Emergency Management
Science and Technology

REVIEW

Open Access

https://doi.org/10.48130/emst-0024-0004

Emergency Management Science and Technology **2024**, 4: e005

A review of coal mine fire extinguishment methods

David S. Hallman*

Applied GeoLogic LLC, Evergreen, Colorado 80439, USA

* Corresponding author, E-mail: dhallman@appliedgeologic.com

Abstract

Wherever coal mining occurs, so do coal seam and coal mine fires. Besides depleting non-renewable resources, coal fires create health hazards through venting of hot combustion gases and toxic fume emissions, create large surface cracks, fissures and other subsidence openings as the coal burns, trigger wildfires and have forced entire communities to be abandoned. Unfortunately, the same properties that make coal valuable as a fuel source make these fires extremely difficult to extinguish. Each coal fire is unique and the extinguishment method or combination of methods that offer the best opportunity for success will be a function of the local site conditions and length of time the fire has been burning. As a result, it is important to understand the specific instances or situations in which various mine fire abatement techniques have been successful. Equally as important, is a detailed understanding of the reasons or cause for failure under conditions and in situations for which the methods used were unsuccessful. To aid in this process, this paper provides an overview of coal mine fire extinguishment methods, their applicability to various active or inactive mining situations, and relative effectiveness based on published results where possible. This review can serve as an initial screening tool and also hopefully promote research into more reliable and cost-effective extinguishment methods.

Citation: Hallman DS. 2024. A review of coal mine fire extinguishment methods. *Emergency Management Science and Technology* 4: e005 https://doi.org/10.48130/emst-0024-0004

Introduction

A well-established fire which has been burning in an underground coal mine for any appreciable length of time represents a highly complex three-dimensional geological problem. More often than not, underground mine fires are more complex than originally suspected, often considerably so, and this is frequently the cause for failure of extinguishment efforts attempted. Case histories of fires in abandoned mines which were simpler than originally believed and easy to extinguish are virtually non-existent. For this reason, it is particularly important to review published case histories and research on mine fire control efforts as thoroughly as possible when developing a control strategy. Each mine fire is unique and the extinguishment method or combination of methods that offer the best opportunity for success will depend on the site conditions; how long the fire has been burning, geology of the coal bearing strata, mining history, depth, topography, location, access, material availability, etc.

Fire control methods

In order to extinguish a fire, it is necessary to remove at least one of the three components of the fire triangle; heat, fuel, and oxygen (Fig. 1). One or more of these three components must be isolated, removed or eliminated by some means in order to extinguish a fire. Fuel is removed when it is physically separated from the burning mass. Oxygen removal depends on either the introduction of an inert gas or the isolation of the fire zone from sources of fresh air. Heat removal can be accomplished by injecting a heat-absorbing material; i.e., water, inert gas, foam, grout, etc.

An excellent summary of mine fire abatement techniques that have been commonly or traditionally applied in the United States is presented by Kim et al.[1]. Similarly, Singh[2] provides a list of the current methods and techniques that are in general use throughout the world to extinguish coal mine fires. These lists include the following general techniques or approaches:

- Bulkheads and stoppings
- Inertization, nitrogen or carbon dioxide gas injection
- Dynamic pressure balancing, ventilation control
- Application of fire-fighting chemicals
- Application of a surface coating or sealant material to prevent oxidation
- High-expansion foam
- Excavation
- Isolation
- Inundation with water
- Surface seals
- Remote sealing
- Noncombustible barriers
- Hydraulic backfilling or 'flushing'
- Pneumatic stowing
- Grouting

Some of these methods are only suitable for combating fires in active coal mines with operating ventilation equipment, or where direct access is possible, and are not applicable for fires in abandoned coal mines. Others such as surface sealants, inert gas, high-expansion foam, etc. have a short effective life and are suitable only for relatively recent fires. Fire control methods that temporarily block or remove oxygen from the fire zone may stop active combustion, but they are unlikely to be effective for permanently extinguishing a well-established fire in an abandoned mine. In the case of a coal mine fire that has been

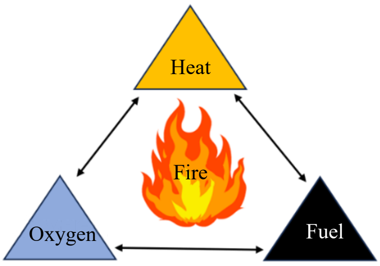

Fig. 1 Fire triangle.

burning for a long time, the fire will re-ignite once oxygen is reintroduced as a result of the residual heat energy stored underground unless the temperature of the coal has cooled, and a more permanent solution is required.

