatively few fires involving hydraulic machinery underground. However, any fire underground has serious potential consequences and in addition, the number relating to hydraulic machinery does appears to be increasing. The reason for this increase is unclear, but the upward trend in fire numbers seems consistent. The controls used most widely are the selection of hydraulic fluids and the provision of fire extinguishing equipment.

Our laboratory testing of the hydraulic fluids sampled during the site visits revealed that the poorest performing fluids are the mineral oils, which are commonly used in hydraulic equipment in above-ground situations. However, these were still found in some underground machinery during the site visits.

The fluids with by far the best fire performance were those designated as HFA, HFB and HFC fluids (these fluids have a significant water content and were developed specifically for use in high fire risk situations such as coal mines). However, there are relatively few operating machines that use these hydraulic fluids; only one such machine was noted during the site visits carried out during this project.

More commonly used were HDFU fluids, originally developed for use in tunnelling machinery. They are now the most widespread fluids used in underground mining. When tested, HDFU fluids had a fire performance that fell between that seen in mineral oil fluids and the HFA/B/C fluids. We did not observe a decline in performance comparing new, unused HDFU fluids with those that had been used

The main advantage of HFDU fluids is that they have a significantly higher ignition temperature than mineral oils. Thus, an accidental leak is less likely to be ignited if it meets a hot surface (such as an exhaust or turbocharger outlet in a machine’s engine compartment).

However, the HFDU fluids show little or no difference to mineral oils when it comes to the ease of ignition by other ignition sources (hot sparks or contact with a pre-existing fire). If a pool of an HFDU fluid is ignited, then the behaviour is like a mineral oil. The results from testing hydraulic fluids in spray fire situations were variable when considering the HFDU fluids.

During the mine visits for this study, it was noted that many users were unaware that the fire protection provided by HFDU fluids was limited. The perception was often that use of ‘fire resistant’ fluids would effectively eliminate any fire concerns except, perhaps, in the most extreme circumstances. This would be correct for water-oil emulsion fluids (HFA/B/C), but it is not the case for HFDU fluids.

Given the potential for harm, it is important that all reasonable steps are taken to prevent hydraulic oil leaks that could lead to a fire, and to mitigate the consequences if a leak does arise. It is impractical to prevent all leaks, so controls also need to be in place to reduce the ignition risks should fluid still leak from a hydraulic system. One relatively straightforward control is the inclusion or retro-fitting of shields to stop fluid from the most likely leak points reaching the most likely ignition sources (hot engine components, electrical systems that may arc). Additionally, the size and duration of a fire can be reduced if it is actively extinguished, either through effective use of manual fire extinguishers or fixed fire systems where appropriate, such as for spray fires or hard to access areas where fires may occur (for example, hidden beneath panels). Within the mineral mining industry in Great Britain, many of these controls are commonly, though not universally, implemented.

Conclusions

While fire-resistant hydraulic fluids should always be preferred above mineral oils in the enclosed mine environment, the choice of which type of fire-resistant fluid is less clear cut.

HFA/HFB/HFC fluids only burn under exceptional circumstances, most likely only if other materials are present as the main fuel for the fire. They therefore present a much lower fire risk, but there are increased equipment costs and can require bespoke systems. The choice to use another fluid needs to be a conscious decision based on what is reasonably practicable considering this.

HFDU fluids do reduce some fire risks and are often a ‘drop-in’ replacement for mineral oils. This allows the use of more standard hydraulic systems and simplifies the modification of pre-existing machines for use underground. However, when these are used, the focus needs to be on following best practices around reducing failure rates, particularly around likely leak points. It is also important to consider rigorous implementation of further controls aimed at actively extinguishing any fires that do occur.

Findings from this report will be of interest to the users and managers of hydraulic systems underground.

HSE have already shared these findings with the mining industry through presentation at the Midlands Institute of Mining Engineers annual Safety Seminar in 2023.

Contents

Introduction

The work described in this report was initially prompted by concerns that fire resistant hydraulic fluids may lose their fire performance over their lifetime, becoming a progressively greater fire risk. This is of particular concern in underground mines, where such fluids are often integral to fire safety management. The perception was that the properties that mitigate combustion in some ‘fire resistant’ hydraulic fluids may be altered as they repeatedly pass through machinery creating high pressure and high fluid shear throughout the working lifetime of the fluid.

At an early stage of the project, it was recognised that addressing this very specific fluid-ageing concern was only one aspect of a broader review of the use of hydraulic fluids in underground mining. Undertaking that broader review would provide useful information to help HSE regulators frame their approach to the use of hydraulic machinery within underground workings. This knowledge would be used primarily in mines but also in tunnel construction, which shares many of the same processes.

Fire is a significant risk in underground workings because heat, smoke and harmful gases produced by a fire are confined in the same enclosed areas occupied by people. Smoke can fill escape routes, slowing escape times and potentially requiring the use of respiratory protective equipment. From many underground areas there may be only a single route leading toward the surface, which is used for people and equipment in both normal work and in an emergency. A fire in this route can potentially lead to people being trapped in-bye of the fire, with no way around it to safety.

During the 20th century, most of the mining in Great Britain was for coal extraction. The requirement to handle a combustible product and the potential for release of flammable methane gas trapped in the coal-bearing seams led to a safety regime where combustible materials were very tightly controlled. This often required the use of procedures, equipment and materials that were unique to coal mining, even when equipment performing similar tasks was available from other industries.

One area where this was particularly noticeable was in the fluids used in hydraulic machinery. Most hydraulic systems use mineral oil-based hydraulic fluids, which are combustible and can be ignited relatively easily. Hydraulic systems used in coal mines, to power cutting machines for instance, were specifically built to use fluids that were an emulsion containing a high proportion of water to reduce their flammability. The operational disadvantages of such systems – increased costs due to non-standard components, maintenance costs and shortened working life for the fluids and the machinery – were offset by the need for extremely robust control of the inherent fire and explosion risks associated with coal mining.

A standard set of terminology was developed to describe various ‘fire resistant’ hydraulic fluids:

> “HFA” fluids are ‘oil in water’, typically containing over 80% water;
>
> “HFB” fluids are ‘water in oil’, typically containing around 45% water;
>
> “HFC” fluids are water / glycol mixtures with no mineral oil content; and
>
> “HFD” fluids are water-free but are designed to have some fire resistance gained in other ways. HFD fluids are further divided into “HFDR” fluids based on phosphate esters (now largely phased out following concerns over their toxicity) and “HFDU” for any other materials. The most common HFDU fluids are based on polyol esters.

Although fire in any underground situation is a serious event, mining of non-combustible products and tunnel construction works did not face all the fire risks associated with coal extraction.

Thus, ways of working developed in which specialised underground equipment was based on standard hydraulic system designs. In some cases, construction plant items such as loaders and excavators designed for use on the surface were also employed underground. Since the hazards of fires on the surface are significantly lower than those occurring underground, this equipment was developed with less attention paid to the removal and protection of ignition sources, the incorporation of on-board fire suppression systems and the reduction of fuel inventories. Generally, for overground use, these hydraulic systems use mineral oil-based fluids at high pressures between 200 and 300 bar.

The use of such hydraulic systems has led to some serious incidents underground. One example is a major fire that occurred following an oil leak on a hydraulic-drive truck at Tara Mine in the Republic of Ireland (Irish Times, 1999). Another is a fire initially fuelled by a mineral oil fluid on an operating funicular railway at Kaprun, Austria in 2000 led to 155 deaths (Wikipedia, 2022). Such events clearly show the potential for fire where such fluids are in use underground.

As well as the hydraulic fluid used to drive vehicle systems such as transmission, hoists, drills, etc., other aspects of machinery can introduce a significant fire load underground. This is borne out by incidents in operational transport tunnels and in underground workings.

An operating tunnel example is the fire in the Tauern Tunnel in Austria in 1999 (Leitner, 2001), in which diesel fuel played a significant role in the deaths of 12 people.

An example in underground workings is a fire on a locomotive operating as part of the tunnelling work during expansion of the Paris Metro (New Civil Engineer, 2003). This fire, largely fuelled by the locomotive’s own diesel fuel, led to 19 workers being trapped within the working area for several hours and needing to rely on emergency air supplies within the tunnel boring machine until the fire was brought under control and they could be rescued.

In response to this situation, hydraulic fluid manufacturers developed a new class of synthetic hydraulic fluids based on fatty acid esters. This class of fluids, known as HFDU fluids, is intended to provide a more fire-resistant alternative to mineral oil hydraulic fluids without requiring major changes to existing hydraulic systems. They can operate in standard hydraulic machines with, at most, a change of seals and gaskets. Even this is not always required, as some seal and gasket materials are suitable for both mineral oil and HFDU fluids.

HFDU class fluids first gained wide usage in the tunnelling industry and are now often used in mines as well.

With the decline of coal mining to the current point where underground mines produce only minimal amounts of coal, underground working in Great Britain is dominated by tunnelling and mining of other materials.

This means that almost all hydraulic machinery underground is using mineral oil or HFDU fluids.

HSE, the regulator for safety in Great Britain’s underground workings, has undertaken the work described in this report to better understand the scope of hydraulic fluid use underground and the extent of any practical benefits of HFDU fluids.

Initial experience with HFDU fluids indicated that the perception in the industry is very positive, to the point where many operators believe that fire risks are largely eliminated when HFDU fluids are used.

Initial evidence is that the temperature at which ignition occurs is significantly higher for HFDU fluids than for mineral oils, which can be expected to reduce many fire risks. However, HFDU fluid’s benefits if an oil leak creates a spray are not as well-established. There are two main tests for spray combustion and, although HFDU fluids satisfy the requirements of the ISO 15029-1 test (International Standards Organisation, 2019), they have initially performed poorly in the ISO 15029-2 (International Standards Organisation, 2017).

There was also a suggestion that HFDU fluids did not show significant benefits in the type of fire situation assessed by ISO 14935 wick tests (International Standards Organisation, 2020). Finally, there were also indications that the fire resistance of HFDU fluids might degrade over time as they were being used in machines.

The current project first sought to identify the range and type of machinery in general use and to classify the machines in terms of the complexity of their hydraulic systems. Then, through quantifying the fuels present and the hydraulic system operating conditions, specify a range of potential fluid release scenarios leading to a suite of potential design fires. This would define the type and characteristics of the fires most likely to occur and against which most control measures should be assessed.

Through the development and application of a risk assessment procedure for each machine type, the project then sought to quantify the benefit provided by the range of control and mitigation measures which might be applied. Such measures include the use of a different type of hydraulic fluid, shielding of major fuels or isolation of potential ignition sources.

The final goals were to use the scientific evidence to define a potential approach to reducing the likelihood and severity of underground fires involving hydraulic oil and to identify the implications of this for operators and regulators.

Current mining equipment

The first stage of this work was to determine the range of equipment used underground in Great Britain's non-coal mines and the environment in which they operate. To this end a series of visits was carried out over a period from 2017 to 2019. In addition to four mines with active mining machinery, a visit was made to the Sirius Minerals (now Anglo American) site at Wilton, Teeside to survey a Tunnel Boring Machine (TBM) in use there. The sites visited are detailed in Table 1.

Table 1: Visit programme

Site	Operator
Fauld (Gypsum)	Saint-Gobain Construction Products UK Limited, British Gypsum
Stoke Hill (Dimensional Stone)	SigmaRoc, Bath Stone Group
Boulby (Polyhalite fertiliser)	ICL Cleveland Potash Ltd
Milldam (Fluorspar)	Fluorsid, British Fluorspar
Wilton (Tunnelling for polyhalite extraction)	Strabag and Anglo American

Information Gathering

To facilitate the collection of information a questionnaire was drawn up. This is included here as Appendix 1. The questionnaire covered general site information such as details of the mine ventilation system, roadway dimensions, and any fixed fire detection and suppression installed. Other general information included the numbers of personnel underground at any time.

The questionnaire also sought information on the machinery in use. Initially the numbers of each model of machine and their annual usage would be determined.

It was anticipated that a section could be completed for each type of machine used underground. These sections were included to provide the type of information which could be used to specify the types and sizes of fires which might occur on the machine. They included the types and volumes of hydraulic fluids, the operating pressure of the system and an identification of and numbers of the different components.

The survey also planned to identify the major combustibles on each machine, so the engine compartment, cab and exterior of the machine were examined for the presence of plastics and other combustibles and the inventory of any liquid fuels such as diesel and brake fluids was obtained.

Another area of the questionnaire covered machine fire protection, both active and passive. Thus, information on any on- board fire detection and suppression system fitted was identified, including information on the suppression medium and the number and positioning of the nozzles for its delivery. The provision of manual fire extinguishers was noted. Details of any passive fire protection measures fitted to the machine were also sought. Thus, questions were asked to confirm or otherwise the presence of shielding for high temperature engine components such as exhausts or major fuels such as tyres and measures taken to protect against release of flammable hydraulic fluids such as the use of braided and Kevlar-protected lines and joints.

Mobile Equipment Underground

At an early stage it became apparent that it was very time consuming to complete the questionnaire for each piece of equipment with the level of detail required to fully assess the potential for fire. Due to the limited time available from both HSE staff and mine operational personnel, it would not be possible to fully specify the full range of machinery encountered underground during these visits. Thus, a decision was taken to use the survey visits as an opportunity to gain an overview of the equipment and the underground operational environment and then use other sources of information to provide the necessary detail.

To this end, machinery manufacturers' user/service manuals were sourced for a number of machine types encountered underground. These include, as examples, manuals for an Atlas Copco ST14 Scooptram (Atlas Copco, 2007) and a JCB 525 Series Loadall (JCB, 2018).

These manuals provided the necessary information to estimate the fire risk from their hydraulic systems. In particular, they allowed an assessment of the number and types of components, especially the hydraulic lines and joints.

The questionnaire did not provide a suitable structure for gathering information on the TBM at Wilton. Although a single machine, it incorporated many, largely independent systems, including multiple separate hydraulic systems.

As with mines using many individual machines, the resources and time required to complete a detailed examination of a machine with this complexity would have been prohibitive. Hence the on-site survey comprised a machine walkdown, identifying individual hydraulic systems and their operating parameters.

To simplify the picture, the machines were classified into a scheme comprising four broad vehicle types according to the complexity and scale of their hydraulic systems:

- PTVs – Personnel Transport Vehicles. These are vehicles used throughout the mines to provide rapid access to the various work areas.
- LPVs – Light Plant Vehicles. These are relatively small and simple vehicles for a variety of task, including machines such as forklift trucks and light loaders.
- HPVs – Heavy Plant Vehicles. These are larger vehicles, generally with lengths >10 m. They were usually used for loading or transporting material about the mine.
- SPVs – Special Plant Vehicles. These are more specialised vehicles with more extensive hydraulic systems and/or electric traction systems. These were, primarily, drill rigs or cutting vehicles.

The hydraulic systems of these four vehicle types have been characterised in some detail with the numbers and types of components identified and the locations of potential leaks and the number of leak sites enumerated. The results of this exercise are summarised in Table 2, which details each machine type in a manner useful for the conduct of a risk assessment on a machine.

An inventory was compiled of all equipment encountered at all the sites visited and the characteristics of each machine were identified. Using the data obtained during the site visits and the categorisation of machinery detailed above, an assessment was carried out on the mining machinery encountered underground.

This analysis is presented in detail in Appendix 2.

An overall summary of the number of machines in each category is given in Table 3.

This shows that there are a range of vehicle types in use at most sites, but the numbers and distribution vary significantly from site to site.

Table 2: Typical equipment details for each generic machine type

Vehicle type	Components	Operating conditions		Numbers of potential hydraulic leak locations					
		Pressure (bar)	Volume (litres)	Hoses	Hose connections	Steel pipes	Control valves	Oil seals	Cylinders
PTV	Pump Balancing valve Reservoirs	100	15	16	32	1	3	5	-
LPV	Pumps Accumulators Valves Cylinders/Rams Coolers Filters Reservoirs	200-240	50-100	87	174	9	44	10	7
HPV	Pumps Accumulators Reservoirs Valves Cylinder/Rams	200-250	300-400	85	170	9	48	12	8

Vehicle type	Components	Operating conditions		Numbers of potential hydraulic leak locations					
		Pressure (bar)	Volume (litres)	Hoses	Hose connections	Steel pipes	Control valves	Oil seals	Cylinders
	Cooler Filters								
SPV	Pumps Valves Cylinders/Rams Filters Reservoirs	200	300	80	160	8	40	13	8

Table 3: Summary of machine types and numbers

Type of Machine	Site				Total
	Fauld	Stoke Hill	Milldam	Boulby	
PTV	8	0	0	38	46
LPV	5	5	0	29	39
HPV	4	1	12	18	35
SPV	2	4	1	17	24

Previous incidences of fire in British mines

A review of fire incidents in mines within Great Britain over the last 30 years has been carried out to inform this study, particularly where fire may relate to the use of hydraulic fluids underground. Data from previous incidents can give useful information on the frequency and types of fire event which can occur, including the source of ignition, the main fuels involved and the effectiveness of any fire suppression system or other mitigation deployed.

Since mine fires in Great Britain are thankfully rare, such data is sparse and all available sources must be utilised. The study included information on incidents in both coal and non-coal mines going back as far as 1989. More recent data, including incidents up to 2021, have also been included.

Appendix 3 looks at the incident review in detail.

The findings of the review that are most relevant to this work are:

- When mobile compressors and generators are included, fires involving mobile equipment dominate the occurrence of fire in non-coal mines. Mobile equipment accounted for between 50% and 60% of incidents over the period 1993 to 2021.
- Using the mobile equipment grouping discussed earlier, of the fifteen incidents on mobile equipment between 2012 and 2021, five were reported on Light Plant Vehicles (LPVs), five on Heavy Plant Vehicles (HPVs), one on a vehicle used for personnel transport (PTV) and the remaining two on Special Plant Vehicles (SPVs).

  The type of vehicle involved in the eight fires on mobile equipment between 1993 and 2000 were not identified.

  The remaining fires originated either on conveyors or items of fixed plant such as ventilation fans.

- Historically, many fires in coal mines occurred on belt conveyors. During the period from 1993 to 2000, thirty-eight of the sixty-one fires reported in coal mines were associated with conveyors (62% of the total).

  In the same period there were no reported fires originating on conveyors in non-coal mines.

However, between 2012 and 2021, six out of the twenty-six fires reported in non-coal mines involved conveyors (23% of the total).

- As well as more conveyor fires in non-coal mines, there is also an increasing number of fires on mobile equipment.

  Between 1993 and 2000 there were eight such incidents; an average of 1 per year.

  Between 2012 and 2021, fifteen fires were reported – an average of 1.5 per year.

- Without further interrogation of incident reports, the reason for this increase is unclear.

- Only eighteen of the twenty-six incident reports specify how the fires were extinguished.

  Of those eighteen fires, eleven were extinguished using portable extinguishers including eight of the fires on mobile equipment (more than half of the mobile equipment fires).

  In contrast, only two of the reports of fires on mobile equipment mention the use of an on-board fire suppression system. In both of these cases the on-board systems were manually activated by the operator before leaving the machine.

Although the number of these events which might have developed into a serious incident cannot be identified, the utility of portable fire extinguishers is clear.

None of these incidents developed to cause injury or loss of life. However, given an increase in the number of fire events, it appears that they have an increasing potential to do so.

Hydraulic fluids used underground

Current Usage

During the survey it was noted that there were a variety of hydraulic fluid types in use underground.

Hydraulic fluids in a machine are replaced after a period, as their properties can degrade over time as they are used. This raises the question of whether the fire performance of fire retardant fluids is also affected by ageing.

Testing of fire retardant properties is based on a series of standard tests that are carried out on fresh fluid. The test standards were, typically, developed some time ago when the specific hazards and machinery found in the coal mining industry were the main focus for safety concerns.

Nevertheless, results from these standard tests are the only fire properties that end users have to use in a risk assessment.

The findings of the survey were used to revisit the standard tests and consider whether they remain relevant to current and future use in non-coal mining.

From the survey it was seen that mineral oils were in limited use, HFDUs (polyol esters and rape seed oil-based products) were widely found and there was one instance of an oil/water emulsion HFB fluid on a machine.

Samples of most of these fluids, both new and aged, were obtained from the users. These were subjected to a test programme at HSE's Science and Research Centre in Buxton to identify the properties describing their likely behaviour in a fire.

Hydraulic Fluid Testing: Ignition

A wide range of ignition tests is available from tests designed to determine an ignition temperature to those designed to measure the burning characteristics of a spray.

The mine visits and the examination of recent data suggest that currently the most likely source of ignition is a hot surface. Within the engine compartment of many machines, a significant proportion of the hydraulic system is present alongside engine components at temperatures in excess of 400 °C. The hotter components are the exhaust system, particularly in the area closest to the engine, and the turbocharger, where these are fitted.

Looking ahead, with a move towards the use of electrically powered vehicles, it is likely that electrical arcing may become increasingly important as a potential ignition source.

Other sources of ignition that have been a concern in the past are as self-heating and frictional heating from conveyors. Self-heating requires a combustible material, and so is unlikely to be important in most non-coal mines. Frictional heating continues to be a potential cause of fire; however, this hazard is now well-understood and can be effectively controlled using fire-resistant belting.

Thus, fluid testing should include an assessment of potential for the fluid to ignite in the presence of a hot surface and, in the future, the electrical energy required to ignite a fluid in a spray as this is the state where the least energy is required for ignition.

In 2001/02, Jagger *et al* (2002) performed a large number of tests on a range of fluid types. At the time of those tests, most HFDU fluids were either polyalkylene glycol or polyol ester formulations and HFDU formulations based on renewable natural oils were being introduced. Thus, the work by Jagger specifically included a “biodegradable” HFDU based on a rapeseed oil as a separate case to other HFDUs.

Despite this earlier terminology, polyol esters in general are biodegradable, though they do not necessarily have renewable source materials and may contain additives that are not biodegradable.

It is perhaps indicative of the current market drivers that all the HFDU samples submitted for the present study were polyol ester formulations are marketed as biodegradable, although none claimed to be from renewable (i.e. plant-based) oils.

Ignition on hot surfaces

The 2001/02 tests by Jagger *et al* included ignitions on hot surfaces.

They heated surfaces with areas up to 1 m² and presented these surfaces to fluid sprays at a number of orientations. Ignitions were difficult to obtain, largely due to the tendency of the spray to bounce off the surface. They also examined the ignition of fluid released as a stream rather than a spray, along with the autoignition temperature of bulk fluid.

Tests were carried out dribbling fluid onto a heated tube used to model a hot exhaust manifold. These used the procedure described in *ISO 20823: Determination of the flammability characteristics of fluids in contact with hot surfaces – Modified Hot Manifold Ignition Test*.

Tests to determine the autoignition temperature (AIT) were made using the procedure described in *DIN 51794: Testing of mineral oil hydrocarbons - Determination of ignition temperature*.

Both these tests produced usable results with, in all cases, the hot manifold ignition temperature result being above the AIT.

An assessment of each of the two tests was carried out. This concluded that the situation modelled in the AIT test, with isotropic heating of a very small sample, was not a realistic model of any real incident situation. While the AIT test was likely to produce a conservatively low temperature for a fluid ignition, the value obtained was unlikely to be representative of ignition temperatures in a practical situation.

Jagger *et al* chose measurement of the hot manifold temperature as the most useful and realistic test. Since then, no new data has been produced that challenges this conclusion, and so this remains the situation.

Therefore, a series of hot manifold tests were performed on each of the samples of fluids provided by the operators of the facilities visited.

Figure 1 shows a photograph of the hot manifold test rig. The sloped tube is heated electrically to a predetermined temperature and, once at temperature, a sample of the test fluid is dropped onto the top of the tube at the centre point. This is then observed for production of smoke, flame, burning droplets that fall from the tube and whether these continue to burn on the tray below.

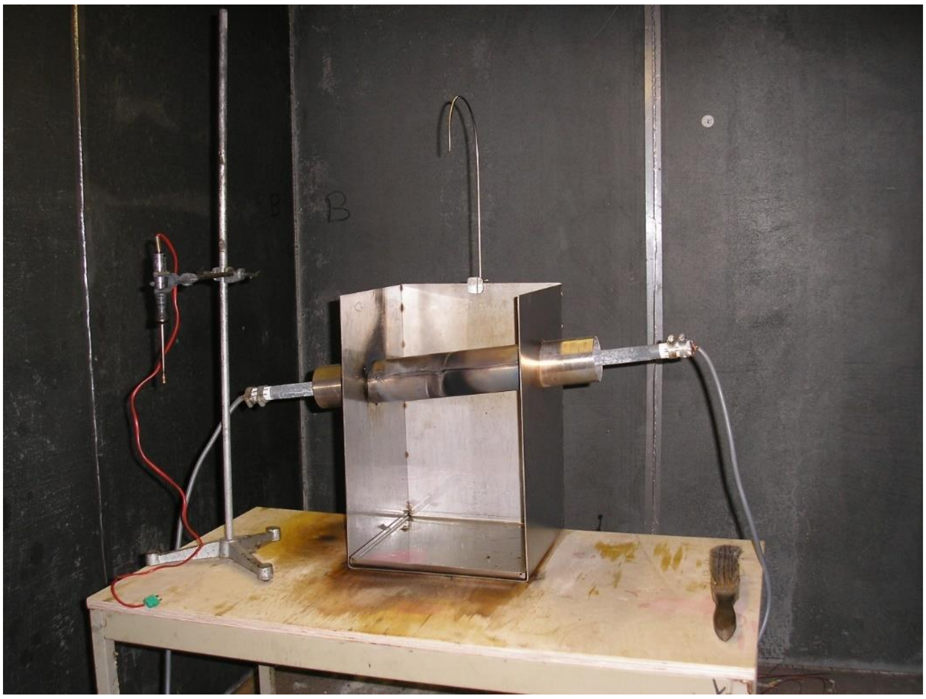

Figure 1: Hot manifold test rig

Test samples of different fluids were requested from the operators that took part in the site surveys. All the fluid samples they supplied were tested. As such, HSE did not select which fluids would be tested.

Further, it should be noted this is not (and was not intended to be) an exhaustive look at the full range of fluids that are available.

The outcomes from this programme are described in Appendix 4, and the results are summarised in Table 4. The identities of the various fluids have been anonymised in the table.

Table 4: Hot manifold test results

Fluid	Condition	Measured Hot Manifold Ignition Temperature
MIN#1	New	419±3 °C
	Used, hours not reported	417±3 °C
HFDU#1	New	499±3 °C
	Used, 2857 hours	501±4 °C
HFDU#2	New	513±3 °C
	Used,400 hours	515±3 °C
HFDU#3	New	515±3 °C
	Used, 514 hours	526±2 °C
HFDU#4	New	521±4 °C
	Used, 807 hours	520±2 °C
HFDU5	New	522±3 °C
	Used, 694 hours	517±3 °C
	Used, 1212 hours	516±2 °C
HFB#1	New	653±3 °C
	Used, 500 hours	662±4 °C

The results from the hot manifold testing confirmed that:

- The mineral oil had the lowest ignition temperature;
- The HFDU fluids had ignition temperatures 80 °C to 100 °C higher than the mineral oil;
- The HFDU fluids all had similar ignition temperatures, with a range of less than 25 °C between the highest and lowest;
- The HFB fluid had an ignition temperature 240 °C higher than the mineral oil; and
- The HFB fluid had an ignition temperature 130 °C higher than the highest HFDU.

A possibly more interesting finding is that none of the fluids showed a significant change in their hot manifold ignition temperature after a period of use of several hundred hours (even, in one case, after nearly 3,000 hours use).

Ignition of spray leaks by a spark

The 2002 study by Jagger *et al* used an *ad hoc* test apparatus assembled to measure the energy of sparks required to ignite fluid sprays.

This was dismantled after that testing was complete and was no longer available to test the samples in the current study.

However, data from those earlier tests provide an indication of the energies required to ignite the types of fluid currently in use. These are summarised in Table 5.

Table 5: Spark ignition energy for hydraulic fluids (*Jagger et al, 2002*)

Fluid type	Minimum spark energy for ignition
Mineral oil	Significantly below 1 Joule
HFDU	Approximately 1 Joule
HFB	56. 7 Joules

To give context to the ignition energy values found in the work from 2002, the minimum ignition energies of typical flammable gases are below 1 mJ and those of combustible dusts are often between 20 mJ and 100 mJ. Data on ignition of sprays is less prevalent, although some studies show similar ignition energies to dusts in small scale lab testing. However, the few studies at larger scale suggest that much higher ignition energies are required in practice.

Ignition of spray releases in surface applications was studied in an HSE-led joint industry project, MISTS, focussed on DSEAR assessment of oil mists formed by spray leaks (Bettis *et al* 2017). The test work in this project used a 1 Joule spark ignition source, which was considered a ‘worst case’ for typical industrial equipment. The perception of the industry members of the project was that equipment producing higher energy sparks does exist, but that sparking with higher energies would be regarded as a wider safety issue. Therefore, spark energies up to 1 Joule were unlikely in most circumstances but would not be remarkable.

From this it can be seen that typical electrical systems may have the potential to ignite mineral oil sprays, would be borderline at worst for HFDU fluids and the likelihood of igniting HFBs this way is negligible.

With rapid developments in battery storage and electric vehicle technologies, it is not yet clear whether there will be a need to revisit the likely spark energies that could be found in mines when such equipment is adopted more widely.

Hydraulic Fluid Testing: Combustion

Based on the type of machines in use for mining, hot surfaces and electrical sparks are seen to be the most likely means by which a fluid leak could be ignited.

The testing described in previous sections shows that hot surfaces need to be considered in detail, while sparks are unlikely to ignite fluids other than mineral oils.

Other ignition sources, while less frequently found, cannot be ruled out. For example, one obvious scenario would be a fire on other materials leading to damage to a hydraulic system and releasing fluid into an existing fire.

Fire risks can be reduced if any burning of ignited hydraulic fluids is limited.

Several tests are also available to measure specific characteristics of burning fluids such as heat release rate, flame morphology and smoke production.

Again, Jagger et al (2002) examined a range of standard tests for this purpose and also carried out a number of related *ad hoc* tests to examine the consequences of combustion.

As part of this *ad hoc* testing, several medium scale pool fires with an area of ~1 m^2 were carried out to examine the behaviour of bulk fluid when burning. In general, these tests produced extremely useful data including heat release and smoke production as a function of time. However, such tests are expensive and time consuming to perform, therefore they are not suitable to be carried out routinely in a standard test protocol.

Data from these tests relevant to the fluids encountered in this study have been abstracted and are presented in Table 6.

In the 2002 work, a distinction was made between ‘standard’ polyol esters and plant-based ‘biodegradable’ fluids, as the latter type had recently been introduced. All the HFDU samples provided in the present study were polyol esters that, while not plant-derived, are sold as biodegradable.

These data indicate that a burning pool of HFDU fluid can release more heat than a similar pool of mineral oil. Thus, temperatures around burning pools of HFDU fluids are likely to exceed those of a burning mineral oil pool.

However, mineral oil produces more smoke and carbon monoxide. As a result, away from the immediate vicinity of a burning pool, fires involving the HFDU fluids will pose a lower toxic threat and will take longer to form smoke that could hinder escape.

Table 6: Pool fire combustion data (Jagger *et al*, 2002)

Fluid	Fluid burn rate ($g{\cdot}s^{-1}$)	Heat release rate (kW)	Smoke production (m^3 OD1 smoke$\cdot g^{-1}$)	Carbon monoxide production ($ppm{\cdot}g^{-1}$)
Mineral oil	9.30	343.4	0.44	2.48
Biodegradable oil	11.7	601.1	0.21	1.90
Polyol ester	10.9	478.1	0.34	3.07
HFB	27.2*	204.5	0	0

* This fluid did not burn continuously and self-extinguished after 4 minutes. The fluid burn rate was obtained using an assessment of the amount of fluid remaining in the tray after this initial burn. This figure may, therefore, be unreliable. As an HFB (water/oil emulsion), the apparently high ‘burn rate’ will include significant evaporation of water which will not contribute to the production of heat and may remove smoke and gases as it condenses in the fire plume.

There are several tests available to assess the hazards posed by a burning oil spray. The 2002 report from Jagger *et al* (Jagger, 2002) examined these, and a paper by David Phillips (Phillips, 2009) also critically reviewed some of the tests available.

Many of these spray tests produce a pass/fail result against some arbitrary criteria. Such tests are often reported by fluid manufacturers, notably the persistence of burn test described in ISO 15029-1 (2019), as a pass/fail is simple to understand.

Such tests are unsuitable for use in a more detailed risk assessment where a comparison of fluid performance helps determine selection. In pass/fail tests, fluids are either ‘good’ or ‘bad’ and the test results do not distinguish between ‘good’ and ‘better’.

However, three of the tests described in the literature measure performance of a fluid spray on a continuous ranking scale.

“ISO 15029-3”

The ‘Swedish spray test’ or ‘large-scale spray test’, is carried out under a large calorimeter collection hood. The test fluid is forced through an atomising nozzle at a high flow rate using a pump. The release pressure is fixed and carefully controlled, and the fluid ignited using a gas burner (tests are carried out with three different burners ranging from 10 kW to 200 kW). The combustion products are collected and analysed to produce a fluid heat release rate. The fluids are then simply ranked according to this heat release rate with the best performers having the lower heat release rates. No other property of the combustion is measured but the test has the potential to provide data on the characteristics of the combustion such as smoke production which could then be used in a risk assessment. However, due to its large scale very few manufacturers have used this test to assess the performance of their fluids and, although sometimes described as “ISO 15029-3”, its formal standardisation has not been pursued.

FMS 6930

Another available test procedure is the Factory Mutual Standard 6930 (2002). This method is widely used in the United States due to insurance requirements. The test was also an attempt to move away from pass/fail test criteria and provide a test to rank all fluid types.

As in the “ISO 15029-3” method, the chemical heat release rate is the main test parameter computed from measurements of carbon monoxide and carbon dioxide and the test is carried out under a large combustion products collection hood.

In the early stages of test development, it was found that some volatile and flammable solvents such as ethanol and heptane also gave low release rates and might therefore be classed as fire-resistant hydraulic fluids. To avoid this, Khan (1991) introduced the concept of ‘critical heat flux for ignition’ measured using a separate test rig. Using parameters derived from these two test rigs, a Spray Flammability Parameter, SFP, was defined combining the heat release and heat flux measurements:

$$\text{SFP}_{\text{normalised}} = 11.02 \times 10^6\, Q_{ch}/\rho_f \cdot q_{cr} \cdot m_f$$

where $q_{cr} = \alpha \times \sigma \times T^4$

Q_{ch} = the chemical heat release rate (kW),

ρ_f = fluid density (kg/m^3),

q_{cr} = critical heat flux for ignition,

m_f = mass flow rate,

α = fluid emissivity (assumed = 1),

σ = Stefan-Boltzmann constant (5.67 x10^{-11} kW/m^2 K^4), and

T = the fire point[1] temperature (K).

This test can produce information suitable for use in a risk assessment. For example, since measurements of the SFP fall on to a continuous ranking scale, it can be adapted to scale the performance of different fluids to facilitate a comparative risk assessment. The test rig can also be used to measure smoke production.

Unfortunately, the test cannot be applied across the full range of fluids used in mining machinery. The main test is problematic with water-based fluids, which led to the development of a separate test procedure for them. This is not a satisfactory situation as the different tests preclude a direct performance comparison across the full range of fluids in industry.

Also, there are potential problems with phosphate-based fluids because the calculation of heat release rate assumes that only carbon monoxide and carbon dioxide are produced. This may not be the case where phosphorus compounds are involved.

ISO 15029-2

The third test developed for assessing the hazards of spray releases of hydraulic fluids is the New Buxton Spray Test – Determination of Spray Ignition Characteristics of Fire-Resistant Fluids. This was originally developed by HSE at the Buxton laboratories and is now standardised as ISO 15029-2.

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[1] Where the flash point is the temperature at which the vapour above a liquid can be ignited and show a brief flash of flame, the fire point is the somewhat higher temperature at which the liquid continues to burn once ignited.

This test employs a carefully controlled propane pilot burner to ignite a horizontal spray of fluid. Heat from the burner flame is used to stabilise combustion in the spray and the extent of combustion (or fraction of the fluid burned) is inferred from measurements of temperature in the exhaust. The temperature measurements in the exhaust (and those obtained with the pilot burner alone) are used to produce a normalised ignitability factor for ranking (*RI*).

A photograph of the test chamber with a fluid under test is shown in Figure 2.

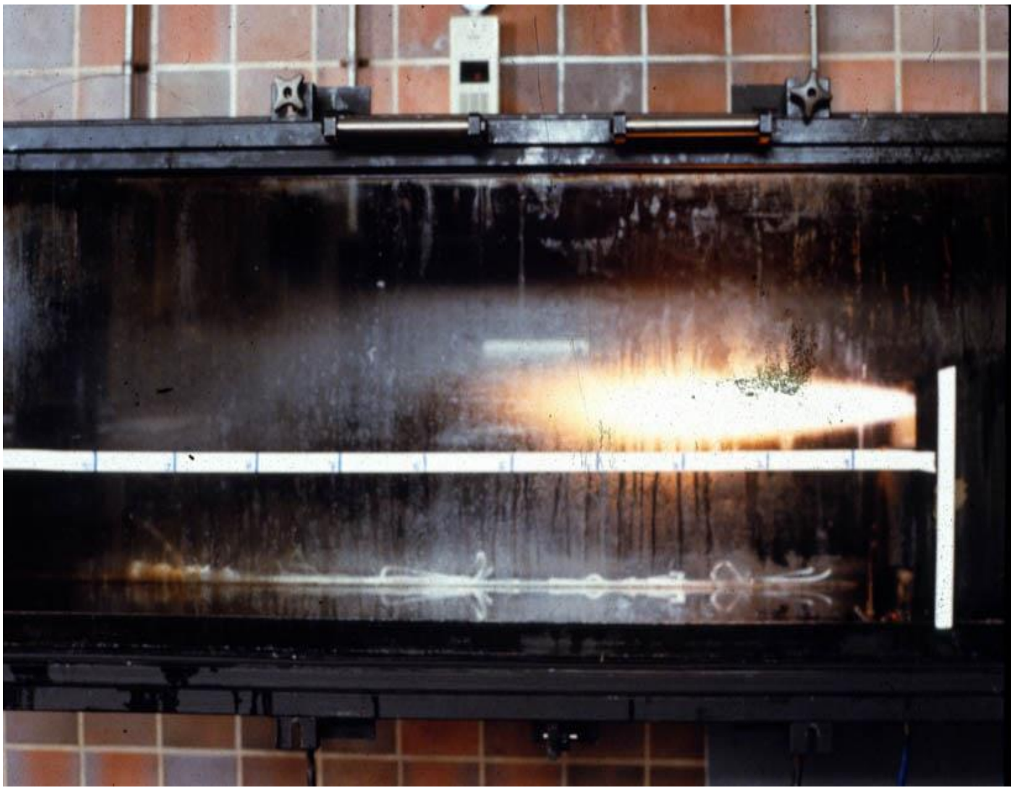

Figure 2:The New Buxton Spray Test rig with a fluid undergoing a test

Different fluids combust to differing extents in the rig and thus produce varying temperatures in the exhaust with the lower flammability fluids producing the lower temperatures. This allows the ignitability factor to be used as a fluid performance parameter. The test can accommodate the full spectrum of hydraulic fluids including the least flammable oil-in-water emulsions by using two sizes of pilot flame, and can also be used to measure the output of smoke and toxic products from burning sprays.

In its basic form, the test does not measure the true heat release rate since the radiative release fraction is ignored; the exhaust temperature measurements giving access to the convective heat flux only. Phillips (2009) has criticised this aspect of the test and also the fact that the test fluid input is specified in volume and not mass terms, stating that this may not allow a true comparison of fluids with a significant variation in density.

Despite these concerns, the ISO 15029-2 test has been adopted in this work to produce data on the fluids. This test was chosen as its spray release attempts to model a realistic release scenario. Also, the test is known to give reproducible results and has a rigorous calibration procedure which allows comparison with fluid testing carried out by any test house and at any point in the test rig's working life.

A twin fluid air-atomising nozzle is used to produce the spray. Measurements have confirmed that the droplet sizes produced from this nozzle at the pressures used are comparable to the best predictions available for accidental releases, being in the range 50-100 µm (see later section on Release properties). Additionally, a twin fluid air-atomising nozzle was selected in an attempt to produce a uniform droplet size across the fluid range and eliminate the effect of polymeric thickeners on spray flammability. Droplet size is considered one of the most important release parameters since it will have a significant effect on the rate of combustion.

The concerns about heat release measurement and fluid density were addressed for this test work.

The test rig at Buxton was adapted so that it could also provide heat release measurements through oxygen calorimetry. Fluid density was also considered. Since the range of fluids encountered is small, it was found that there was little variation in density in the samples. This allows a reliable comparison between the fluids.

One potential concern remains the size of the release. The smallest accidental release considered in risk assessments for mining machinery is usually based on a 2 mm diameter hole. At 120 bar pressure, a 2 m hole gives a flow of around 230 $g \cdot s^{-1}$.

However, to produce such a flow rate in a test situation would require testing in a very large chamber. This would sacrifice the convenience and economy of a laboratory-scale test.

The ISO 15029-2 test uses a volume flow rate of 90 $ml \cdot minute^{-1}$. Using a typical fluid density of 800 $kg \cdot m^{-3}$ this equates to a mass flow rate of 1.5 $g \cdot s^{-1}$, less than 1% of a small accidental release.

The FM 6930 and "ISO 15029-3" tests are carried out in a large, enclosed test hall environment, but even so the fluid flow rates must be scaled down from potential real-world leaks.

For example, the flowrate used in FM 6930 ranges from 5 $g \cdot s^{-1}$ to 20 $g \cdot s^{-1}$. Relatively small fluid release rates are a necessary drawback to all these tests and users of the data must be aware of this weakness of the test result when applying to real fires.

The lower flowrate does not prevent comparison between fluids but scale-up from the laboratory test to a large full-scale release must be a considered process.

While noting these caveats with respect to accidental fluid leaks, the ISO 15029-2 / “New Buxton Spray test” was still seen to provide the most reliable and useable results of the spray tests considered.

Consequently, a programme of testing to this standard was carried out with all the fluid samples submitted by the machine operators. This programme is more fully described in Appendix 4. As well as the samples supplied for this study, relevant measurements were reported by Jagger et al (2002). The data was collected during a programme of ISO 15029-2 spray testing in which additional instrumentation was deployed to allow extended measurements of heat release rate, smoke and carbon dioxide production. This data is summarised in Table 7.

Table 7: Spray test data from Jagger *et al*

Fluid	Corrected ignitability factor, RI	Flame length index, RL	Heat release rate, kW	Smoke production, (m^3 $_{\text{OD1 smoke}}$ · g^{-1})	Carbon dioxide production, (g_{CO2} / g_{fluid})
Mineral oil	5	6.7	81.7	4.9×10^{-3}	2.94
Rapeseed-based oil	7	8.7	75.9	12.8×10^{-3}	2.98
Polyol ester	10	8.3	46.7	8.6×10^{-3}	1.75
Water-in-oil emulsion	30	15.6	11.7	102.7×10^{-3}*	0.21

[*] The high figure for smoke production for the HFB fluid is due to the presence of water droplets condensed from steam produced when water in the fluid was vaporised.

The key data from the tests in the current study are summarised in Table 8. For these values, it should be noted that the ranking ignitability factor (RI) and ranking flame length index (RL) are dimensionless, and that larger values indicate a greater fire resistance.