Fire control methods such as hydraulic flushing or grouting, although permanent, involve materials that tend to flow to low areas because of gravity, and are less effective for fires in upper workings. Even a very small remnant fire in the upper part of a mine can serve as a reignition point if oxygen becomes available.

Putting a coal mine fire out is one thing, keeping it from re-igniting is another. As a result, methods commonly used in an effort to extinguish coal mine fires are not highly successful and are also generally expensive. To increase the opportunity for success it is important to consider a number of factors when selecting a suitable mine fire extinguishment strategy. Is the mine active or abandoned? Fully-mechanized or room and pillar? Is the fire deep or shallow? How long has the fire been active? Following is a more detailed overview of the relative strengths and weaknesses of some of the methods used for combating fires in coal mines.

Common or traditional methods

Bulkheads and stoppings

Placement of bulkheads and stoppings underground to plug or seal off a fire from the rest of the mine is common practice in active operating mines where the workings are readily accessible. In this way, mining can continue uninterrupted in one area of a mine while a fire burns in another area. The seals serve to exclude oxygen and prevent ventilation.

However, it has long been recognized[3] that even when direct access is possible, it is very difficult to make perfectly tight seals as the cover rock is generally broken up to the surface and the fire can obtain air through innumerable unnoticed fissures. In a detailed study of 177 fires in the anthracite coal mines of Pennsylvania (USA), McElroy[4] indicates that underground seals were generally not successful due to the extent of fracturing present and indicates a poor success rate (five of 24 attempts) in these active mine situations. McElroy reports that fracturing of the rock mass above the fire zones (Fig. 2) allowed the fires to breathe to great depth through natural ventilation driven by convection from rising combustion gases.

Barometric pressure variations between the surface and isolated underground workings place tremendous stress on seals used to isolate a fire zone, making it difficult to effect or maintain a good seal. Methane can also accumulate behind a seal, building up pressure as it does so, and cause seals to fail[4].

Inertization, nitrogen or carbon dioxide gas injection

An inert atmosphere that is unable to support combustion is created in sealed off areas as the active fire consumes the available oxygen and combustion gases accumulate. This process can be accelerated through injection of an inert gas such as nitrogen or carbon dioxide to displace and exclude oxygen. However, if leakage occurs before the area around the fire zone cools sufficiently, reignition will occur if an inert state cannot be maintained. In practice, this is often the case and a continuous supply of inert gas must be provided to offset the amount of leakage that occurs.

Ray et al.[5] present a table of inert gas injection rates and volumes that have been used at a number of operating mines to control spontaneous heating and fire. These data indicate a very wide range of injection rates, varying from 190 m^3/h to as much as 3,600 m^3/h with a total volume of up to 7 million m^3 injected. The ratio of the volume of gas injected to the volume of void treated in these cases varied from 1.65:1 to more than 10:1 depending on leakage rates. Ide[6] presents a case study of a full-scale inert gas injection design to extinguish the fire in an abandoned coal mine. Based on a pilot CO_2 injection test, Ide estimates that it would require injection of 100 kg/h (approximately 53 m^3/h for CO_2) of inert gas to overcome the air leakage rate, sustained for approximately 1 year for the fire zone to cool sufficiently to prevent reignition.

Dynamic pressure balancing, ventilation control

Underground seals are not airtight structures due to rock fractures and construction defects and some leakage will occur[7]. Mine workings and bulkheads or seals will 'breathe in and out' with changes in barometric pressure[8]. Leakage can be reduced by controlling the air pressures in the adjoining mine workings using the mine ventilation system. This is done by maintaining positive pressures across underground seals by adjusting for barometric pressure variations. This technique greatly improves the effectiveness of seals but is only applicable for controlling fires in active mines with operating ventilation equipment.

Application of fire-fighting chemicals

There are common chemicals and commercial fire-suppressants available that can inhibit and control heating and combustion of coal with varying degrees of success[9]. These materials can be sprayed onto the surface of the coal to limit the air contact, to reduce spontaneous combustion chemistry reactions, and to remove heat. This includes various gels to both seal off oxygen and lower the temperature.

The use of fire suppressants is generally restricted to local application in active mines due to the cost. For the high-volume injection required to combat an active coal fire or large gob area, cost would be a significant factor. To lower cost, foam can be used to transport and fill the combustion zone with fire suppressants in a more disperse fashion than in liquid form. Gusek et al.[10] present an innovative approach for treating waste rock from hard rock mining operations with foam containing chemical inhibitors to form a coating or thin film that limits oxidation to prevent acid rock drainage.

It is unlikely that fire suppression from a chemical coating could remain effective long enough for heat from a fire to dissipate sufficiently to preclude re-ignition given the spalling and caving that is likely to occur and expose fresh coal. Hence, the

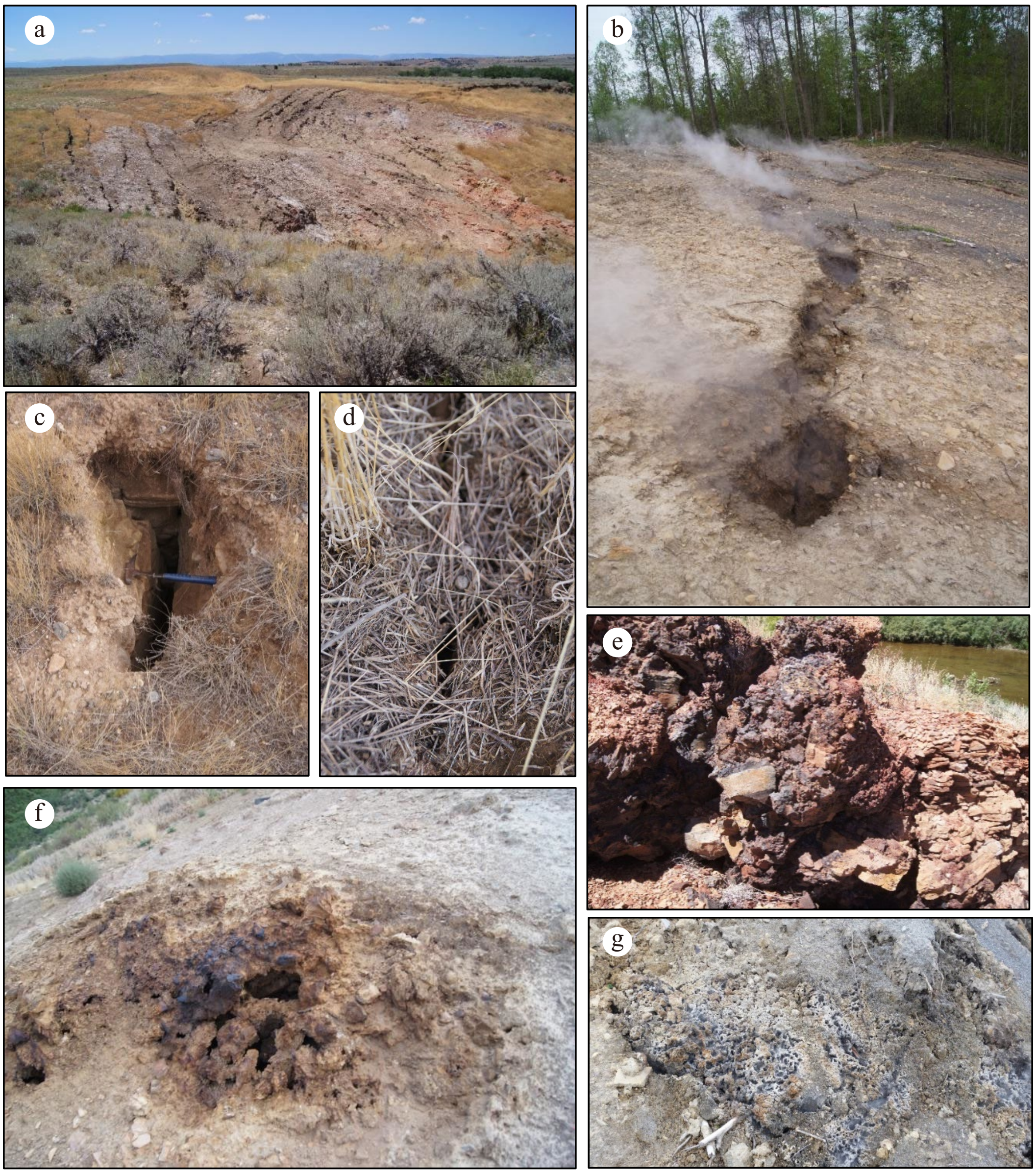

Fig. 2 Surface changes resulting from an underlying mine fire that allow the fire to breathe. (a) Ground fissures and slumping, (b) subsidence fissure venting hot combustion gases, (c) large open fracture, (d) microfractureing, (e) baked rock commonly known as 'clinker, scoria or red dog', (f) and (g) Pyrometamorphic paralava 'sponge' formations created by superheated exhaust vents.

use of fire suppressing chemicals is better suited for inhibiting spontaneous combustion in active mines or storage bunkers, for very recent fires, or when used in conjunction with other extinguishment methods to enhance their effectiveness.

Application of a surface coating or sealant to prevent oxidation

Similar to chemical inhibitors, sealing and lining agents have been applied to coat the coal surface to prevent oxidation. Sealing agents typically combine an inhibitor such as calcium chloride, sodium chloride, potassium chloride, ferrous sulphate, and aluminum sulphate with a binding agent and filler such as bentonite[11]. Physical coatings of gypsum as well as plaster, hydrated lime, cement, and fly ash have also been used to seal the coal surface[12].