Table 8: ISO 15029-2 test results on supplied samples

Fluid	Condition	Corrected ignitability factor, RI	Flame length index, RL
Shell Tellus (Mineral Oil)	New	7.2	9.2
	Used, hours not reported	6.4	6.2
Shell Naturelle HF-E68 (HFDU)	New	9.7	6.3
	Used, 2857 hours	10.7	8.4
Castrol Anvol SW46 (HFDU)	New	7.8	6.3
	Used,400 hours	9.5	7.6
Plantoflux (HFDU)	New	17.3	6.3
	Used, 514 hours	15.7	8.3
Condat D68 (HFDU)	New	11.1	7.1
	Used, 807 hours	5.6	8.3
Quaker Quintolubric 888-68 (HFDU)	New	12.9	7.2
	Used, 694 hours	9.0	8.3
	Used, 1212 hours	11.5	8.3
Aquacent LT100 (HFB)	New	72.5	49.0
	Used, 500 hours	57.7	47.2

The results from Jagger et al in 2002 are similar to those from the current study in 2021. The performance of 2021 mineral oil is close to the 2002 vegetable-derived oil, the 2021 polyol esters are similar to the one from 2002, and the 2021 water/oil emulsion performed even better than the 2002 example.

Taken together, the spray data in Table 8 and Table 7 plus the pool fire data in Table 6 produce important findings.

The polyol esters showed a significantly higher ignition temperature than the mineral oil.

They largely continue to out-perform the mineral oil when ignited in a spray, but the benefits are more marginal for ignitability factor and flame length index. In both spray and pool fires, the polyol esters produce more smoke.

Across the tests, the oil/water emulsion performed markedly better than the mineral oil and HFDU fluids on all counts except in measured smoke production. It is likely that the smoke measurements for the HFB fluid are misleading. For the mineral oil/HFDU fluids, the light obscuration in the rig exhaust is the result of carbon particulates from partially burned oil. For the HFB fluid, it is more likely that the obscuration comes from steam produced after evaporation of the HFB fluid’s water content rather than production of smoke from the limited fraction of oil

Potential fires involving hydraulic fluids underground

For a hydraulic fluid fire to occur underground there also needs to be some sort of failure in hydraulic fluid management that leads to a spill or leak, and the subsequent ignition of that fluid.

The preceding section discussed the way that the hydraulic fluid itself can affect the potential for fire by reducing the likelihood of ignition or sustained burning during unexpected leaks.

This section considers the likelihood of such a leak in hydraulic machinery, how the characteristics of different types of leak may affect the likelihood of an ignition, and the factors that will determine the size and duration (and thus the potential consequences) of any subsequent fire.

Potential failures of the hydraulic system

Data from a range of industries indicate that a common cause of fire is the release of a flammable fluid from hydraulic systems. Experience from previous mining incidents indicates that one of the most common causes of fire underground is fluid leaks from the hydraulic systems of mining machinery. These releases may occur from reservoirs and other components such as pumps but most commonly occur in pipework including hoses, couplings, steel pipework, control valves, seals, etc.

The nature of these releases is varied and can include:

- drips from joints;
- liquid streams from larger holes and full bore pipe releases;
- sprays from flange failures; and
- sprays from pinholes in hoses.

Releases from drips from joints and releases from larger failures may accumulate to form liquid pools, while releases from small holes at high pressure are likely to form fluid sprays.

Should these sprays not immediately encounter an ignition source, they may impinge on nearby surfaces. These may include adjacent parts of the machine, covers, body shell parts, and nearby machinery or walls. A proportion of the impacting liquid may break up further, resulting in a secondary spray of smaller droplets. The remaining liquid may adhere to the surface and eventually run off to form a pool.

Thus, the majority of leaks would result in a pool of one size or another, and some leaks may also create a spray of fine droplets.

Failure frequencies

The total number of hydraulic mining machines currently operating is relatively small, so statistical data from those machines alone would not be a good basis for predicting future failures.

Most of the hydraulic machinery that is similar in design and use to mining equipment is used in surface construction industries, so records from those machines would help inform the likely failure frequencies underground. However, in much of the surface industries there is a lack of record keeping systems for ‘minor events’. As only a low proportion of leaks result in a significant incident, most leaks are simply repaired and go unrecorded. Thus, there is little hard data on hydraulic fluid releases and component failure rates on surface construction machinery.

Therefore, this report has had to rely on older, historical data collected from the coal mining industry. That industry had a safety approach that produced more complete documentation of events such as leaks and their causes, as these were used to provide evidence of safe working. The size of the industry meant that a large body of data was available, and the industry could support efforts to collate and analyse failure statistics. The Safety Reliability Service collated data from machines in coal mines to determine failure rates for various component types. An example of these data for one type of machine, the coal shearer, is given in Table 9 (Grint, 1989). These data have been obtained from operational experience with coal shearers.

The data is given as failures per million calendar hours for a shearer. 1 million hours corresponds to 114 machine years, so the hose coupling failure rate of 11 per million hours suggests that such a failure might occur once in 10 years for a typical shearer.

It is recognised that a shearer operates in a different manner from much of the current range of mining machinery. It is largely stationary and with much of its hydraulic system exposed.

Nevertheless, it does have several similarities to machinery in current use.

Table 9: Failure rates for hydraulic components in coal shearers (Grint, 1989)

Component	Failures per million calendar hours
Hose	28
Hose coupling	11
Control valve	2
Steel pipe (including couplings)	3
Oil seals	3

The exposure of shearer hydraulic pipework/systems to damage from events such as rockfalls mirrors that of many of the Special Plant Vehicles such as drilling and cutting machines.

Although shearer travel is relatively slow, there is constant motion with resulting vibration and the potential for damage through scuffing and trapping by moving parts. These factors also occur in transport vehicles and loaders used underground.

Additionally, most current underground plant is built to similar manufacturing standards and operates at similar hydraulic pressures to a coal shearer. In fact, most current machines work at slightly higher pressures of 200-250 bar compared to the 170 bar more typical of a shearer.

The data from the shearer thus appears reasonably useful when considering likely failure rates in current mining machinery.

The data in Table 4 require some adaptation before they can be used with current mining machinery. The factors that need to be considered are machine complexity, length of pipe/hose runs and operating hours per year.

Complexity

The failure rate data are presented in terms of failure per machine per component type, with individual component failure rates aggregated over all components of the same type across the entire machine. Different machines may have more, or fewer, components of each type.

For comparison between the coal shearer used to obtain failure rate data and current mining machines, Table 10 shows the number of critical components on the coal shearer (from Grint, 1989) alongside those found on the machines observed underground during this project (extracted from the hydraulic system summaries in

Table 2).

Table 10: Estimated number of components on hydraulic systems

	Hoses	Hose couplings	Control valves	Steel pipes	Oil seals
Coal Shearer	66	136	13	0	26
Personnel Transport Vehicle	16	32	3	1	5
Light Plant Vehicle	87	174	44	9	10
Heavy Plant Vehicle	85	170	48	9	12
Special Plant Vehicle	80	160	40	8	13

Hose and pipe length

A coal shearer was large relative to most current mining machines, and it had particularly long moving sections. This means that hoses and other pipework were often much longer on a coal shearer than those in current mine machines.

As the risk of damage leading to a leak will be greater on longer runs of pipe, the pipework failure rates need to be reduced for current machines.

The lengths of hoses and steel pipe vary between machines, so any comparisons with a coal shearer are difficult to generalise.

A simple, proportional reduction in risk of damage to any individual hose or pipe run can be developed by estimating a general hose/pipe length scale for each class of machine compared with the average length of shearer hoses/pipes.

Such relative scales have been estimated based on the dimensions of typical machines. These are shown in Table 11.

Table 11: Hose and pipe lengths relative to coal shearer

Machine type	Estimated scaling compared to shearer	Length correction factor (L_c)
Personnel Transport Vehicles (typically very short hoses)	2.5%	0.025
Light Plant Vehicles	25%	0.25
Heavy Plant Vehicles	50%	0.50
Special Plant Vehicles	50%	0.50

Time in use

A further correction is required to account for the length of time the machines are in use.

The statistical shearer data is given in failures per million calendar hours. However, the vast majority of failures occur when the machine is working, and this is only a fraction of the calendar hours. Thus, the failure rate per operating hour will be greater.

Taken over each year, it was known that a typical coal shearer was in operation for only 14% of the available hours. Current mining machines are normally in use for more of the time.

To estimate typical machine operations, the downtime for each machine can be considered in two categories.

For part of the time the machine will be unused because it is out of operation, whether for planned maintenance, for unplanned repairs or because it is not needed at that time.

Even when the machine is in use, it may only be operating for part of the day.

For this study it has been assumed that a typical ‘working’ machine will be running for two eight-hour shifts per day, seven days per week.

It has been further assumed that the machine will be unused for half of the time.

Thus, the typical machine is assumed to be running for one third (33%) of the total calendar hours.

Compared with the shearer, this gives a time correction factor, T_c, given by:

$$T_c = 0.33/0.14 = 2.4$$

Assuming that failures are a simple function of working hours, the failure rates in calendar hours for current machines should therefore be 2.4 times those taken from the historical coal shearer data.

Estimated failure rates in current machines

Applying the adjustment factors for complexity, pipe lengths and operating hours to the statistical data on shearer component failure rates gives an estimate for the failure rate per calendar hour (FPH_c).

These failure rates, which are shown in

Table 12, were obtained using the relation:

$$FPH_c = F_s.(N_c/N_s).L_c.T_c$$

Where

F_c is the failure rate of that type of component in the shearer statistics;

N_c is the number of such components on the machine;

N_s is the number of such components on a shearer;

L_c is the length correction factor (used only for hoses and steel pipework); and

T_c is the time correction factor

Table 12: Failure rates (per million calendar hours) for components on each machine type.

	Hose	Couplings	Control valves	Steel pipes	Oil seals
Personnel Transport Vehicle	0.4	6.2	1.6	3.4 x 10^{-2}	1.3

Light Plant Vehicle	22.1	33.8	23.6	1.5	2.6
Heavy Plant Vehicle	43.3	33.0	25.7	3.1	2.1
Special Plant Vehicle	40.7	31.0	21.4	2.7	3.4

An estimate for the failure rate at a specific mine can be obtained by multiplying each value by the number of that type of vehicle in the mine, and then totalling the values for each component. Note that this presumes there is no difference between mines in those factors contributing to failures.

Potential release characteristics

Failure of these components will produce releases of varying characteristics, since the failures themselves are likely to encompass a range of sizes and shapes. Experience indicates that pipework failure can result in a range of different releases, such as pinholes or longitudinal cracks, for example.

Some leaks will occur in components under pressure, but others may be in low pressure or unpressurised parts of the system.

For most risk assessment methods, leaks are divided into different sizes. These are typically called small, medium and large, although the definitions for each size can vary according to the situation being considered. For the purposes of this study, small and medium holes are taken to be 2 mm and 5 mm diameter respectively. Large releases are taken as being the result of events such as guillotine failures or connector separations that result in leaks from the full pipe bore.

Historical data obtained from a range of plant/machinery experience, including process plant, indicate that leaks are divided between the different sizes in the following proportions (Thyer, 1998):

Small hole (2 mm)	60%
Medium hole (5 mm)	35%
Large (full bore)	5%

In the absence of data specific to hydraulic systems, it is reasonable to assume that this ratio will be seen with hydraulic hoses, steel pipes and couplings.

It has also been assumed that half of the small and medium sized hole releases may occur in a low pressure or unpressurised part of the system and result in a ‘drip’, while the other half are under pressure and will create a spray.

Some pressurised releases may result in jets which impinge on nearby surfaces, for example within an engine compartment. There is a risk of ignition if the surfaces are hot enough, but sprays on a cooler surface may produce streams or drips of fluid flowing toward the floor.

The large releases will lead to rapid loss of any pressure, so it has been assumed that all large releases form streams of fluid rather than fine sprays.

Thus, from all pipe/hose/coupling releases, the result is that a liquid pool and a spray are formed for 52.5 % and 47.5 % of all occasions respectively.

For leaks from valves and seals, the leak path is likely to be much longer than a hole penetrating a pipe or hose wall. Only small leaks can be produced this way, and a long path within the component will allow pressure to drop before the fluid is released. For these components it has been assumed that 90 % of leaks will result in small drips/streams and 10 % will produce small sprays.

These assumptions can be combined with the estimated failure rate data to derive frequencies for the different release types.

As an example, for a Light Plant Vehicle:

Hoses produce:

22.1 failures per million calendar hours

60% of these will be small holes

= 13.3 small holes in hoses per million calendar hours

and 50% of these will form a spray

= 6.6 small sprays from hoses per million calendar hours

Valves produce:

23.6 failures per million calendar hours all of these will be small holes

= 23.6 small holes in valves per million calendar hours

and 10% of these will form a spray

= 2.4 small sprays from valves per million calendar hours

Extending these calculations across all the potential failures gives, for each Light Plant Vehicle (per million calendar hours):

19.8 small spray events;

40.8 small drip/stream events;

10.0 medium spray events;

10.0 medium drip/stream events; and

2.9 full bore stream events.

Note: these figures imply that a typical light plant vehicle, such as a forklift truck, might be expected to see a total of 83.5 leak events per million calendar hours, equating to around one leak every 16 months.

Release properties

Small leaks

Drip releases are likely to form a slowly growing liquid pool beneath a machine or in the roadway. The size and shape of any pool formed from drips is dependent on factors including the nature of the substrate and the presence of any obstructions. Following visits to a range of mines it is considered that, due to the size of the machines and roadways, the largest pool which may be formed would have an area of ~3 m^2 (roughly 2 m across).

Pools of any greater extent are unlikely to remain undetected beneath a machine and it is likely remedial action will be taken. At the calculated spill rates, the time for formation of such a pool is ~2 minutes with the likelihood of detection increasing at longer times.

Fluid flowrates for larger leaks

For spray and full bore releases the discharge rate can be estimated using the equation:

$$m = A \cdot C_d \cdot (2\rho \cdot [P_1 - P_2])^{1/2}$$

where m = the discharge rate,

A = the area of the hole,

C_d = the discharge coefficient (0.6 for a sharp-edged orifice),

P_1, P_2 = the hydraulic system and atmospheric pressures respectively,

and ρ = the fluid density (assumed to be ~920 kgm^3).

Both the area of a leak and the driving pressure will depend on the circumstances of any single event. For the purposes of this report, representative areas corresponding to hole diameters of 2 mm and 5 mm and representative pressures of 100 bar and 225 bar have been assumed.

Table 13 details the predicted flows for these representative leaks.

Table 13: Representative release rates resulting from hydraulic systems leaks

Release	**Release rate, kgs^{-1}**	
	100 bar system pressure	**225 bar system pressure**
2 mm diameter hole	0.24	0.36
5 mm diameter hole	1.59	2.39

Spray releases

Spray releases occur when a leak breaks up into an aerosol of droplets, and the size of these droplets is an important factor in the release's subsequent behaviour.

Droplet breakup is frequently parameterised in the literature in terms of the Weber number, We, defined by:

$$We = \rho_l \cdot U_d^2 \cdot d_d \cdot \sigma^{-1}$$

where ρ_l = the liquid density;

U_d = the droplet velocity;

d_d = the droplet diameter; and

σ = the fluid surface tension.

Several correlations between the droplet size in a release and the Weber number can be found in the literature.

One such correlation was developed by DNV (2006) for use in their PHAST suite of hazard analysis software and takes the form:

$$d_d = \sigma\, We_{crit} / U_f\, \rho_a$$

where We_{crit} = a critical value for the Weber number;

U_f = the fluid velocity as it reaches atmospheric pressure; and

ρ_a = the ambient air density.

Taking a suggested critical Weber number of 12.5 together with a typical hydraulic fluid surface tension of 2×10^{-2} Nm^{-1} gives a suggested release droplet size of about 50 µm. Such an estimate must be treated with caution and used only as a guide. There are many uncertainties in the release situation, such as the nature of the failure and the resulting hole (which is unlikely to resemble a smooth plain orifice).

Recent work (Bettis, 2022) has confirmed that leaks through rough-edged holes and narrow slots form small, ignitable droplets at lower velocities than leaks through the simple circular orifices used in most laboratory studies.

Releases from holes greater than 5 mm diameter are less likely to break up into sprays. It has been assumed that leaks over 5 mm in diameter, including most full-bore pipe releases, will result in liquid streams and the formation of pools. These larger holes will give greater release rates with the possibility of pools covering an area greater than 3 m^2.

Fire development

Having derived the frequencies and characteristics of releases which may occur on the machines, the next stage in the process is to consider how an incident might develop when a leak occurs.

For example, should a pool from a non-spray release ignite, it is possible that the heat release rate from a fire under a machine will be smaller than if the same pool was burning in the open roadway. The structure and wheels of the machine will only allow a restricted supply of air to the burning pool, which may result in fuel rich and incomplete burning.

If restricted air flow was the only factor, a fire under a machine would be smaller than one in the open but of longer duration.

However, the presence of the machine may alter more than just the air flow. For example, the proximity of the bottom surfaces of a machine may result in increased radiative feedback to the pool of spilt oil, resulting in increased fuel evaporation and a larger fire size.

In considering fire risks in the wider context, other factors are also important.

For example:

- what is the likelihood of intervention to stop the spill?
- what is the likelihood that these spills will ignite?
- what is the probability of a fire being extinguished by automatic fire suppression systems?
- what is the probability of a fire being extinguished by personnel using a manually triggered system or hand-held extinguishers?

Considering each of these factors is the process of developing design fire scenarios.

The development of an incident can be broken down into several stages beginning with the release and following the incident through its key events to one of a range of final outcomes. Outcomes can range from the release being made safe without further harmful consequences up to the occurrence of a large, fully developed fire.

The possible courses of an incident can be represented using an event tree. Each fork in the event tree represents a point where there are different directions in which the incident may develop. For example, a machine operator could activate an extinguishing system or, for whatever reason, fail to activate it. In the branch where the extinguisher is activated, the next fork may be whether the extinguisher puts out the fire. At each fork, a probability can be assigned to each of the possible outcomes.

In the event trees considered here, each fork only has two possible outcomes. As one of the outcomes must occur, the sum of probabilities must be one. Thus, a probability only needs to be found for one outcome as this also defines the probability for the alternative outcome.

Event trees have been developed for releases of hydraulic fluid on the various machine types seen underground during the mine survey. Figure 3 and Figure 4 show event trees for drips/streams and sprays respectively. The key difference is that the mist of fine oil droplets in a spray release has the potential to create an explosive atmosphere, which is not possible with leaks that only create drips or liquid streams.

Incident outcomes

The complete list of potential outcomes, in order of likely severity, is:

- an oil mist explosion, which may be followed by a fire;
- a large fire which burns for an extended time;
- a small fire which burns for an extended time;
- a small fire which is successfully extinguished after a short time; and
- a liquid spill that is unignited.

There is little information available from incident experience and the literature from which to select numerical values for these probabilities due to the low number of incidents. The risk assessment, in such circumstances, is usually driven forward using judgement values selected by a fire expert. The risk assessment then incorporates an exercise to test the sensitivity of the results to the choice of values made.