The application process must be completed before significant heating or ignition starts and must be maintained indefinitely. The lining must be reapplied where deformation and cracking of the roof or spalling of pillars or ribs occurs. This technique is not suitable for treatment of large volumes of broken gob or for extinguishing an active fire.

High-expansion foam

High-expansion foam makes it possible to convey moisture in the foam to all parts of a coal mine including the upper levels and fractures in the roof and overburden. Typically, the foam would be generated underground at a safe distance from the fire and blown toward the fire to completely fill the roadways and mined out areas and block oxygen. Introduced for combating mine fires in 2003, compressed gas foam offered greatly improved performance over high-expansion foam. This included the use of much finer textured foam with smaller bubbles that greatly enhanced the effective life of the foam and the ability to inject foam remotely through boreholes.

In 2003, CAFSCO Fire Control, a commercial firefighting company from Burleson, Texas (USA) used biodegradable foam made with compressed nitrogen to help isolate and control a relatively recent fire in an operating mine, along with remotely installed fly ash-cement seals. About 18 million gallons of nitrogen-enhanced foam were injected over a period of 9 d to isolate the fire and seal the gob for inerting with nitrogen[13]. This allowed recovery teams to re-enter the mine to erect underground seals around the fire and for mining to resume just 3 months later.

CAFSCO pumped more than 700 million gallons of compressed nitrogen foam into an operating coal mine in Virginia (USA) in 2007 to put out a very large mine fire[14] and claimed the method had worked on dozens of coal fires across the US by 2012[15]. There are no details available on any of these efforts in the literature, so it is not known if these were surface or underground; operating, closed or abandoned coal mines. Unfortunately, the company ceased operations in 2014 when its founder developed cancer from exposure to smoke from the very fires he fought to extinguish[16].