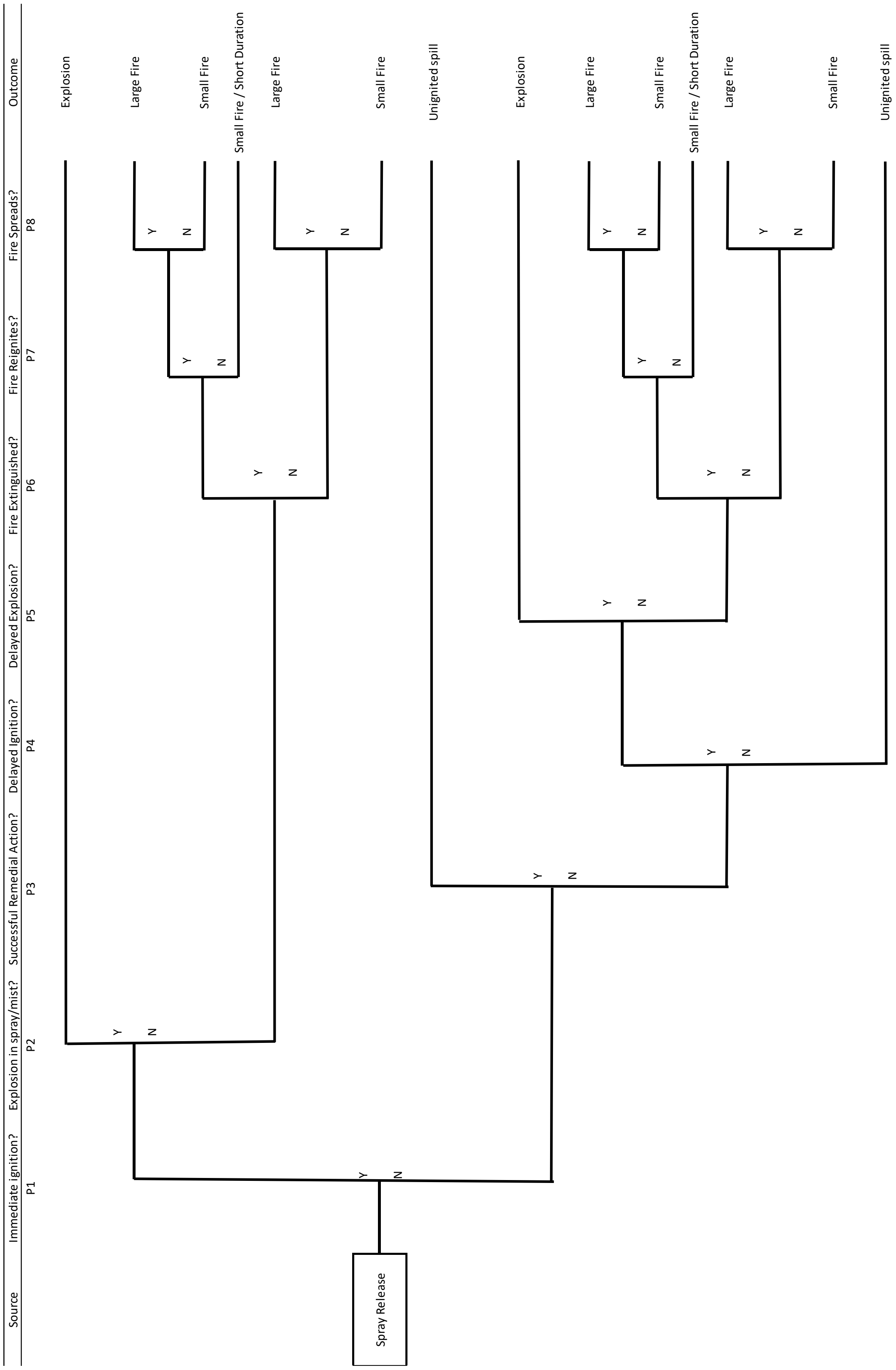

Figure 3: Event tree for spray Leaks

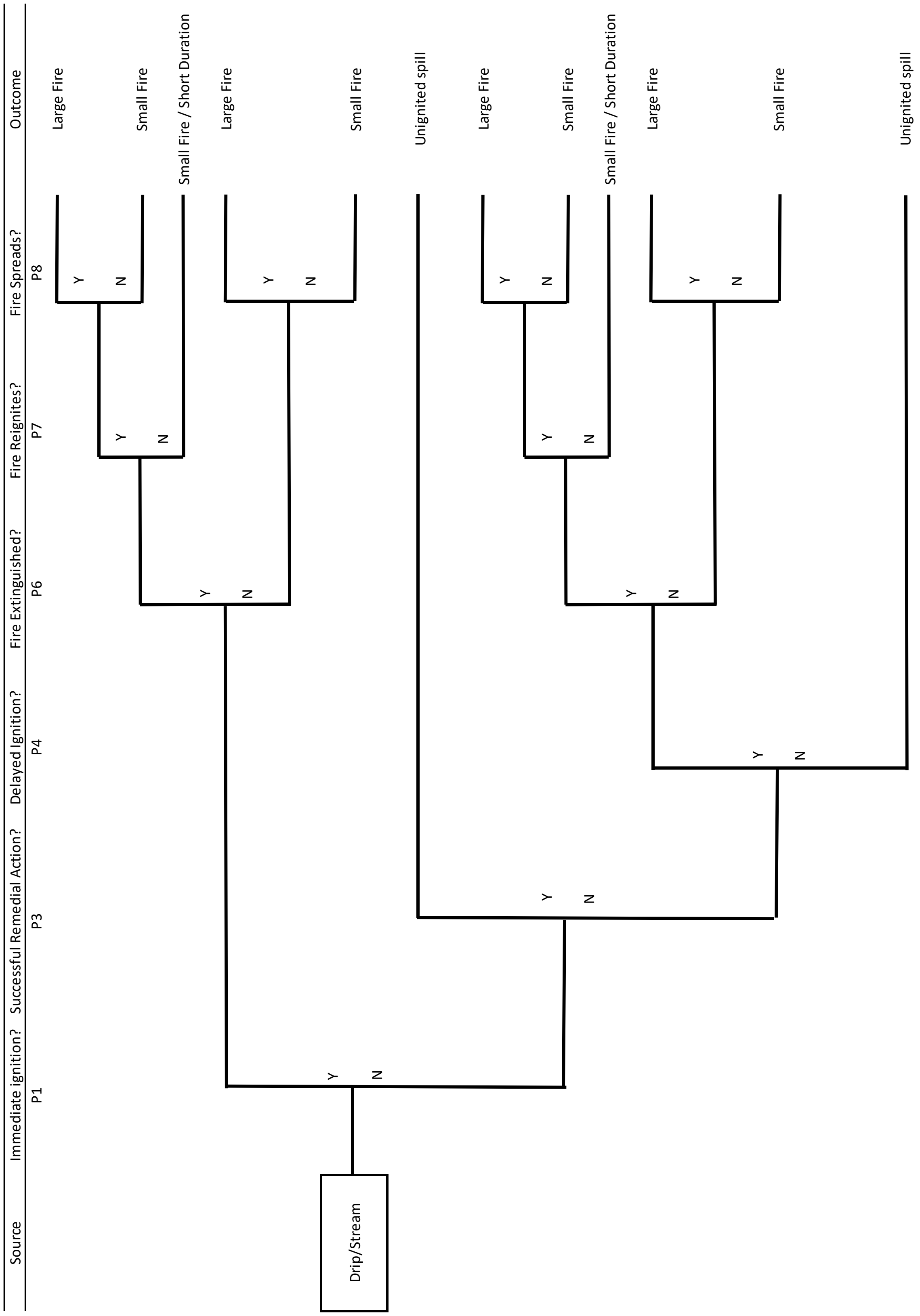

Figure 4: Event tree for drip/stream leaks

The relative likelihood of these various outcomes depends critically on the values assigned to the probabilities P1 to P8 shown in Figures 4 and 5. These probabilities are defined as:

F: the probability of a spray release rather than a drip or stream.
P1: the probability of an immediate ignition.
P2: the probability of an explosion if a spray/mist is ignited.
P3: the probability of stopping the leak before it can be ignited.
P4: the probability of a delayed ignition.
P5: the probability of an explosion following a delayed ignition.
P6: the probability of a fire being extinguished.
P7: the probability of a re-ignition of the leak once a fire has been extinguished.
P8: the probability of a fire spreading beyond the initial small pool.

The individual probabilities are combined to produce the probability for the identified outcomes.

For some outcomes the calculation is simple. For example, an immediate explosion requires that component failure leads to a spray release (probability F), which is immediately ignited (probability P1) and that ignition results in an explosion (probability P2).

Thus, the probability of an immediate explosion is given by: $P_{ei} = F \cdot P1 \cdot P2$.

For other outcomes the calculation can be more complex. For example, a delayed explosion requires that component failure leads to a spray release (probability F), which is NOT immediately ignited (probability 1 - P1), remedial action to halt the leak is NOT successful (probability = 1 - P3), a delayed ignition occurs (probability P4) and that ignition results in a delayed explosion (probability P5).

Thus, the probability of a delayed explosion is: $P_{ed} = F \cdot (1 - P1) \cdot (1 - P3) \cdot P4 \cdot P5$.

Each of these outcomes is an explosion, and for some (perhaps most) purposes a delay may not be relevant.

The overall probability of an explosion is simply the sum of each explosion probability:
$P_e = P_{ei} + P_{ed}$

Similar calculation will provide the probability of each outcome.

Specification of probabilities

Assigning values to the various probabilities is based on several factors, such as the properties of the hydraulic fluid used on the machine, the design of the machine including the type and distribution of ignition sources, the provision of manual and/or automatic firefighting equipment and the training of personnel.

This section documents the factors that were considered in assigning probabilities to each event and presents suggested values representing the best judgement of the lead author.

Probability of ignition

On a machine there are a range of potential ignition sources; some present during normal operation and some which only arise from a fault condition.

Hot surfaces

On diesel-powered machines, experience suggests that the major ignition sources for hydraulic fluid leaks are hot engine components. These are frequently located near major parts of the hydraulic system. There may be further hot surfaces present, for example hot brakes, bearings, and surfaces with electrical heating.

Fluid sprays from leaks in the confined engine compartment of a machine are highly likely to impinge on hot engine components and may adhere to them to produce a fluid film. This situation is exactly the one modelled by the hot manifold test arrangement.

Exhaust manifolds and turbochargers normally operate at around 400 °C to 450 °C. There may be times when plant is working particularly hard and the temperatures are even higher, for example if a fully loaded truck has to climb a long or steep slope. Developments in engine technology has led to increases in these temperatures, particularly as the operating pressure of turbochargers has increased, leading to hotter compressor bodies and air ducts.

There are still some items of mining plant using mineral oils. As these oils have ignition temperatures below even the normal working temperatures of engine components, the probability of a leak igniting is dominated by the probability that a release will encounter a hot surface. This will give high ignition probabilities.

The selection of a fire-resistant hydraulic fluid with an ignition temperature above the normal engine temperatures will greatly reduce this possibility of ignition. This is the major advantage of polyol esters now commonly found on current mining equipment. Tests carried out during this work indicate that the HFDU fluids generally have hot manifold ignition temperatures above 500 °C. In this case the ignition probability can be appropriately reduced as fewer, smaller surfaces will be at such temperatures, and then only intermittently.

Further testing carried out during this study also showed that fluids containing water have hot manifold temperatures above 600 °C. The use of such fluids can add an additional level of safety and will produce a further significant reduction in the ignition probability.

While the use of HFDU (or even HFB / HFC) fluids does not eliminate the possibility of an ignition, that ignition will only be possible if further abnormal conditions are present at the same time as the fluid release.

Some additional hot surfaces may occur from fault conditions.

High temperatures may be produced by frictional heating from rubbing or poor lubrication of parts such as bearings. It is even possible that a common cause may produce both a fluid leak and a hot surface. For example, an unclipped hose may rest against a rotating component which rubs and simultaneously abrades the hose to the point of failure and heats it by friction while this occurs.

Electrical heating/sparks

Electrical sources of ignition are present on almost all equipment. Electrical components are normally protected against ingress of foreign bodies, but those on vehicles in most mines are not normally designed to be intrinsically safe. Thus, an ignition could arise from an oil spray entering sparking equipment.

There is little data on the ease with which fluid releases are ignited by sparks. Jagger et al (2002) reported work with sprays from a hollow cone nozzle and found sprays of mineral oil relatively easy to ignite with energies < 1 J.

That work also found that an HFDU fluid gave little benefit over the mineral oil and could be ignited by similar spark energies. However, ignition of an HFB fluid (water in oil emulsion) required a significant increase in spark energy and an HFC fluid (water glycol) an even greater increase.

Thus, the probability of ignition by an electrical source can be reduced for HFB and HFC fluids but will remain higher for both mineral oils and HFDU fluids.

Some special items of plant are now equipped with electric traction and their hydraulics are powered by electrically driven pumps. It is likely that an increasing proportion of plant and machinery will be electrically powered in the future.

Many of the hot surface ignition sources associated with a diesel engine are absent in electric vehicles. Although there are more electrical ignition sources present these are intermittent and can be more easily controlled than hot surfaces. The probability of an electric powered machine igniting a hydraulic fluid leak is likely to be significantly lower than for a diesel-powered machine.

Ignition of pools

The ignition probability for pools of fluid is significantly lower than that for sprays and mists.

Testing by Jagger et al (2002) indicated that any hydraulic fluids in bulk quantities are extremely difficult to ignite with any ignition source up to and including open flames. The ignition probabilities chosen must therefore reflect this and, for all machine types, will be reduced from the probabilities used for sprays.

Hot works

Shorter-lived ignition sources could also arise from hot work, for example during maintenance. It has been assumed that the possibility of an ignition in these circumstances will be largely eliminated by the application of strict safety procedures and personnel well-versed in and trained to follow those procedures. For this situation the possibility of an ignition will exist only if these procedures break down.

Probabilities

The ignition probability appears in two places, *P1: immediate ignition* and *P4: delayed ignition*.

The available data does not provide any clear evidence to assign a different probability to each of these cases. The same values have, therefore, been assigned to both P1 and P4. The suggested probabilities are shown in Table 14.

Table 14: Suggested probabilities for P1 and P4 (immediate and delayed ignition)

	Small spray (2 mm)	Large spray (5 mm)	Small drip	Large stream (5 mm / full bore)
Mineral oil	0.1 (= 10^{-1})	0.1 (= 10^{-1})	0.01 (= 10^{-2})	0.01 (= 10^{-2})
HFDU fluid	0.01 (= 10^{-2})	0.01 (= 10^{-2})	0.001 (= 10^{-3})	0.001 (= 10^{-3})
HFB/HFC fluid	0.001(= 10^{-3})	0.001 (= 10^{-3})	0.0001 (= 10^{-4})	0.0001 (= 10^{-4})

Probability of explosion

Explosions are only possible for spray releases.

There is little data on the number of ignitions which result in an explosion as opposed to a fire only, so it is difficult to assign values with confidence. For spray releases any ignition could produce an oil mist explosion. The possibility depends on the droplet size, the temperature of the droplets, the volume of the mist cloud and the flammability of the fluid.

Mist explosions involving hydraulic fluids are known to have occurred in engine crankcases where the fluid is hot (for example Stewart and Jagger, 2007). However, given the low flammability of the fluid and the wide range of possible droplet sizes, an explosion in a mine is considered an unlikely occurrence.

The explosion probability appears in two places, *P2: explosion following immediate ignition* and *P5: explosion following delayed ignition*.

The available data does not provide any clear evidence to assign a different probability to each of these cases. The same values have, therefore, been assigned to both P2 and P5. The suggested probabilities are shown in Table 15.

Table 15: Suggested probabilities for P2 and P5 (immediate and delayed explosion)

	Small spray (2 mm)	Large spray (5 mm)	Small drip	Large stream (5 mm / full bore)
Mineral oil	0.1 (= 10^{-1})	0.1 (= 10^{-1})	0	0
HFDU fluid	0.01 (= 10^{-2})	0.01 (= 10^{-2})	0	0
HFB/HFC fluid	0.001(= 10^{-3})	0.001 (= 10^{-3})	0	0

Probability of successful intervention

The prospect of successful intervention to stop a leak before further harm occurs will depend initially on the rapid detection of the incident, be this by human or electronic means.

There is no evidence in incident reports on which to assess the proportion of releases made safe prior to an ignition. However, the success which personnel successfully extinguish small fires on machines before they grow suggests that the probability of successful intervention is high.

Leaks creating sprays make intervention more difficult. Two main factors decrease the likelihood of successful intervention. The larger volume and spread of spray make it more difficult to access the site of the leak and reduces the likely time delay between the leak beginning and an ignition occurring.

There is no obvious reason to suppose that the type of fluid will affect any intervention.

The intervention probability appears as *P3: successful remedial action?* The suggested probabilities are shown in Table 16.

Table 16: Suggested probabilities for P3 (successful remedial action)

	Small spray (2 mm)	**Large spray (5 mm)**	**Small drip**	**Large stream (5 mm / full bore)**
Any fluid	0.5 (= 5 x 10^{-1})	0.5 (= 5 x 10^{-1})	0.9 (= 9 x 10^{-1})	0.9 (= 9 x 10^{-1})

Probability of extinguishing the fire

A small but growing fire may be extinguished by manual or automatic means. The former involves the use of hand-held extinguishers by mine personnel. Information from the site visits suggested that all staff are trained in the use of such equipment and there is evidence from incidents of many such successful interventions.

Pool and drip fires will be easier to extinguish than sprays, particularly where this is done manually. Smaller pool fires will be easier to extinguish than larger ones, as they are easier to approach and require less extinguishing agent to be effective.

Fires in the engine compartment will be more difficult to extinguish manually. They are more likely to be sprays, they will be more difficult for personnel to detect at an early stage and the engine housing will hamper access to the fire.

Reliance must, therefore, be placed on automatic means of detection and suppression of fire in the engine compartment (or any other enclosed area).

Most equipment used underground is now equipped with automatic suppression equipment. There is little information in the literature on the methods used for design and testing of such systems, so it is difficult to assess their likely success.

Most are directional systems with a relatively small number of nozzles directed at high temperature ignition sources. The systems work either by cooling the area or by introducing materials that interrupt the combustion chemistry.

While the type of hydraulic fluid will affect the likelihood of a fire occurring in the first place, there is no evidence to quantify any difference in the ease or difficulty of extinguishing a fire if one does occur.

The probability of extinguishing a fire appears as *P6: fire extinguished?.* The suggested probabilities are shown in Table 17.

Table 17: Suggested probabilities for P6 (fire extinguished)

	Small spray (2 mm)	**Large spray (5 mm)**	**Small drip**	**Large stream (5 mm / full bore)**
Any fluid	0.5 (= 5×10^{-1})	0.5 (= 5×10^{-1})	0.85 (= 8.5×10^{-1})	0.75 (= 7.5×10^{-1})

Probability of re-ignition

Once they have been deployed, fire extinguishing systems have only a limited period of operation. Such systems do not preclude the possibility of re-ignition if an ignition source is present and either the extinguishant has time to disperse or continued leaking of fluid creates a new fire potential.

It can be expected that different types of hydraulic fluid will alter the likelihood of re-ignition in just the same way as they do for an initial ignition.

If equipment is not shut off, any ignition source present before the fire is likely to continue. Also, the fire itself may create additional ignition sources, either by leaving hot surfaces that take some time to cool down or by leaving areas of smouldering or small, concealed areas of fire that are not extinguished.

The likelihood of re-ignition is significantly reduced if there is a facility to remove the pressure from the hydraulic system either automatically on detection of a fire on a machine, or through the operator powering the machine down. This will result in a decaying release from the hydraulic system, particularly in the case of a spray, and the fuel for the initial fire will be removed.

Also, a machine fitted with a dual agent suppression and extinguishing system is less likely to experience a ‘successful’ re-ignition.

Some ‘double knock’ systems simply add a second extinguisher supplying the same fire suppression system. These are intended to be operated to provide a second chance to extinguish a fire that continues to burn, or to have a second shot in the event of re-ignition. However, such systems are likely to be of limited success as the fire has already overcome their protection once before.

In contrast, an indirect dual agent system allows a combination of agents to be used, such as dry powder and foam / water. The advantages of this allow quick knockdown of the fire followed by a cooling effect to help prevent re-ignition.

Other secondary systems provide ‘total flooding’. Rather than being directed at critical components these systems give a volume protection to the entire engine compartment, for example by reducing oxygen concentrations below those capable of supporting combustion.

The probability of re-ignition appears as *P7: fire re-ignites?*. Probabilities for re-ignition have been suggested for single shot, double shot, and single shot + total flooding systems. These are shown in Table 18.

Probabilities of fire spread

There is little data on the processes by which a limited fire involving only the hydraulic system spreads to involve other combustible parts of the machine, such as the tyres, and perhaps to eventually involve the entire machine.

The records for mines in Great Britain do not show any such occurrence, at least over the past 30-50 years. During that time frame there were probably more than 1000 fires in mines.

These have included large fires, but these have been developed from initiation factors such as hot work or conveyor belt bearing failure, rather than being associated with mobile machinery or hydraulic system failures.

As discussed earlier, between 50% and 60% of the recorded fires have involved mobile machinery. This implies that there will have been between 500 and 600 machine fires, none of which have apparently grown to be very large fires.

This suggests that the observed probability for fire spread is zero, but that even if the next mine fire happens to be a large fire originating on a machine, the likelihood will still be less than 1 in 500. It is therefore suggested that a probability for this fire spread could reasonably be taken to be between 1×10^{-3} and 1×10^{-4}.

The probability of a fire spreading to become a large fire appears as *P8: fire spreads?*.

For the purposes of this report, the value for P8 has been assumed to be 5 x 10^{-4}.

This is an assumption that only 1 in 2000 machine fires will spread to become large fires involving the whole machine and beyond.

Table 18: Suggested probabilities for P7 (fire re-ignites)

	Small spray (2 mm)	**Large spray (5 mm)**	**Small drip**	**Large stream (5 mm / full bore)**
(Single Shot)				
Mineral oil	0.01 (= 10^{-2})	0.01 (= 10^{-2})	0.001 (= 10^{-3})	0.001 (= 10^{-3})
HFDU fluid	0.001 (= 10^{-3})	0.001 (= 10^{-3})	0.0001 (= 10^{-4})	0.0001 (= 10^{-4})
HFB/HFC fluid	0.0001 (= 10^{-4})	0.0001 (= 10^{-4})	0.00001 (= 10^{-5})	0.00001 (= 10^{-5})
(Double Shot)				
Mineral oil	0.005 (= 5 x 10^{-3})	0.005 (= 5 x 10^{-3})	0.0005 (= 5 x 10^{-4})	0.0005 (= 5 x 10^{-4})
HFDU fluid	0.0005 (= 5 x 10^{-4})	0.0005 (= 5 x 10^{-4})	0.00005 (= 5 x 10^{-5})	0.00005 (= 5 x 10^{-5})
HFB/HFC Fluid	0.00005 (= 5 x 10^{-5})	0.00005 (= 5 x 10^{-5})	0.000005 (= 5 x 10^{-6})	0.000005 (= 5 x 10^{-6})
(Total Flood)				
Mineral oil	0.001 (= 10^{-3})	0.001 (= 10^{-3})	0.0001 (= 10^{-4})	0.0001 (= 10^{-4})
HFDU Fluid	0.0001 (= 10^{-4})	0.0001 (= 10^{-4})	0.00001 (= 10^{-5})	0.00001 (= 10^{-5})
HFB/HFC Fluid	0.00001 (= 10^{-5})	0.00001 (= 10^{-5})	0.000001 (= 10^{-6})	0.000001 (= 10^{-6})

Application of the model

Using the probabilities from the previous section, the probability of each outcome on the event trees can be determined. These can be combined with the frequency of the initial failure events, covered in the failure frequencies section beginning on page 27, to give predictions of the frequencies of each outcome.

Taking, as an example, the same Light Plant Vehicle that provided an example in the section on *Potential release characteristics* beginning on page 32, the frequency of a 2 mm spray leak was estimated as 19.8 events per million calendar hours.

Following the event tree and using the probability estimates for each event creates the summed probability for each type of outcome. For a typical LPV using an HFDU fluid and fitted with a 'single shot' fire suppression system, the predicted frequencies of the outcomes are (per million calendar hours):

Small fire event: 0.3 events

Large fire event: $7.3 \cdot 10^{-5}$ events

Explosion: $3.0 \cdot 10^{-3}$ events

The same approach can be used to compare the effect of using different types of fluid on the same event scenario.

Taking the 2 mm spray leak considered above, the predicted frequencies of a small fire event when different fluids are in use can be calculated as (per million calendar hours):

HFDU fluid (as above): 0.30 events

Mineral oil: 2.57 events

HFB/HFC: 0.03 events

In this case the benefit arises through the different values chosen for ignition probability of the different fluids. These feed directly through to the estimated fire frequencies with those for a mineral oil being an order of magnitude greater than those for HFDU fluids and those for HFB/HFC fluids an order of magnitude less.

When considering the results from such modelling, it is important to remain aware of the fact that the probabilities being used are based on a small amount of data and ‘best judgement’. This means that the picture could easily change significantly if further evidence and future events reveal that these probabilities required modification.

For example, the model could be used to assess the benefit of requiring a ‘second-strike’ total flooding fire suppression system. The current probabilities assume a relatively high probability of success for the initial extinguishing system and a relatively low probability of re-ignition. This means that the sequence of events rarely requires a second strike, and thus the overall benefit could be seen as quite low.

However, if only those rare re-ignition events are considered, then a second-strike system is likely to be of considerable benefit.

Considering overall risk alone does not determine whether a control measure will reduce a risk to the required ALARP level.

Assessment of the consequences of mining equipment fires

Introduction

The preceding sections have proposed a range of failure scenarios resulting in the release of a hydraulic fluid. The event trees allow the development of these incidents to be followed and the likelihood of a range of outcomes assessed. Sometimes the outcomes will be minor. At other times a release could lead to an explosion or one of a range of pool and jet fires. Such events may even spread to involve other fuels on the machine to produce very high consequence events.

This section considers the characteristics of these outcomes to assess the potential to harm people in the mine, both those close to the incident and those who may be affected further away. The types of harm that are considered are:

- ‘Blast’ injuries arising from the pressure waves produced during an oil mist explosion;
- Burn injuries from the heat generated in a fire or explosion; and
- Acute health effects from exposure to toxic combustion products and smoke.

Explosions

In some situations, an ignition of a fluid spray release as an oil mist could give rise to an explosion. Such explosions occur in enclosed spaces such as engine transmissions and sometimes in the open, but the latter are very rare. Grint (1989) discussed the case of oil mist explosions and estimated that an ignition would lead to minimal pressures of only a few tens of millibar and the overall hazard would be dominated by any subsequent fire.

However, when Thyer and Jagger (1991) examined Grint’s assumptions they noted that the pressure prediction was based on data taken in the open air. They argued that the decay of any overpressure in a tunnel would be less rapid than suggested by Grint, and the shock wave would propagate to much greater distances. As a result, they concluded that theoretical over pressures in the region of 1 bar might be possible.

Nevertheless, the low flammability of the hydraulic fluids now commonly used underground and the likelihood that any unintentional spray release will comprise a wide range of droplet sizes means that, though such explosions may be theoretically possible, in practice high explosion pressures are unlikely.

Fires

Pool fires

Many hydraulic fluid leaks will produce a spreading liquid pool beneath a machine and/or in the roadway.

It is suggested that the maximum practical size of such a pool is ~3 m^2, limited by the release rates and the likelihood of a leak being stopped or reduced once the pool has grown to a size where it can be spotted.

In general, pools of hydraulic fluid are difficult to ignite but, if ignited, they can produce a significant fire with high potential for fire spread to other fuels/combustible materials in the vicinity.

For this kind of pool in the open air, there is a wealth of experimental data reported in the literature with well-established correlations for such properties such as heat release, flame height and radiative flux.

Even in the confines of a mine roadway, there will be plenty of air to support a fire of this size and the combustion will be fuel-controlled (limited by the area of burning fuel). Jagger et al (2002) examined the behaviour of hydraulic fluid pools in a small tunnel, reporting properties such as smoke and toxic species production from a range of fluid types.

These data can be applied to the representative fluid leak situations developed earlier in this report. Table 19 summarises the results that are relevant to the safety of personnel in mines.

Further pertinent data on hydraulic fluid pool fires has been given earlier, in Table 6.

Table 19: Predicted characteristics of hydraulic fluid fires

Fire scenario	Burn rate $kg\cdot s^{-1}$	Heat release rate MW	Flame length m	Radiative surface emissive power $kW\cdot m^{-2}$
3 m^2 pool	0.1[1]	1.5	1.4	70-100
Spray fires (2 mm – full bore)	0.2-3	3.5-73	4-16	150-200

[1] Here the burn rate has been taken for a pool on a rough/pebbled surface as suggested by Ingason (2005)

In some circumstances a pool fire beneath a machine may behave differently from one in the open. The confinement could reduce the air supply to the fire and the presence of the vehicle floor may increase radiative feedback to the pool. As a result, there may be locally ventilation-controlled burning with a reduced burn rate and increased production of both smoke and carbon monoxide. However, such effects are affected by many factors, including the geometry of the vehicle, the airflow around it and the geometry of the immediate surroundings. This complexity means that such fires are difficult to predict and replicate experimentally so there is little data to identify the resulting hazards.

Spray/jet fires

Sprays of fluid are most likely to occur within the confines of the machine, which is also where most potential ignition sources are to be found. Calculations based on the proposed example failures in mining equipment hydraulic systems suggest fluid release rates might range from around 0.2 $kg \cdot s^{-1}$ to around 2.4 $kg \cdot s^{-1}$.

Such spray releases can produce flames several metres in length and of a volume likely to fill the engine compartment of mining machinery. Figure 5 shows a spray fire from a release of a mineral oil based hydraulic fluid at around 100 bar. The flowrate is small compared with the example leaks, only around 0.05 $kg \cdot s^{-1}$, yet the flame is well over 2 m long.

Spray fires are thus likely to ignite any other combustible materials present.

Table 19 also summarises the properties of spray fires relevant to a hazard assessment.

This information has been obtained from two sources:

- experiments carried out to quantify the hazards from chemical process plant (Lees, 1996); and
- runs of the release code PHAST (DNV, 2008) which includes a module for computing the effects and properties of a jet fire.

However, these figures are likely to over-estimate the dimensions of a jet flame since most of the available data is for process fluids rather than hydraulic fluids which are generally of higher molecular weight and are likely to produce sprays with larger droplet sizes.

Additional relevant data from extended small-scale testing on hydraulic fluid sprays by Jagger et al (2003) has previously been given in Table 7. These data identify the differences between spray combustion for a range of hydraulic fluids.

Figure 5: Hydraulic fluid (mineral oil) spray fire

Again, any large fire within the confines of an engine compartment may be restricted by a lack of oxygen, resulting in ventilation-controlled burning. The rate of combustion will then depend on several factors, including the shape of the compartment and the details of the openings. There appears to be no published information on such situations and therefore no data available to allow their consideration in hazard assessments.

Large fires

Should intervention fail to make the release safe, or if attempts to extinguish the fire are unsuccessful, then the initial fire has the potential to propagate to other fuels in the vicinity to produce a very large fire, perhaps involving the entire machine and beyond.

There has been significant work in this area, for example the work of Beard and Carvel (2005). This has been driven largely by the need to parameterise fires for the design of transport tunnels. Several large-scale experimental programmes have been carried out on various vehicle fires, including cars (Park et al, 2019), heavy goods vehicles (HGVs) and railway vehicles (both of the latter are considered in Carvel and Marlair, 2005).

Of particular relevance here, a series of papers by Ingason and co-workers (Ingason, 2009; Hansen and Ingason, 2013; Hansen, 2019) have examined the heat release from vehicle fires.

These studies have attempted to build deterministic heat release curves using a quantified fuel inventory on each vehicle and postulating a chain of events starting with an initial pool fire beneath the machine, in which fire spread occurs as each succeeding fuel source is exposed to a critical heat flux for ignition. These critical heat fluxes are independently determined from laboratory test data.

Ingason and Hansen also used this sequential approach to develop analytical expressions in an attempt to predict the time variation of the heat release for fires on vehicles underground. These were based on experiments focussed on transport tunnels, rather than mines, and included fires on a range of road vehicles from passenger cars to buses and HGVs.

These may have some relevance, for example mine personal transport vehicles (PTV) are of a similar size to passenger cars.

The evidence from experimental tests with cars indicated that the heat release rate peaks anywhere between 3 and 9 MW with a generally accepted value around 4 MW. The initial growth rate is dependent on where the fire started and on details such as whether the windows were open at the start of the fire. Ingason has also suggested a mass optical density of smoke from a burning car of 381 $m^2 \cdot kg^{-1}$ – this is around one tenth of the smoke levels from an equivalent pool of burning oil.

Some have proposed a rapid quadratic fire growth ($\sim\alpha t^2$ where $\alpha = 0.01$ kWs^{-2}) followed by a slow quadratic decay ($\alpha \sim 0.001$ kWs^{-2}). This would give the heat release curve shown in Figure 6. This may be a reasonable model for a mine PTV although, unlike most private cars, some PTVs used underground include a fire suppression system.

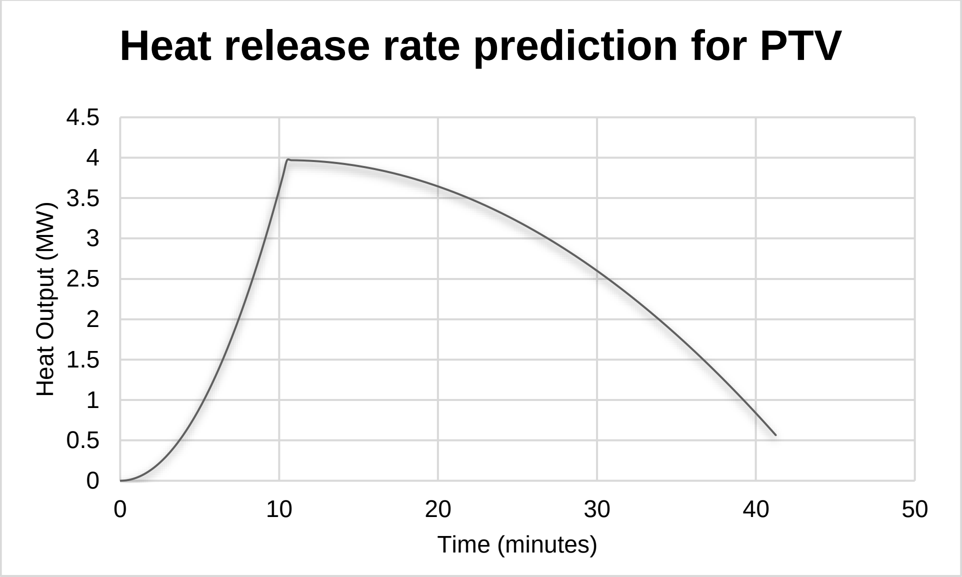

Figure 6: Modelling heat release for PTV based on typical road car

Hansen and Ingason have also reported experimental fire tests on vehicles used underground in mines in a real rough wall mine. Fire tests were carried out on both an Atlas Copco Drill Rig and a much larger Toro Loader.

The loader was a much larger vehicle than the drill rig. From the viewpoint of a fire, the main differences between the two vehicles were:

- the mass of the tyres - these were much larger on the loader;
- the hydraulic fluid system – this was more extensive on the drill rig; and
- the volume of diesel fuel that could be on board.

These tests can be placed in the context of the earlier categorisation of vehicles found in mines in Great Britain.

It is tempting to identify the Hansen and Ignason Loader test with the Heavy Plant Vehicle vehicle category and, taking account of vehicle dimensions, to align the Drill Rig with the Light Plant Vehicles.

However, with its extensive hydraulic system, the Drill Rig may have more similarity with the Special Plant Vehicle category, although many of the latter have electric rather than diesel traction.

Using data from a variety of sources, including openly published machine information and an analysis of the various Hansen and Ingason tests, a proposed fuel inventory typifying the four categories of mine vehicles is given in Table 20.

Table 20: Representative fuel inventories of the various mine vehicle types

Fuel	Heavy Plant Vehicles	Light/Specialist Plant Vehicles	Personnel Transport Vehicles
Diesel Fuel (litres)	280	100$^{(1)}$	50
Hydraulic Fluid in tanks (litres)	500	350	15
Hydraulic Fluid in hoses (litres)	70	150	2.5
Hydraulic hoses (kg)	170	390	5
Tyres (kg)	1560	250	75
Cab seats (kg)	10	10	25
Other cab plastics (kg)	5	5	15
Bodywork plastics (kg)	20	20	20
Electrical Cabling (kg)	1.5	25$^{(2)}$	2.5

[1] *This figure is zero if the vehicle has electric traction*

[2] *This figure rises to 450 kg if a power supply cable reel is used.*

For Hansen and Ignason’s experiments (Hansen and Ignason, 2013), a section of a mine was instrumented to measure local and downstream conditions in the mine including the heat release rate. Each vehicle was fitted with sensors to identify the course of fire development.

The heat release from the two vehicles gave results that might appear counter-intuitive given that the smaller drill rig had only half the total fuel inventory of the loader.

In both tests, the initiating fire was a pool fire beneath the rear engine compartment.

The loader fire peaked at around 14 MW after about 10 minutes. The initial peak included the burning of the initial pool fire and fire spreading to one pair of tyres. This was followed by a rapid decay to about 6 MW after 20 minutes. Around the burning tyres, the fire spread slowly until the remaining pair of tyres caught alight, creating a second peak of 8-9 MW at 45 minutes. The fire then slowly died down over a further 3 hours.

In contrast, the drill rig fire showed only a single peak of heat release rate, but this reached 25 MW after 20 minutes as the hydraulic hoses burned and allowed the large inventory of hydraulic fluid to leak into the fire. As the fluid was consumed, the fire decayed steadily for the next 40 minutes to give a fire of about 1 hour total duration.

Thus, it appears that fires on mine vehicles can develop in very different ways depending on when the different fuels become involved.

The most recent of these papers (Hansen, 2019) includes predictions for heat release over time for several mine fire scenarios. These are based on the experimental results from the mine vehicles, an assessment of the fire loading and different types of fuel found in a range of mine vehicles, and the sequential modelling approach originally developed for road vehicles.

The scenarios that were modelled cover a range of different machines and initial fires. Examples of scenarios based on the same machine (a large dump truck in a roadway facing down a shallow slope) are shown in Figure 7 and Figure 8.

The prediction shown in Figure 7 shows the heat release for Hansen’s scenario #1, an initial pool fire beneath the machine close to one front wheel. The initial heat output for the first five minutes or so is due to the heat output from this pool. This is followed quickly by a rise in heat output as the fire spreads to the nearest tyre. The fire slowly spreads to involve the other front wheel, creating a second peak starting an hour or so later as that tyre burns. In this case the fire does not spread to the rear set of tyres.

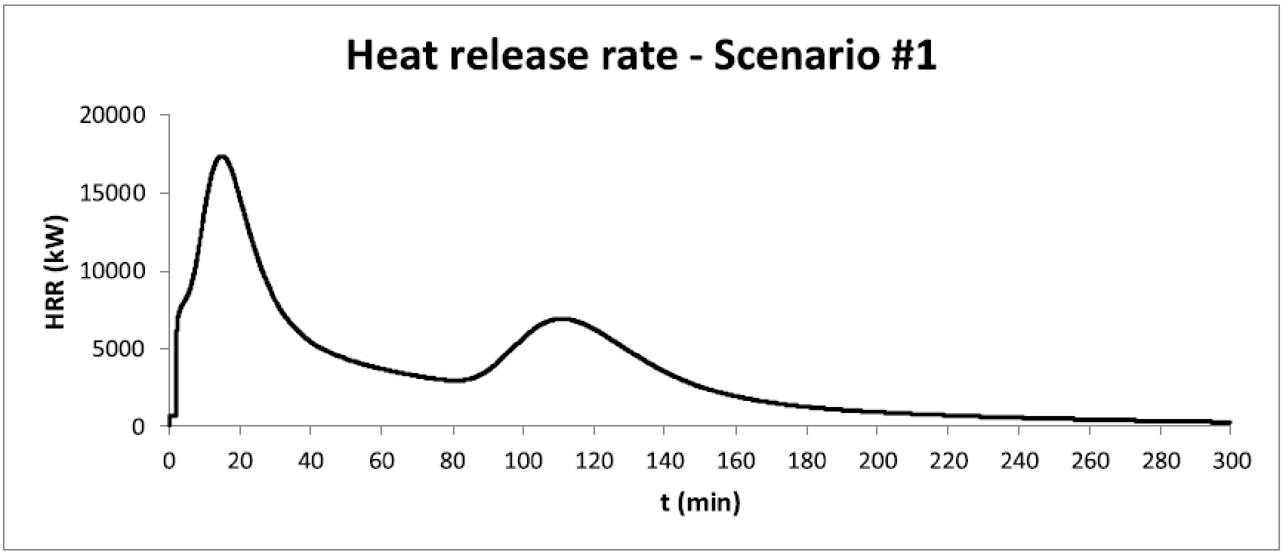

Figure 7: Deterministically constructed heat release curve for a mining truck *(from Hansen, 2019)*

In Figure 8, Hansen's scenario #7, the situation is the same as scenario #1, but in this case a second truck is stopped a little further down the slope, immediately ahead of the truck on fire. The initial events closely follow scenario #1, but for reasons that are unexplained in the original paper, the spread of fire to the other front wheel takes much less time. After around 90 minutes the fire spreads to involve the second truck. On the second truck, the fire spread to all four wheels and to the hydraulic system, creating a much larger fire. This resulted in the highest heat output of around 30 MW.

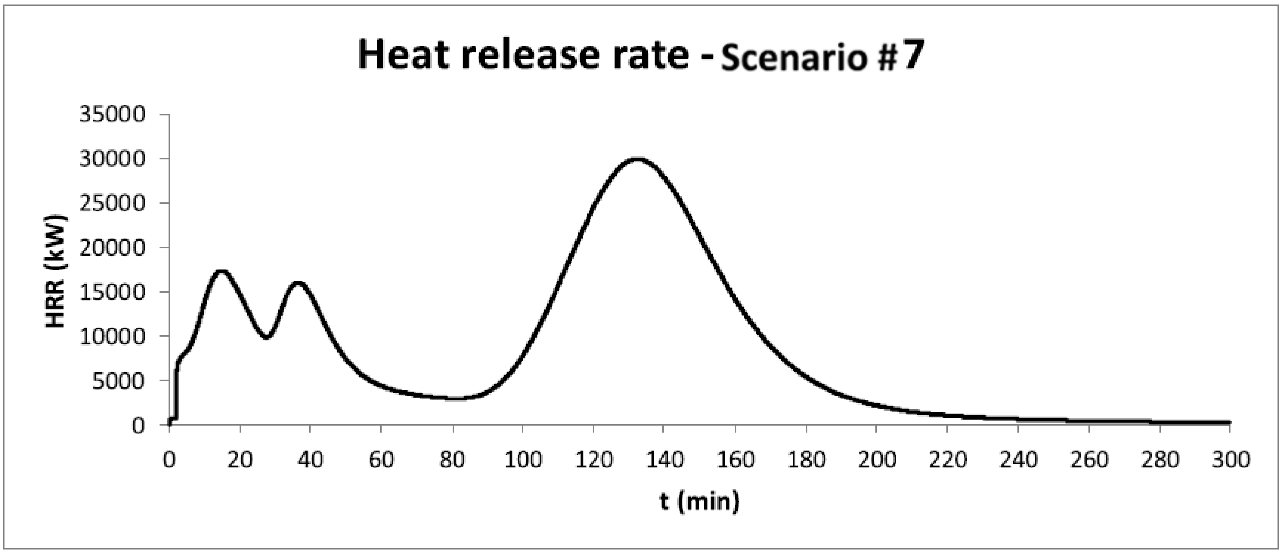

Figure 8: Deterministically constructed heat release curve for a mining loader *(from Hansen, 2019)*

Thus, the findings from Hansen's modelling identified a number of possible fire scenarios from a single vehicle. This is mirrored in the test results, although relatively few tests have been carried out on vehicles of any one type.

However, some general lessons can be drawn:

- Fire durations may range from 1 hour to 4 hours;
- The peak heat release rate can vary between 12 MW and 25 MW; and
- The peak heat release rate does not necessarily correlate with the physical size nor the total fuel inventory of a given vehicle.

For vehicles found in UK mines, therefore, it does not seem possible to draw a meaningful distinction between HPVs, LPVs and SPVs in terms of fire behaviour.

An appropriate but conservative worst-case choice for a fire on any of these vehicles would be to assume a peak heat release rate of 25 MW and a fire duration of up to 4 hours.

Consequence assessment models

In a mine, large fires pose a hazard to those in the immediate vicinity, whether from burns due to direct flame contact, thermal radiation or hot fire gases, or the effects of inhalation of hot smoke and toxic combustion products.

The hazards they pose can also propagate away from the fire location to more distant areas of the mine. Smoke and toxic combustion products can move throughout the mine, driven by both the mine's own ventilation systems and/or air movement caused by the fire itself.

For hydraulic oil fires, the main toxic product will be carbon monoxide (CO). Fires in plant may produce other toxic gases, primarily from burning of polymers. These will be in relatively low amounts but can include gases that are highly irritant, causing coughing and watering eyes in unprotected people – this will then impact on their ability to escape by reducing movement speeds and hampering navigation.

A number of tools have been developed to predict the spread of any fire products (often simply called "smoke") throughout a mine.

Models originally developed for designing mine network ventilation have been adapted to this task. MFIRE is a well-established example of such a model, with the inclusion of pollutant transport and/or sub-models to specifically describe the near-field of a fire (Danzinger and Kennedy, 1982).

Models based of the methods of Computational Fluid Dynamics (CFD), which are able to model the near-field surrounding the fire in great detail, have also been applied to the problem, for example Lea (1995) who predicted the conditions arising from an HGV fire in the Channel Tunnel.

Such approaches can be too complex and resource intensive for use in a more basic risk assessment, as multiple applications of a model are required to predict the consequences from a wide range of different potential fires.

Ingason (2005) has suggested a much simpler one-dimensional approach. This approach considers the near- and mid-field of the mine predicting the conditions both up- and down-stream in a single tunnel only. Details of such a model are outlined in Appendix 5.

Effects on people within the mine

A fire, and particularly a large fire, will obviously impact on those close to the source of the fire. If initial attempts to extinguish a fire are unsuccessful, those nearby may have the chance to escape the immediate area while the fire is developing.

However, the confined environment of a mine means that heat, smoke and toxic gases will spread into a growing area away from their source. The fire could affect people at a significant distance from its actual location and may prevent some personnel from escaping to safety.

Using a model such as that described in Appendix 5, when combined with the fire parameters summarised in Table 19 and Table 6, allows the conditions downstream of the fire to be calculated and thus allow the hazards to personnel to be assessed.

As an example, the conditions downstream of several potential fires in a roadway with a 5 m by 5 m cross-section and a ventilation rate of 2 $m \cdot s^{-1}$. For the purposes of calculating thermal effects, the background roadway temperature has been assumed to be 15 °C.

For simplicity in the calculations, rather than model a fire that slowly grows to a peak and then decays away, it has been assumed that the fire is at a steady state with a constant heat output. This assumption is not unreasonable for some fire scenarios, as it approximates to a fire with a very rapid growth phase during which all fuels become involved. Such fires have been observed with some vehicles, particularly passenger cars, and will also be characteristic of small- or medium-sized pool and jet fires.

Steady state smoke and gas concentrations will then be established in the tunnel, as any time variations are the results of changes in the size and fuel mix of the fire.

Table 21 gives the results of calculations of conditions at several distances downstream of the fire.

The level of visibility is calculated assuming the smoke is well mixed in the roadway. As smoke moves away from the fire, its density will stay largely the same. The result is that a predicted reduction in visibility will affect a growing area of the mine, but the predicted visibility will be the same throughout the smoke-filled areas.

Similarly with toxic gases, a growing area of the mine will be filled with fire products, but the gas concentration will be largely uniform within the affected areas.

The “Stratification” rows under the hazards show whether the model predicts a definite layer of hot gas and smoke at the top of the roadway, or whether the smoke and gases mix more generally throughout the roadway.

This depends on the interaction between the buoyancy forces due to the fire and inertial forces due to the forced ventilation. A strongly stratified flow implies the dominance of buoyancy effects due to the temperature gradients and generally results in separation of the flow into a buoyant smoke layer at the ceiling and a clear layer at the floor. This breaks down with increasing distance from the fire until at some distance, which varies according to fire strength, the flow in the tunnel is well-mixed and tends toward homogeneity.

In the modelling, the degree of stratification is determined by reference to the Froude number (Appendix 5).

The degree of stratification will alter the exposure of people to the hazards from a fire, particularly in larger roadways. For example, if smoke is concentrated near the roof of the roadway and that roof is well above head height, then people escaping along the roadway may still be in the clear air below. On the other hand, if the smoke is mixed throughout the roadway then visibility will be reduced, and escape will be slower and more difficult.

However, it is not always certain that stratification is beneficial. Hot smoke and gases will be at a much higher temperature if they are in a narrow layer at the ceiling than if they are mixed with cool air in the roadway. The heat given off by the hot layer may affect people’s ability to escape particularly in roadways with lower roof heights where the hot layer is closer and may even require people to bend over or crawl to avoid the high temperatures.

As discussed previously, the likelihood of a fire starting with an HFDU fluid is much lower, particularly for hot surface ignition, but if an HFDU fluid does catch fire it then burns in a similar way to a mineral oil. Jagger et al (2003) found no significant difference in the production of both carbon monoxide and smoke when comparing mineral oil and HFDU fluids. The calculations have been carried out using figures for a mineral oil but would be similar for an HFDU fluid.

Table 21: Modelled tunnel conditions downstream of representative fires

Fire	Heat output	Hazard	Distance from fire, m					
			10	25	50	100	250	500
3 m² pool	1.5 MW	Temperature (°C)	33	31	28	24	19	17
		Carbon Monoxide (ppm)	0.9					
		Visibility (m)	2.0					
		Stratification	Weak					None
Small spray	10 MW	Temperature (°C)	119	107	90	65	30	19
		Carbon Monoxide (ppm)	5.7					
		Visibility (m)	0.27					
		Stratification	Strong				Weak	
Large vehicle fire	25 MW	Temperature (°C)	273	242	200	139	50	23
		Carbon Monoxide (ppm)	14.3					
		Visibility (m)	0.11					
		Stratification	Strong					Weak
Large spray	75 MW	Temperature (°C)	792	701	567	384	117	33
		Carbon Monoxide (ppm)	42.9					
		Visibility (m)	0.04					

Fire	Heat output	Hazard	Distance from fire, m					
			10	25	50	100	250	500
		Stratification	Strong					

Effect of toxic gases and toxic smoke

Due to the relatively low yields of carbon monoxide obtained when these fluids combust, the toxic hazards are quite small. For all but the largest fires, the predicted levels of CO are below the workplace exposure limit for mines (even using the lower level of 20 ppm that will apply from 2023). If the mine has a background level of CO, for example from normal plant operation, any CO from the fire will add to this.

The toxic effects of chemicals in the smoke particles are not well-known, but it is likely that they could make a significant contribution to the toxic load and incapacitation, particularly if the fire gases contain irritants. With the concentrations of smoke implied here, it would be advisable to take this into consideration in a more detailed study.

Effect of smoke

The predicted level of smoke infers a significant loss of visibility.

Assuming full mixing across the tunnel cross-section, only for the small pool fire would sufficient visibility be maintained to allow ready evacuation.

For the other fires, evacuation would be difficult with visibility reduced to the point where signs and direction markers would be very difficult to discern.

Effect of heat

Close to the fire, the main effect will be thermal radiation directly from the flames. However, this falls off quickly with distance; dropping by a factor of four if the distance is doubled. Further away, heat effects will be from hot gases mixing with the air in the roadway and increasing the ambient temperature for people escaping.

HSE’s preferred measure of acute thermal effects is the number of thermal dose units, which combine both the level of thermal radiation and the time of exposure. A Thermal Dose Unit (TDU) is 1 $(\mathrm{kW{\cdot}m^{-2}})^{4/3}{\cdot}\mathrm{s}$. It is widely accepted that the effects of thermal radiation on the human body correlate well with this measure of dose (for example O’Sullivan and Jagger, 2004).

HSE sets a dose level of concern of 400 TDU for the general population.

Exposures have been computed for personnel evacuating from a fire. The calculations cover people starting at specified distances from the fire and, after an initial reaction time of 10 s, escaping at a walking speed of 1 $m \cdot s^{-1}$. This escape speed may seem low, but it has been used previously in similar studies (Thyer and Jagger, 1997) and is based on studies of actual walking speeds in smoke-filled environments and when wearing self-rescuers. For the example, the escape route is assumed to end at the tunnel exit or a suitable refuge that is located 500 m from the fire.

The thermal effects are calculated from the direct thermal radiation when close to the fire and then the conservative assumption of a well-mixed flow with the evacuee enveloped in hot gases. The atmosphere in the roadway is taken as being at the temperatures given in

Table 21 and assuming a gas emissivity of 0.1.

Table 22 presents values for thermal hazards to which a person will be exposed if they are initially located at a given distance from the fire and choose to escape along the roadway away from the fire. These have been calculated using the predicted temperatures listed in

Table 21 (which are reiterated in the table). The table is coloured to indicate conditions that are hazardous (possibly fatal) in red, survivable in green and marginal (likely to be survivable for fit adults if they are able to escape to safety) marked in orange.

The radiant heat exposure appears to be less of a hazard than the average temperatures in the roadway. The larger fire events would be harmful to anyone close to the fire when it is fully developed.

The figures for thermal exposure in Table 22 indicate that any person located within 50 m of a large spray fire will suffer a significant thermal dose sufficient to make any escape a difficult proposition. For those initially ca 25 m or less from the fire, there is a high chance of death.

The risk of this happening can be inferred by combining these results with the frequencies of occurrence of the relevant fire computed in the section on *Specification of probabilities*.

It should be recalled that these exposures are based on time after the fire has reached its peak. For many fires, there will be a period of several minutes during which the fire is growing. For example, the PTV (passenger transport vehicle) fire depicted in Figure 6 takes 10 minutes or so to reach its peak size.

It is expected that in most cases even people in the “hazardous” zone will be able to escape to safety before the fire grows to a size that could prevent this.

In the case of spray fires, the full extent of the fire can be reached very quickly, in many cases flames can expand to their maximum extent in just a second or two. This will particularly affect people close to the fire. Further away, there will be some delay before the hot gases reach any given location, allowing at least a little extra escape time.

Table 22: Hazards calculated for example roadway fires

Fire	Hazard	Distance person starts from fire (m)					
		10	25	50	100	250	500
3 m² pool (1.5 MW)	Thermal (TDU)	155	151	146	137	120	74
	Temperature (°C)	33	31	28	24	19	17
Small spray (10 MW)	Thermal (TDU)	224	209	191	166	133	77
	Temperature (°C)	119	107	90	65	30	19
Large vehicle fire (25 MW)	Thermal (TDU)	539	453	358	257	161	82
	Temperature (°C)	273	242	200	139	50	23
Large spray (75 MW)	Thermal (TDU)	9509	6461	3622	1473	314	98
	Temperature (°C)	792	701	567	384	117	33

Other risk assessment techniques

The assessment described above includes relatively complex calculations for the likelihood of fire events and prediction of the consequences should they occur.

Other simpler risk assessment techniques are available that may be more appropriate if, for example, there is no requirement to perform a full consequence assessment and the need is merely to compare the safety performance of two different fluids in a particular end-use situation.

Jagger et al (2003) described a risk indexing method in which a ‘risk score’ or ‘risk value’ can be derived from a number of predefined attributes, weighted according to their impact on safety.

A risk score, S, can be derived by adding the weighted values, using the equation:

$$S = \sum_{j=1}^{n} w_j r_j$$

Where:

$w_j =$ weighting of n attributes j

$r_j =$ normalised value of attribute j

Several attributes, for example ignition temperature, burning rate and smoke production, are chosen to characterise each situation. The attributes can be selected based on the important aspects identified in fire scenarios or loss statistics. The weights assigned to each attribute can be derived through an assessment of probabilities or directly from practical evidence such as major incidents or experimental test work.

In these schemes numerical values are introduced for each attribute using normalised scales to give r_j values. The weighting values, w_j, are chosen to give the anticipated likelihood and consequences in appropriate incident scenarios.

The impact of a change in any attribute can then be readily assessed by recalculating S.

This method was successfully employed by Jagger et al to compare the use of different fluids in different end-use environments.

Controls for Hydraulic Fluid Mine Fires

Despite the low occurrence of fires from hydraulic fluid releases from hydraulic systems, and the fact that there have been no large fires in recent years initiated in hydraulic systems, there are credible fire events with potentially severe safety consequences.

An analysis of using the results from the survey of equipment and application of the risk assessment technique developed during this project highlights the areas where existing controls are most effecting and identified potential areas for further improvement.

The risk assessment indicates that the most effective method of reducing the chances of a fire is to reduce the ignition probability. Minimising the potential for interaction of fuel and ignition source will contribute to this.

As the fuel source of concern here in is an unintended leak of hydraulic fluid in an operating machine, controls that reduce the likelihood of leaks will play a significant role in reducing fire risks.

Reducing likelihood of leaks

The failure rate data (as shown earlier in Table 9) show that failures in hoses and their connections are the most likely sources of fluid leaks. During the site visits it was noted that some hoses were sheathed with Kevlar tape, particularly where they were in areas with potential exposure to falling rock. Extending such shielding to other areas, for example to sections of hose which may be subject to mechanical abrasion, will reduce the likelihood of damage to the hose itself, and therefore the risk of a fluid leak.

One of the most important factors when operating hydraulic mobile plant is to have a suitable maintenance scheme including pre-use checks. Over the past few years, many mines have adopted a ‘no leak’ policy. If a leak is detected the plant does not operate until it has been repaired, irrespective of where a hose or joint is leaking.

In addition, shields covering joints may also provide significant risk reduction. This measure is widely used elsewhere, for example in the power generation industry, although often on larger bore pipework. These ‘spray guards’ do not prevent a leak occurring at the joint, but rather channel the leak into a slow drip or stream and prevent even a high-pressure leak from forming a jet of sprayed fluid. This means that the worst case is a pool immediately below the joint, rather than a growing cloud of fine droplets. The possibility of an explosion is eliminated, the likelihood of the fluid reaching a more distant ignition source is reduced and the likelihood of ignition at any source is reduced as pools require more energy input to ignite.

While the number of leaks can be reduced, there will always be a residual possibility of them occurring.

Because of this, it is also important to manage the control of ignition risks. This can be done by controlling the number of ignition sources.

Ignition sources

It is impractical to eliminate ignition sources such as hot surfaces in the engine compartment and electrical components and junction boxes with the potential to produce sparks and arcing.

However, such ignition sources can be shielded to prevent contact with hydraulic fluid leaks or sprays. This can be done as part of the original design, or shields can be retrofitted by the end users.

Type of hydraulic fluid

The area where simple changes could produce the most significant risk improvement is with the type of hydraulic fluid used in the machines.

Three types of fluid were found in use: mineral oils, HFDU fluids (polyol esters and biodegradable fluids) and HFB fluids (water-in-oil emulsions). By far the most common of these were HFDU fluids.

There have been clear improvements in recent years through the widespread adoption of HFDU fluids. However, during the site visits it did not appear to be generally recognised that safer fluids are available, and there appeared to be an incorrect perception that using HFDU fluids largely eliminated fire risks.

The area where HFDU fluids provide significant benefit is in cases where the fluid might be ignited by a hot surface (such as engine exhausts, turbocharger outlets or faults such as overheating bearings). The hot surface ignition temperature for typical HFDUs is around 100 °C higher than that for mineral oils. As a result, the ignition temperature is above the typical temperature of the hot surfaces normally found in mining machines. This makes the ignition of fluid leaks within the machine far less likely.

There is limited data on spark ignition for polyol esters, but other HFDU fluids are already known to provide little benefit over mineral oils when ignited by electrical sparks. In contrast, HFB (and HFC) fluids provide significant benefit and are resistant to spark ignition.

Open flame sources such as cutting flames, match sources and small fires could be expected to be even worse than electrical sparks. HFB/HFC fluids are, once again, not ignited.

More surprisingly, many HFDUs (and other HFD fluids) pass the ISO 15029-1 test which uses an oxyacetylene ignition source. In these cases, the spray is typically ignited but the burning extinguishes once the igniting flame is removed. The test criterion is that the flame persists for less than 30 s.

However, in other circumstances, even with a similar spray, the same HFDU fluids have been seen to give continuous burning.

Thus, despite standard test results, it is difficult to conclude definitively that HFDU fluids always give the same benefit that HFB/HFC fluids provide for these other ignition sources.

Once a fluid is burning, the experimental data suggest that HFDU fluids give little, if any benefit over mineral oils, while HFB/HFC fluids give a significant advantage.

For example, when tested as a spray in an extended ISO 15029-2 test, the performance of some HFDU fluids showed little or no improvement over a mineral oil in ignitability factor, flame length or smoke production. Polyol ester HFDUs appear to give some reduction in heat release rate (the intensity of burning is lessened), although the reduction is small compared with that seen for HFB/HFC fluids.

Similarly, when burning in a pool, the HFDU fluids show no significant difference to a mineral oil. Again, this contrasts with the clear reduction in fire with an HFB/HFC fluid.

In summary, HFDU fluids provide a clear advantage over mineral oils for the most common risk situation, leaks of fluid onto hot surfaces.

However, in many other risk situations the benefit of using HFDUs is much less significant.

HFB fluids show a more widespread benefit in most if not all fire situations. For this reason, HFB fluids were previously used in hydraulic machinery underground in the UK coal industry and reduced the occurrence of hydraulic system fires to very low levels.

In other industries, including mineral mining, equipment manufacturers and users avoid HFB fluids due to their inferior lubrication properties. These often require systems and components specifically designed for use with HFBs or HFCs.

The machinery used in many mineral mines is often based on, if not identical, to equipment originally intended for surface use. Thus, the use of HFB/HFC fluids may not be practicable.

In contrast, in many machines HFDUs can often be a simple ‘drop in’ replacement for mineral oil hydraulic fluids.

If the use of HFB or HFC fluids is not a practical alternative for a given machine, then other controls can be used to reduce the remaining fire risks.

Finally, controls can be implemented to reduce the likelihood of a small fire growing to become a large fire of long duration.

The most effective controls are removal or isolation of combustible material in the machine.

As was seen in the tests by Hanson, the greatest contributor to fire load on a mining vehicle is often the large tyres. If these become involved, then the fires are likely to become substantially worse and longer lasting. Preventing the involvement or one or more of the tyres can have a significant mitigating effect.

Experience shows that fires spread to vehicle tyres either by direct flame impingement from an initial spray or pool fire or by exposure to a critical heat flux sufficient to cause ignition from a pool fire beneath the vehicle. The incorporation of shields to prevent such exposures is one way of preventing the involvement of tyres in the fire and removes a significant proportion of the fuel inventory.

It is also possible to limit the amount of hydraulic fluid involved in a fire, particularly a spray fire. Many machines are fitted with emergency shut-down systems initiated, after a fire has been detected, by the operator evacuating the machine. If, in addition to powering down the machine, this system also ensures that the pressure in the hydraulic system is relieved, then the flow through any pressurised leak will quickly decay. This also will reduce the potential for re-ignition by potentially removing the fuel for any fire initiating event.

Contrary to the principle of removing combustible materials, the survey of machines used in mines revealed a growing use of composite, plastic and rubber body panels. Where the machines were designed primarily for surface use, and especially where they were also used as construction plant, replacement of metal panels with lighter weight but combustible materials is becoming increasingly common. These are more easily ignited, burn more fiercely, and produce greater quantities of smoke and toxic products than traditional metallic-based components. During the survey visits, there appeared to little appreciation of these increased hazards underground.

Looking to potential future changes, the replacement of diesel-powered vehicles with electric vehicles would significantly reduce fuel inventories underground. It is likely also that the overall number of ignition sources on electrically driven machines is lower than those with internal combustion engines. However, there has been some concern over fires in battery installations, and the issue of fire safety and batteries should be addressed before any widespread transfer to electric traction is implemented.

Once the amount of material that can be involved in a fire has been minimised, other controls can be used to reduce the harm from a fire.

An obvious approach is to extinguish the fire if one occurs.

Incident reports indicate that personnel intervention with hand-held extinguishers are highly effective in preventing the escalation of an incident. Relevant staff training is essential in ensuring that situation is maintained or improved. This training should include sight and experience of combatting the type of fires they might encounter on machines underground. This should include spray fires at high pressures and large pool fires.

In addition to hand-held extinguishers, many mining machines are fitted with some form of fixed fire suppression system, either as part of their original design or retrofitted before the machine is used in a mine.

However, it is essential that these systems are designed for the size of fires which may occur on the machine to have some confidence in their effectiveness. Thus, it is reasonable for both operators and regulators to ensure that the design fires for these systems are appropriate for the potential fire scenarios.

Spray fires are difficult to extinguish and to be effective, suppression systems must be designed with these fires in mind. As well as an having an effective design for distributing the extinguishing agent to everywhere it may be needed, the suppression system needs to contain sufficient suppressant to ensure an operational time exceeding the expected duration of the release. There are known instances of a re-ignition of a release following exhaustion of a primary system suppressant.

It should be noted that the risk assessment considered earlier places a high probability on extinguishment of the initial fire because it has been assumed that the suppression system is appropriately designed and sized. A system installed without that level of design will have a much lower probability of working effectively.

If it is not possible to ensure that the operational time of the primary system exceeds the potential release time, it is possible to fit a secondary system. This could be a ‘second knock’ supply to the suppression system, but another option is a separate, total flooding system to cover the high-risk areas on the machine, principally the engine compartment.

Such systems are also fitted in cases where they are not mandated by the design fire scenarios but serve as a means of reducing fire risks from primary system failures or as a more general ‘catch all’ for a wider range of less severe fire situations.

In the risk assessment considered earlier, the effect of a re-ignition on the overall risk was small. However, this was largely due to the high probability for effectiveness of the initial extinguishment system, leaving a low probability of a situation where a fire might be re-ignited.

Conclusions

Before the decline in coal mining in Great Britain, the approach to fire safety for equipment using hydraulic systems was largely driven by the requirements of coal mining. Such mines had the presence of combustible product and unavoidable formation of flammable coal dust, together with the potential for release of flammable methane gas often found within the coal seams. These enhanced fire and explosion risks led to the adoption of a highly risk averse approach to hydraulic equipment.

Current mineral mines in Great Britain do not, by and large, have the same fire risks associated with the extraction of their products. The much smaller size of the mineral mining industry also means that there are reduced opportunities to benefit from economies of scale when considering the use of highly specialised equipment and components.

Nevertheless, fire in an underground mine remains a significant risk and therefore a major hazard; flames, smoke and hot, toxic gases are confined in the same working areas and roadways used by personnel. A fire within a roadway has the potential to trap people in an enclosed space with no safe escape route.

Thus, while fire safety of hydraulic machinery remains a concern that needs to be addressed, the balance of reasonably practical controls for fire risks may well be different from that in coal mines.

The studies covered in this report have examined:

- The hydraulic machinery currently being operated in mineral mines;
- The history of fires occurring on such machines;
- The respective likelihood of a range of fire scenarios;
- The potential consequences of such fires; and
- The controls available to reduce the fire risks.

These factors can be combined to identify the areas where controls have the greatest effect and to assess the relative benefits of the control options.

Key conclusions are:

There are many hydraulic machines currently in use underground, covering a wide range of activities, physical sizes and system complexity.

There are relatively few fires involving hydraulic machinery underground. Nevertheless, there continue to be some such fires and the number appears to be increasing. The reason for this increase is unclear, but the upward trend in fire numbers seems consistent.

The controls used most widely are the selection of hydraulic fluids and the provision of fire extinguishing equipment.

Hydraulic fluids are available with a range of fire performance.

The poorest performing fluids are the mineral oils commonly used in hydraulic equipment in surface applications. Some mineral oils are still used in underground machinery. It is difficult to see how future, long-term use of mineral oils can be justified.

The fluids with by far the best fire performance are those with a significant water content (designated as HFA, HFB and HFC fluids depending on proportion of water in the fluid and the type of oil the water is mixed with). However, these fluids have significant costs both for the fluids themselves, the relatively short working life of the fluids and the need for components specifically designed to be used with water-containing fluids. Relatively few operating machines use these water-containing fluids; only one such machine was noted during the site visits carried out during this project.

Between these two are fluids based on oils other than mineral oil. In practice this means HFDU fluids, which are typically based on polyol esters derived from mineral or vegetable oils. Originally developed for use in tunnelling machinery, these are now the most widespread fluids used in underground mining.

The main advantage of HFDU fluids is that they have a significantly higher ignition temperature than mineral oils. Thus, an accidental leak is less likely to be ignited if it meets a hot surface (for example the exhaust or turbocharger outlet in a machine’s engine compartment).

However, the HFDU fluids show little or no difference to mineral oils when it comes to the ease of ignition by other ignition sources (hot sparks or contact with fire).

If a pool of an HFDU fluid is ignited, then the behaviour is like a mineral oil.

With spray fires the picture is less clear; some HFDU fluids are seen to be self-extinguishing under the ISO 158029-1 test conditions, although there is some suggestion that they can continue to burn as a spray in some circumstances.

During the mine visits for this study, it was noted that many users were unaware that the fire protection provided by HFDU fluids was limited. The perception was often that use of ‘fire resistant’ fluids would effectively eliminate any fire concerns except, perhaps, in the most extreme circumstances. This would be correct for water emulsion fluids, but it is not the case for HFDU fluids.

While more fire-resistant fluids should always be preferred above mineral oils in the enclosed mine environment, the choice of which type of fluid is less clear cut.

HFB/HFC fluids present a much lower fire risk but have increased equipment costs and can require bespoke systems.

HFDU fluids do reduce some fire risks and are often a ‘drop-in’ replacement for mineral oils. This allows the use of more standard hydraulic systems and simplifies the modification of pre-existing machines for use underground.

In the opinion of the authors, any decision to use HFDU fluids rather than HFB/HFC fluids should be a conscious choice and supported by a rigorous implementation of further controls so that the overall fire risks remain as low as reasonably practicable.

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Appendix 1: Questionnaire on fluid usage

PH00761: Fire Resistant Hydraulic Fluids Underground

Details of Fluid Usage

Issue 2

Site Details

Name:

Operator:

Contact:

Telephone:

Email:

Mine Details

No. underground at any time:

Tunnel diameter:

Ventilation velocity: **Normal:** **Emergency:**

Charging stations:

Fuelling stations:

Maintenance stations:

Hot work operations:

Plant

Machine			Number	Usage
Manufacturer	Type	Model		

Machine 1

Fluid:

Type:

Operating pressure: **Feed** **Return**

Operating temperature:

Fluid volume:

Hydraulic System

Pump maximum flow:

Leak shut-off protection:

Pipework: **No of hoses:**

No of steel pipes:

Pipe diameters: **Feed** mm **Return** mm **Other** mm

No of control valves:

No of cylinders:

No of oil seals:

Relevant vehicle details

Hot surface temperatures: **Turbo:** °C **Exhaust:** C

Other: C C

Presence of lagging/absorbent materials: Yes No

Electrical system:

Other fuel inventories:

Fuel: kg **Greases/ Gear oil:** kg

Bodywork(Plastics/GRP): kg

Tyres: kg

Other (hoses, cab fittings/seat): kg

Condition monitoring:

System	Purpose	Action level/Action

Modifications for use underground:

System	Details

Fire detection

Vehicular:

System/Manufacturer	No of detectors	Location

Mine:

System	No of detectors	Location

Fire protection

Joint shielding: Yes ☐ **No** ☐

Details:

Hand-held operator systems:

System	Agent	Run time

Fixed systems on vehicle:

System	Agent	Location	No of nozzles	Delivery rate	Run time	Design concentration	Activation: Manual/ Auto

Mine extinguishing systems:

System	Agent	Location	No of nozzles	Delivery rate	Run time	Design concentration

Maintenance

Location: **In-bye** ☐ **Out-bye** ☐

Oil condition monitoring: ☐

Oil renewal: **Frequency** ☐

Top-up ☐

Appendix 2: Range and characteristics of equipment found in the sites visited

A2.1 Range and characteristics

Table A2.1 lists the range of hydraulic equipment found underground on each site. Again, the TBM on the Sirius Minerals site has been omitted due to the entirely different nature of that installation. The information in Table A2.1 is not necessarily complete. There may have been other equipment in parts of the sites not visited, machines may have been removed for maintenance and, although every attempt was made to provide a comprehensive view of the mines, machines may have been inadvertently overlooked by mine personnel.

The majority of this equipment is diesel-powered though there was some evidence of the increasing use of electric traction vehicles. In general, the equipment could be classified into four main categories according to its potential to cause serious fires. These four categories were defined as:

> Category 1: Vehicles used for transporting personnel about the mine, for example Land Rovers;
>
> Category 2: Light plant items such as forklift trucks (FLTs), small dumpers or tractors;
>
> Category 3: Items of heavy plant such as large loaders, scalers or drilling rigs; and
>
> Category 4: Special items, for example machines with electric drive.

The entries in Table A2.1 are colour-coded according to this classification using black, red, blue and green for Categories 1, 2, 3 and 4 equipment respectively.

Table A2.1: Equipment using hydraulic systems used underground at the sites visited

FAULD MINE

Equipment	Numbers
Various Land Rovers	~8
T770 Bobcat	2
Merlot Telehandler 3	3
Fletcher 3312-RD Scaler	1
GHH LF4 Scoop	3
Atlas Copco Boomer Driller	1
Stationary crusher	1

BOULBY MINE

Equipment	Numbers
Land Rover	14
NPC	15
Service Vehicle	3
John Deere Gator	3
Kubota RTV	3
Massey Ferguson MF399 Tractor	1
Kramer 2506 Telehandler	15
Kramer 4507 Telehandler	2
JCB 520/40 loader	2
Wacker Neuson 701s Skid Steer Loaders	3
Wacker Neuson Dumper	2
Manitou 470	3
Joy Continuous Miner	7
Joy Shuttle Car	10
GHH LF4.4 Loader	4
GHH LF7.4 Scaler	2
EIMCO Rock Bolter	9
Wagner ST6C Scoop	2
Wirtgen Dinting Machine	1
Powertran Mobile Generator	1

STOKE HILL

Equipment	Numbers
Fantini GU 50-SC Stone Saw	3
Beretta T21 Rock Bolter	1
CAT 236B 3 Skidsteer Fork Lift Truck	1
Cesab SID-P80 Fork Lift Truck	1
John Deere 4066M Tractor	1
Takeuchi TB235 Compact Excavator	1
Wagner ST6C Scoop	1
JCB Forklift Truck (not examined)	1

MILLDAM MINE

Equipment	Numbers
David Morgan Explosive Mixer	1
Atlas Copco ST1030 Loader	3
Atlas Copco ST7 Scoop loader	1
Dux DT20 Carrier	1
Atlas Copco S1D Drill	1
Atlas Copco S7D Drill	1
Atlas Copco T1D Drill	2
Atlas Copco MT2010	2
EIMCO 913 Loader	1

All vehicles encountered contain significant quantities of fuel. There are flammable liquids present in varying quantities in the form of diesel fuel, lubricating oils and hydraulic fluids and solid fuels such as greases, hydraulic and other hoses, and electrical cabling. Plastics can now make up a large fraction of the bodywork while, in the cab, flammable upholstery is found in the seat and plastics are used in the control equipment. However, perhaps the major contributors to the fuel load on most of the vehicles are the tyres. On the larger vehicles these can weigh between 1500 kg and 2000 kg.

Depending on the functionality of these vehicles, the complexity of the hydraulic system can vary widely. The vehicles, in addition to their primary purpose such as loading, drilling, etc, were equipped with a variety of hydraulic features such as hydraulic steer, transmission and suspension. Their hydraulic systems therefore comprise a varying number of components such as pumps, valves, hoses, pipes, coolers, etc. and operate at different pressures.

The vehicles have several inherent ignition sources. Those with diesel engines have surfaces with very high temperatures around 400 °C to 500 °C associated with their exhaust and their turbocharger (where they have one). All vehicles have electrical systems, and frictional heating due to moving components can occur. There is the possibility that the hydraulic fluid may overheat within the system and machines are often fitted with special coolers to combat this.

Thus, in classifying the equipment, the main considerations were the quantities of combustibles present on the vehicle including the quantities of hydraulic fluid used on the machine, the complexity of the hydraulic systems including their operating pressure and the number and extent of the potential ignition sources present.

A2.2 Personnel Transport Vehicles

The vehicles used for transport of personnel are typically four-wheel drive machines such as Land Rovers, Kubota RTVs and John Deere Gators. They have small inventories of fluids, generally comprising up to 5 litres of power steering/brake hydraulic fluid/greases and up to 50 litres of diesel fuel. They have limited hydraulic systems for steering and brakes only which tend to operate at pressures up to 100 bar, though heavy duty off-road vehicles may have steering systems operating at ~160 bar. The fluids are generally conveyed about the vehicle in hoses, braided and non-braided. The only steel pipe is in the fuel supply. The other main fuels comprise tyres and plastic/composite body components. Internally the trim levels are more spartan than vehicles used above ground but there is still seating, plastic controls and other trim. In addition, the wiring loom and the hoses are flammable. The majority of these vehicles have minor changes for use underground and are usually retro-fitted with a manual fire suppression system in the engine compartment, relying on human intervention for detection of fire. They almost universally use mineral oil-based fluids.

The major ignition sources on such vehicles are the high temperature components in the engine compartment – the exhaust system and the turbocharger. As they become more extensive, the electrical systems may increasingly add ignition sources, though most vehicles used underground have some of the electrical system stripped away due to redundancy. There is also the possibility of frictional heating due to rubbing of components.

A typical example is shown in Figure A2.1. Table A2.2 (toward the end of this appendix) quantifies the number and type of hydraulic components on such vehicles.

Figure A2.1: A typical example of a Personnel Transport Vehicle (PTV).

A2.3 Light Plant Vehicles

Light plant items, one of which is shown in Figure A2.2, are mainly FLTs, telehandlers or small dumpers which have far more extensive hydraulic systems. They may have hydraulic transmissions, heavy-duty hydraulic steering/brake systems and hydraulic operation of buckets and forks.

The operating pressures of the hydraulic systems are in the range of 200-240 bar with a fluid inventory of 50 - 80 litres. The fuels include some plastic body parts, for example engine covers and mudguards, medium-sized tyres, cab plastics (seat and controls), wiring/hoses and up to 100 litres of diesel fuel.

They frequently have a retro-fitted fire suppression system and are provisioned with manual fire extinguishers.

From the range of light plant vehicles (LPVs) observed underground, the JCB 525-60 Loadall has been selected as a typical example. Therefore, the relevant Service Manual has been sourced and examined (JCB, 2018) and the vehicle compared with others of similar form and function encountered during visits.

Figure A2.2: A vehicle typical of the Light Plant Vehicle (LPV) category.

Most of these vehicles use HFDU fluids, typically polyol esters as their working medium. They operate at similar pressures to larger machines but with lower fluid volumes due to their smaller physical size and lower load capability. LPVs have hydraulic steer, brakes, transmission (usually fully enclosed), cooling fans in addition to their load/transport function. They use pumps, accumulators, tanks, filters, rams and a variety of valves, some enclosed in valve blocks. There are few steel pipes but significant lengths of generally braided hose up to 50 mm diameter. These are usually unprotected.

As with PTVs these vehicles usually have a retro- fitted powder-based suppression system with a small number of nozzles (typically three) pointing at critical high temperature engine components such as the exhaust system and turbocharger. These seem manually activated by the operator evacuating the machine. They also have water/foam manual extinguishers on board for personnel use.

The combustibles on-board are those universally encountered. The fuel load is dominated by the diesel fuel and the tyres, both of major significance in the development of any large fire. Other contributors to the fuel load include the hydraulic hoses, cabling, the hydraulic fluid and cab (with the seat) and body plastics.

Again, Table A2.2 details the hydraulic system, obtained from an examination of the JCB manual, of a typical LPV listing operating parameters, components and extent of hydraulic pipework.

A2.4 Heavy Plant Vehicles

Heavy plant items (HPVs) are large machines frequently more than 10 m in length. They are powered by large diesel engines and have large flammable fluid inventories including several hundred litres of both hydraulic fluid and diesel fuel. They operate at similar pressures to light plant items, in the region of 200 bar to 250 bar. The fuel load is dominated by their large tyres, which can weigh up to 2 tonnes, but also includes plastic body parts such as mudguards, cab plastics such as the seat and significant quantities of flammable hoses and cabling. Figure A2.3 shows one of many examples of this type of vehicle.

To represent a typical HPV and the critical characteristics of such a machine in relation to fire, the service manual of an Atlas Copco Scooptram ST14 (Atlas Copco, 2007), was sourced. This was examined particularly with reference to the hydraulic system, and the literature search was undertaken for any experience of fires on similar equipment.

Most of these machines use polyol esters as hydraulic fluids though there are some instances of machines filled with mineral oil and one machine using an oil-water emulsion. Other potential fuels include several hundred litres of diesel fuel and grease. Most systems on the machines are hydraulically driven including steering, brakes and transmission (though this is generally fully-enclosed) as well as their primary function of loading or carriage. The systems comprise a wide range of components including accumulators, pumps, tanks, filters, coolers, rams and valves. Many of the latter may be incorporated in large valve blocks and therefore may be enclosed. These are connected by hydraulic hose up to 25 mm diameter, generally braided and sometimes also Kevlar-sleeved for additional abrasion protection. Joints are not generally shielded. There appeared to be little rigid steel pipe on board.

Generally, the engine compartments of these machines are equipped with an automatic fire suppression system. These comprise a heat detection sensor, frequently a heat-sensitive pipe running around the engine compartment directing a powder suppressant through a limited number of nozzles (generally three to five) towards critical high temperature engine components such as the exhaust manifold and turbo charger. There is no compartment flooding suppression system, but the machines are equipped with manual water fire extinguishers.

Again, Table A2.2 contains estimates of the numbers of critical hydraulic components and leak locations on a typical heavy plant machine largely obtained from a study of the Scooptram manual.

Figure A2.3: A typical item of heavy plant (HPV).

A2.5 Special Plant Vehicles

Special items of plant (SPVs) are generally either entirely electrically powered or hybrid machines with a mix of diesel and electrical power. Their hydraulics are driven by electric pumps. As a result, they tend to have fewer potential ignition sources. Examples are the Fantini stone saws found at Stoke Hill, the Joy continuous miners used at Boulby Mine, and the Atlas Copco drilling rig at Fauld Mine shown in Figure A2.4.

Those machines which might be considered to fall into this category were found to fulfil a special function such as drilling and therefore had very extensive hydraulic systems. Despite their smaller size and shorter hose runs in comparison to HPVs, they are still considered to have similar quantities of flammable hose. They generally have HFDU fluids, principally polyol esters in their hydraulic systems.

As for PTVs these vehicles usually have a retro- fitted powder-based suppression system with a small number of nozzles (typically three) pointing at critical high temperature engine components such as the exhaust system and turbocharger. These seem manually activated by the operator evacuating the machine. They also have water/foam manual extinguishers on board for personnel use.

Figure A2.4: A drill vehicle, classified in this study as a Special Plant Vehicle (SPV)

The numbers of components listed in Table A2.2 must be regarded as estimates since the machines could not be examined in detail.

In completing Table A2.2, it has been assumed that there are two hose couplings per hose and two for each steel pipe. Oil seals were assumed to be present in pumps, brake units and cylinders/rams. It is possible that some of the valves listed will be enclosed in valve blocks, motor and pump housings and therefore be less likely to be the source of leaks.

Table A2.2: Hydraulic system characteristics of the different vehicle types found underground.

Vehicle type	Components	Operating conditions		Numbers of potential hydraulic leak locations					
		Pressure bar	Volume litre	Hoses	Hose connections	Steel pipes	Control valves	Oil seals	Cylinders
PTV	Pump Balancing valve Reservoirs	100	15	16	32	1	3	5	-
LTV	Pumps Accumulators Valves Cylinders/Rams Coolers Filters Reservoirs	200-240	50-100	87	174	9	44	10	7
HPV	Pumps Accumulators Reservoirs Valves Cylinder/Rams Cooler Filters	200-250	300-400	85	170	9	48	12	8
SPV	Pumps Valves Cylinders/Rams Filters Reservoirs	200	300	80	160	8	40	13	8

Appendix 3: Survey of mine fires in Great Britain

A3.1 Historical Data

HSE has conducted two previous surveys on the incidence of fires underground in mines in Great Britain.

Macmillan (1997) examined the period 1989-1996 for withdrawals from workings due to fire and smoke. However, there are difficulties with using the data from this work since it is unclear if data from non-coal mines were included. At the time of the report, coal mining was by far the most significant sector in Great Britain's mining industry. Within the report there is no differentiation between coal mines and "miscellaneous mines" (the term for most non-coal mines). Even if the data includes fire events in non-coal mines, it will be dominated by the much larger scale of coal mine operations at the time.

A further survey was carried out by Thyer (2001), summarising mine fire data from the period from 1993 to 2000. He found that there had been 77 fires reported during that period. Of these, 61 were in coal mines and 16 in miscellaneous mines. Figures A3.1 and A3.2 show the results from this survey on the origin of these fires in coal and 'miscellaneous' mines respectively.

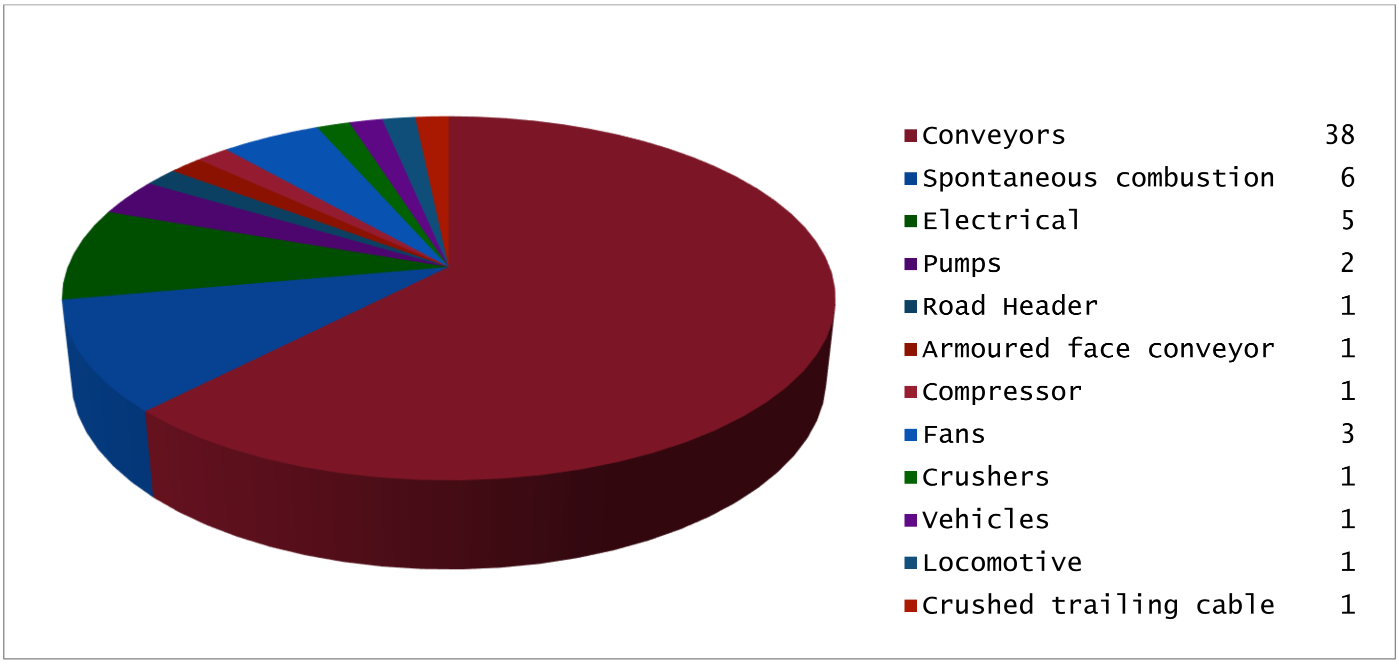

Figure A3.1: Incidence and cause of fires in coal mines 1993-2000. A total of 61 fires.

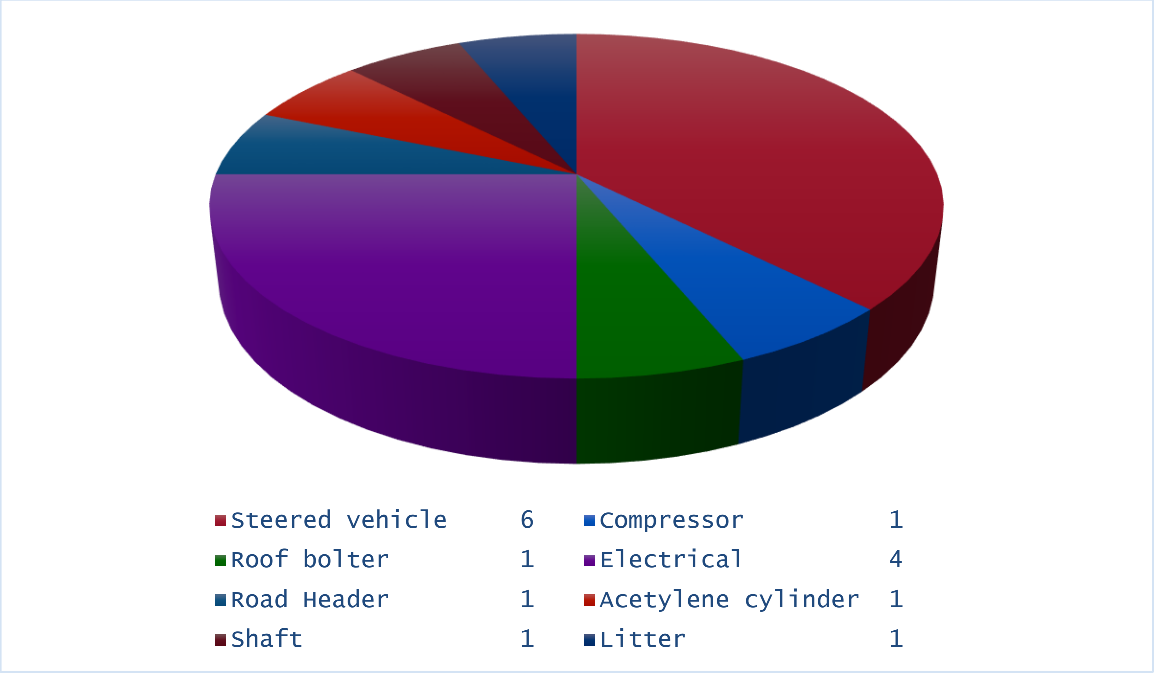

Figure A3.2: Incidence of fires in "miscellaneous" mines 1993-2000 (a total of 16 fires).

Fires on conveyors and occurrences of spontaneous combustion were the dominant causes of fires in coal mines, making up 72% of the total. In miscellaneous mines, mobile equipment including steered vehicles, compressors and roof bolters were identified as the major source of fires, accounting for 50% of the recorded events.

This difference reflects both the combustible nature of coal and the widespread use of conveyors to transport in coal mines. In comparison the products from today's mines are largely non-combustible, and both excavation and transport are mainly conducted using free-steered vehicles.

A3.2 Recent Incidents

Lowe (2021) has interrogated more recent fire reports returned to HSE during the years from 2012 to 2021.

At the beginning of this period, a small number of coal mines were still operational, and a total of 11 fires were reported underground in coal mines during 2012 and 2013. Of those, 7 were due to self-heating/spontaneous combustion events and 4 were on conveyors. The dominance of these causes is in line with the earlier data from 1993-2000.

In other mines, a total of 26 events were reported over the 10-year period – an average of 2.6 incidents per year.

This represents an increase of 30% from the 2 incidents per year observed during the earlier period from 1993 to 2000. However, as the number of incidents is statistically small, any conclusion reached from this change should be treated with caution.

Figure A3.3 identifies the source of these non-coal mine fires.

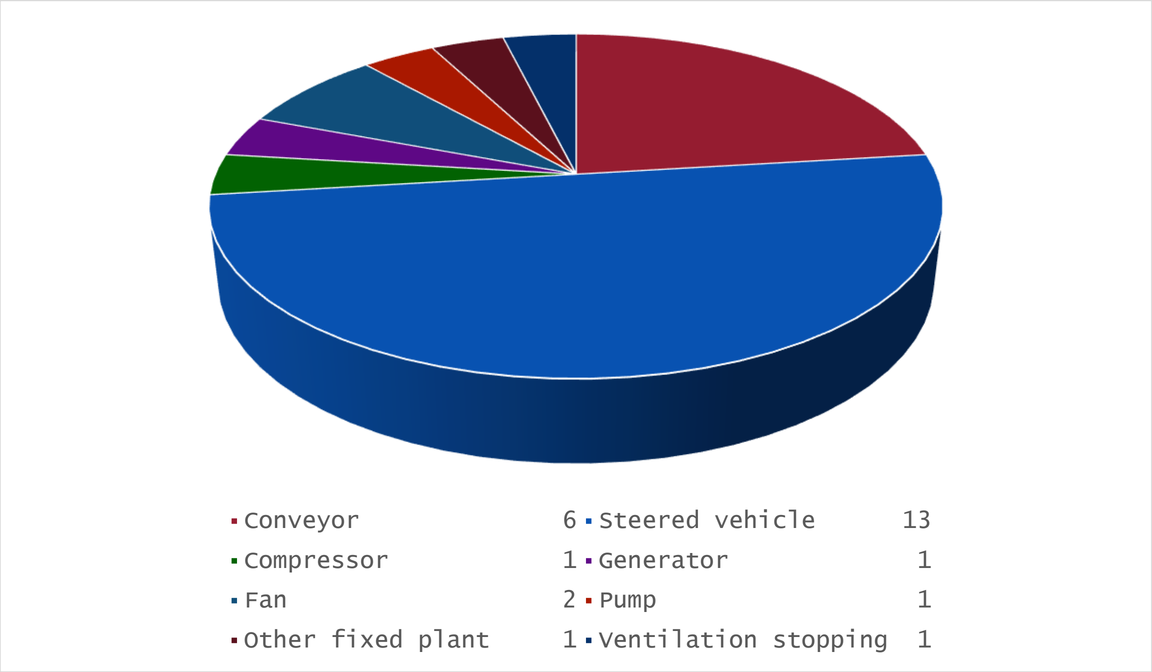

Figure A3.3: Fire incidents in mines for the period from 2012 to 2021. (a total of 26 fires).

Several significant conclusions can be drawn from this data.

When mobile compressors and generators are included, then the occurrence of fire underground is dominated by mobile equipment. These fires account for 15 of the 26 reported fires (some 60% of incidents) over the period.

Of those 15 incidents on mobile equipment, 13 were on vehicles of one type or another. Using the classification scheme developed for this report, 5 fire incidents were reported on Light Plant Vehicles, 5 on Heavy Plant Vehicles, 1 on a Personnel Transport Vehicle and the remaining 2 on Special Plant Vehicles.

The remaining 11 fires originated either on conveyors or items of fixed plant such as pumps and ventilation fans.

Fires originating on conveyors in non-coal mines now appear significant. Between 1993 and 2000 there were no fires originating on conveyors. During the more recent period (2012-2021) there were 6 conveyor fires, which is 23% of the total number of fires.

In summary, these results demonstrate the increasing involvement of mobile equipment in fires underground.

- Between 1993 and 2000 there were 8 such incidents; an average of 1 per year. Between 2012 and 2021, 15 fires were reported – an average of 1.5 pa. Although none of these incidents developed to cause injury or loss of life, they have an increasing potential to do so. Without further interrogation of incident reports, the reason for this increase in conveyor fires is unclear.

- Eighteen of the twenty-six incident reports specified how the fires were extinguished. Although the number of these events which might otherwise have developed into a serious incident cannot be identified, the utility of portable fire extinguishers is clear. Eleven of the eighteen fires were extinguished using portable extinguishers including eight (over half) of those on mobile equipment.

- In contrast, only two of the reports of fires on mobile equipment mention the use of an on-board fire suppression system. In both cases it was manually activated by the operator leaving the machine.

Appendix 4: Results from the fluid fire testing programme

A.4.1 Introduction

Two tests were selected to identify the behaviour, under fire conditions, of fluids encountered underground. These tests were chosen to reflect their relevance to the underground environment including the equipment used, and the range of potential fire scenarios.

The two tests were:

ISO 20823:2003 *Petroleum and related products — Determination of the flammability characteristics of fluids in contact with hot surfaces — Manifold ignition test*.
This was chosen to provide data on the propensity of the fluid to ignite.

ISO15029-2: *Spray Test – Stabilised flame heat release method*.
This was chosen to provide data on the consequences of fluid combustion.

Tests were performed on both new and used samples of fluids. These fluid samples were donated by mine operators from around the country. Most of the "used" fluids had been taken from machines after about 500 hours' use. Two of the samples had been used for longer periods, having been removed from machines after about 1200 hours and 2900 hours respectively.

A.4.2 Hot Manifold Ignition Temperature (HMT) testing

Tests were carried out on all the fluid samples, both new and used, that were submitted. Testing followed the test protocol in ISO 20823. The results are summarised in Table A.4.1. As the fluids were not chosen by HSE, and as the test was not intended to be a comprehensive examination of all available fluids, the source and identities of the specific fluids have been anonymised. The identifiers are those used in the main body of the report.

Table A.4.1: Hot Manifold Temperature (HMT) Test Results

Fluid	Condition	Sample number	Measured hot manifold ignition temperature, °C
HFDU#5	New	19507	522±3
	Used, 694 hours	19508	517±3
	Used, 1212 hours	19509	516±2
HFB#1	New	19505	653±3
	Used, 500 hours	19506	662±4
HFDU#3	New	19503	515±3
	Used, 514 hours	19504	526±2
HFDU#4	New	19501	521±4
	Used, 807 hours	19502	520±2
HFDU#1	New	19475	499±3
	Used, 2857 hours	19476	501±4
HFDU#2	New	19499	513±3
	Used,400 hours	19500	515±3
MIN#1	New	NA	419±3
	Used, unknown hours	20057	417±3

The main findings from this test programme were:

- The mineral oil samples ignited at around 420 °C;
- The HMTs of the HFDU fluids (synthetic polyol esters) were found to be around 100 °C higher in the range 500 °C to 520 °C;
- The HFB fluid (water/oil emulsion) samples submitted showed significantly higher ignition temperatures at 650 °C to 660 °C, some 230 °C to 240 °C higher than the mineral oil; and
- No noticeable reduction in the HMT ignition temperatures was observed for any of the fluid types or brands submitted for testing after use in the machine. There was thus no indication of any degradation in performance, in terms of propensity for ignition, for any of the fluids tested.

A.4.3 Spray Ignition Testing

Tests were carried out on all the fluid samples, both new and used, that were submitted. Testing followed the test protocol in ISO 15029-2. Both “ignitability” and “flame length” factors were determined. Since most of the fluids tested were HFDUs, fluids which produce little smoke, no smoke production measurements were taken. Some relevant smoke data had already been obtained during earlier test work (Jagger et al, 2003).

A rig calibration was first performed to allow the fluid ignitability measurements to be referenced to standard rig values – those which would have been obtained with the rig as originally commissioned. This ensures standardisation of rig performance and rig results allowing a comparison of fluid ignitability factor, RI, and flame length index, RL, obtained from different fluids at different times.

The calibration is done using several ‘standard’ test fluids, mixtures comprising various proportions of laboratory grade ethylene glycol and demineralised water. There are two separate calibrations carried out using the two different rig propane flow rates.
For a propane flow of 0.13 Nm^3/hr, the appropriate ‘standard’ fluids used contained 100:0, 80:20 and 75:25 v/v mixtures of ethylene glycol/demineralised water.
The ‘standard’ fluids for the higher propane flow rate of 0.4 Nm3/hr comprised 60:40, 50:50, 40:60 and 25:75 v/v mixtures.

All these fluids were tested in the rig and their ignitability factors obtained. The values obtained ($RI_{measured}$), are an average of at least seven determinations, and are listed in Table A.4.2, alongside the ‘standard’ values ($RI_{standard}$) that had been obtained when the rig was originally commissioned.

Table A.4.2: Calibration fluid measured and standard RI values

Calibration fluid	Composition, % v/v		Ignitability	
	Ethylene glycol	Water	Measured	Standard
CF_0	100	0	17.0	17.1
CF_{20}	80	20	34.3	34.2
CF_{75}	75	25	42.4	47.1
CF_{60}	60	40	71.0	64.0
CF_{50}	50	50	94.4	81.0
CF_{40}	40	60	131.0	90.8
CF_{25}	25	75	152.9	108

Two least squares straight line best fits were then derived from the pairs of measured and 'standard' values of RI listed in Table A.4.2. These allow the measured fluid RI values to be corrected to a standard rig value. One correction equation is derived for each of the two propane flow rates used in the test.

Using the data in Table 2, these take the form:

$RI_{corrected} = 6 \times 10^{-3}\, RI_{measured} + 0.81\, RI_{measured}$ *(propane flow 0.13 Nm3/hr)* (A.1)

$RI_{corrected} = 2.25 \times 10^{-2}\, RI_{measured} – 0.16\, RI_{measured} + 13.20$ *(at 0.4 Nm3/hr* (A.2)

In (A.1) and (A.2) the $RI_{corrected}$ and $RI_{measured}$ are the 'standard' rig values determined when the rig was commissioned and the current measured values respectively.

Table A.4.3 summarises the measured and corrected ignitability factors and flame length indices for all the samples tested.

In this table the definitions of the ignitability factor, RI, and the flame length index, RL, are such that a higher value indicates a better (lower fire consequence) performance.

Table A.4.3: ISO 15029-2 test results.

Fluid	Condition	Sample number	Ignitability factor, RI		Flame length index, RL
			Measured	Corrected	
HFDU#5	New	19507	14.4±3.4	12.9±3.4	7.2±0.5
	Used, 694 hours	19508	10.3±1.8	9.0±1.8	8.3±0.7
	Used, 1212 hours	19509	13.0±1.0	11.5±1.0	8.3±0.7
HFB#1	New	19505	55.0±3.5	72.5±8.3	49.0±1.0
	Used, 500 hours	19506	48.2±2.5	57.7±5.2	47.2±0.7
HFDU#3	New	19503	18.8±3.5	17.3±3.6	6.3±0.7
	Used, 514 hours	19504	17.2±1.1	15.7±1.1	8.3±0.7
HFDU#4	New	19501	12.5±1.8	11.1±1.7	7.1±0.5
	Used, 807 hours	19502	6.6±0.7	5.6±0.6	8.3±0.7
HFDU#1	New	19475	11.1±1.4	9.7±1.4	6.3±0.7
	Used, 2857 hours	19476	12.1±1.7	10.7±1.6	8.4±0.7
HFDU#2	New	19499	9.0±0.9	7.8±0.9	6.3±0.7
	Used,400 hours	19500	10.9±1.2	9.5±1.2	7.6±0.6
MIN#1	New	NA	8.4±1.5	7.2±1.4	9.2±0.8
	Used, ? hours	20057	7.5±0.8	6.4±0.7	6.2±0.4

Thus, the main features shown in this table and the testing exercise are:

Ignitability factor, RI:

The worst performing fluid (lowest RI value) was the mineral oil.

The HFDU fluids (synthetic polyols) gave a slightly better performance, but the benefit is relatively small.

The HFB fluid showed a good performance.

ISO 15029-2 includes a classification scheme based on the corrected RI value, using different RI ranges to define Classes A to H (best to worst performing).

The mineral oil and all but one of the HFDU fluids would be categorised as Class H, the lowest performance category, defined as having an RI of 13 or below.

The remaining HFDU fluid gave an RI value of around 17, and therefore fell into the next performance class, Class G where $14 \leq RI \leq 24$, albeit in the lower half of the class.

The HFB fluid, comprising a mixture of oil and water, showed a significant improvement in fire performance. The new fluid sample showed an RI just above 70, giving Class C performance ($65 \leq RI \leq 79$). The used fluid showed an RI just below 60, giving a performance in Class D ($50 \leq RI \leq 64$).

There seemed to be no noticeable degradation in performance with use in a machine except for two fluids. HFDU#4 and HFB#1 both showed some evidence of a degradation of performance with usage. The RI factor fell by factors of ca 50% and 20 % respectively, though these results must be regarded with caution due to the small sample size involved in the test programme and the uncertainty in the fluid usage.

Flame length index, RL:

ISO 15029-2 includes a flame length classification scheme based on the corrected RL value, using different ranges to define Classes A to F (best to worst performing).

There was little discernible difference in behaviour between the mineral oil and the HFDU fluids, with all the tests returning values in the range 6.2 to 9.2. This puts both the mineral oil and all the HFDU fluids into Class E, the second lowest classification ($6 \leq FL \leq 10$).

There was no discernible difference in FL between the HFDU fluid in RI Class G and the other HFDU fluids in RI Class H. The average FL for all the HFDU tests was 7.3, and the average for the Class G fluid alone was 7.5.

The HFB oil/water fluid was again the best performer, with both the new and used fluids falling into Class D ($11 \leq FL \leq 50$).

There was no significant evidence of any degradation in performance in terms of flame length with use of a fluid in a machine. All the HFDU fluids showed a small increase in FL with use, although the values only increased by between 1 and 2.

Appendix 5: A simple approach to the calculation of tunnel fire consequences

Roadway temperatures

This approach uses the one-dimensional energy balance approach for bulk flow in a tunnel in which a hot smoke layer, initially at the ceiling, grows to fill the entire tunnel cross-section and is then transported down the tunnel in the form of a plug.

This gives the equation:

$$\frac{\dot{m}_a c_p dT_{avg}}{dx} = h_c P\left(T_{avg} - T_W\right) + \epsilon F_w P \sigma\left(T_{avg}^4 - T_W^4\right)$$

Where:

$\dot{m}_a$ = air mass flow rate,

c_p = the heat capacity of air,

T_{avg} = the average gas temperature over the entire cross section of the tunnel,

h_c = the average convective heat transfer coefficient to the walls,

P = the tunnel perimeter,

T_W = the tunnel wall temperature,

ϵ = effective emissivity between the gas and the walls,

F_w = a radiation view factor, and

σ = the Stefan-Boltzmann constant.

This equation can only be solved numerically but a simple analytical solution is available using a lumped heat transfer approach.

By replacing h_c with $h = h_c + h_r$ and ignoring the radiated heat term, assuming the gas and wall temperatures are equal, an analytical solution becomes available:

$$T_{avg}(x,t) = T_a + \left[T_{avg,x=0(\tau)} - T_a\right]e^{-\left(hPx/\dot{m}_a c_p\right)}$$

where T_a = the ambient air temperature,

h = the lumped heat transfer coefficient, and

$T_{avg,x=0(\tau)}$ = the average gas temperature at the fire source (x = 0) at time $\tau = t - (x/u)$.

Here the use of the time τ allows for a growing fire and may be important for large distances downstream of the fire. It must be noted that this method does not allow for a varying transport velocity due to the increased gas temperature.

An appropriate value for the lumped heat transfer coefficient in tunnels is between 0.02 and 0.04 kW·m^{-2}·K^{-1}.

The average gas temperature over the entire cross-section of the tunnel at the fire location is given by the equation:

$$T_{avg,x=0(\tau)} = T_a + 2Q(\tau)/3\dot{m}_a c_p$$

where $Q(\tau)$ = the fire heat output at the time τ.

This assumes that one-third of the total heat release is radiated away from the fire. Usually, this temperature is much lower than the ceiling temperature at the fire location due to turbulent mixing of the buoyant flow.

These relations allow the computation of the temperature at different locations downstream to be computed.

Stratification

The Froude number, Fr, can also be computed. This dimensionless number allows the degree of stratification to be identified.

$$Fr = u_{av}^2/[1.5(\Delta T_{av}/T_{av})gH]$$

here $\Delta T_{av} = T_{av} - T_a$.

For $Fr \leq 0.9$, the stratification is strong, and the combustion products form a separate ceiling layer.

For $0.9 \leq Fr \leq 10$, there is strong interaction between the buoyancy forces and the horizontal flow and there are temperature gradients and mixing.

For $Fr > 10$, the vertical temperature variation is insignificant and the flow proceeds in the form of a plug.

Toxic gases

This approach can also be extended to allow the calculation of downstream concentrations of toxic species. Using the general equation for the average mole fraction, X, for a given species, i , over the tunnel cross section at a given downstream position and:

$$X_{i,avg} = Y_i \frac{M_a}{M_i} \frac{Q(\tau)}{\dot{m}_g \gamma H_T}$$

Where:

Y_i = the mass yield of species i for well-ventilated fires,

M_a = the molecular weight of air,

M_i = the molecular weight of species i,

H_T = the net heat of complete combustion, and

γ = the ratio of chemical to net heat of combustion.

If the fire does not significantly alter the total mass flow of gas in the roadway, then the total flow, $\dot{m}_g$, is the same as the known ventilation air flow $\dot{m}_a$.

Smoke

The visibility in smoke is a further important parameter in a risk assessment.

Smoke causes disorientation and makes escape routes difficult to follow. Calculation of the visibility allows the possibility of escape to be addressed. Two quantities related to visibility in smoke are the optical density, OD, and the light extinction coefficient, C_s.

$$C_s = (OD/L)log_e(10)$$

Where:

OD = the optical density, and

L = the path length through smoke.

The optical density per unit length can also be expressed in terms of the specific extinction coefficient, smoke production and volumetric flow:

$$\frac{OD}{L} = \delta Y_s \dot{m}_f / \dot{V}_T$$

Where:

δ = the specific extinction coefficient,

Y_s = the yield of smoke,

$\dot{m}_f$ = the mass loss rate of fuel, and

$\dot{V}_T$ = the total volumetric tunnel flow rate.

The optical density can also be related to more commonly measured quantities:

$$\frac{OD}{L} = D_{mass} Q(\tau) / uAH_{ec}$$

Where:

D_{mass} = the mass optical density,

$Q(\tau)$ = the heat release rate at time τ,

A = the tunnel area,

H_{ec} = the effective heat of combustion, and

u = the tunnel flow velocity.

It is known that for objects such as floors and walls in a long corridor (Jin, 1997) the relationship between visibility, V, and extinction coefficient for non-irritant smoke is approximately:

$$V = 2/C_s$$

The visibility through irritant smoke would be significantly less. Jin further suggested that visibility effectively drops to zero for values of $C_s \geq 0.55$ m^{-1} for a lit sign in irritant smoke.

Combining these equations leads to a correlation between visibility and heat release rate which can be used to compute the visibility in an actual position downstream of a fire:

$$V = 0.87 \frac{uAH_{ec}}{Q(\tau) D_{mass}}$$

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Present day mining and tunnelling in GB have different risk profiles to the coal mining that dominated underground work in the 20th century, but fire remains a significant hazard. In any underground work, a fire can be particularly hazardous. Using fire-resistant hydraulic fluids can reduce the risk of fires occurring.

To gain understanding of present-day fire risks due to hydraulic systems used underground, HSE scientists reviewed fire incidents, potential fire scenarios and the controls available to manage fire hazards, and visited 4 mineral mines and 1 tunnelling site. The hydraulic fluids most used at the sites visited were HFDUs. Compared with the hydraulic fluids typically used above-ground, HFDUs need to reach a higher temperature to catch fire, but some fire risks remain. Other fluids are available that are even more fire-resistant, but these are harder to work with.

One concern was that changes in HDFU fluids during use might reduce their fire resistance, but tests carried out on samples taken from working machinery did not find this. HFDU’s fire retardant properties were maintained throughout the useful life of the fluid.

The visits did find that the remaining fire risks were not always fully recognised by workers and dutyholders. Further controls are still needed to effectively manage the risk of harm from fire.

Findings from this report will be of interest to the users and managers of hydraulic systems underground.

DOI: https://doi.org/10.69730/hse.24rr1206

Published by the Health and Safety Executive 09/24