Compressed gas foam has a limited effective life that requires continual injection underground over time to remain effective until the fire is extinguished. In the case of a fire that has been burning in an abandoned coal mine for an appreciable length of time, there is a large amount of stored heat energy present in the rock mass surrounding the fire. Unless the foam can be maintained long enough for the heat to dissipate, re-ignition is likely after the foam dissipates and the supply of oxygen slowly increases.

The use of compressed gas foam systems is better suited for fires in operating coal mines or for very young coal fires, not abandoned mines with long-standing fires. Although CAFSCO claimed in 2012 that it could 'put out' the infamous Centralia Pennsylvania (USA) coal mine fire in a month for about $60 million using compressed nitrogen foam[15], it is unlikely the fire would remain out unless the heat was removed.

In an unsuccessful attempt to extinguish a mine fire, a coal mine in Illinois (USA) injected 46,000 gallons of firefighting foam containing perfluoroalkyl and polyfluoroalkyl substances or PFAS that has since been linked to surface and groundwater pollution[17,18]. Foams containing PFAS are designed for flammable liquid fires, also called Class B fires. The PFAS serve as surfactants that spread the foam to cool and suppress the fire. While extremely effective, PFAS are also a major source of pollution and have now been banned in many states.

Excavation

For fires in shallow abandoned mine workings or coal seam fires, direct attack of the fire by excavating and quenching the burning coal with foam or water is the most reliable method for extinguishing the fire. Once the coal has been quenched and cooled, it is mixed with cool overburden, placed back in the excavation and covered with soil.

As the depth to the fire increases, the cost of this method and the area of surface disturbance increases exponentially, eventually becoming a limiting factor. The excavation method of extinguishment creates a large amount of surface disturbance, essentially requiring the ground to be rebuilt from the coal seam upwards, and cannot be used for mine fires beneath developed areas or in rugged terrain (Fig. 3).

The US Department of Interior Bureau of Mines conducted extensive mine fire research and control efforts from 1910 until 1996, performing control or extinguishment efforts on approximately 347 mine fires[1]. Based on this experience, excavation was found to be the most effective control method, being successful in 57 out of 78 attempts (73%), but it was also the most expensive[19–21].

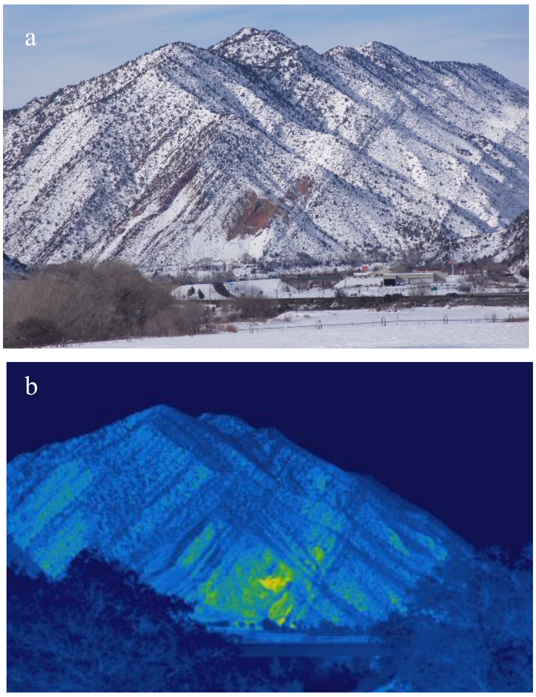

Fig. 3 Coal mine fire beneath rugged terrain in the Grand Hogback at Newcastle, Colorado, USA. (a) After recent snow and (b) with thermal infrared imagery. The rock strata dip to the left at 50 degrees.

Isolation

Excavating a continuous trench around an underground mine fire has been used to create a noncombustible zone to cut-off and isolate the burning coal to prevent the fire from spreading. For relatively shallow mine fires and coal seam fires this is an excellent approach to create a continuous barrier across which the fire cannot spread. However, within the confines created by the barrier, the fire continues to burn unabated with attendant hazards and environmental consequences, and may continue to burn for a considerable period of time. The cost of this method also rises quickly as the depth to the fire increases and has a practical depth limit (Fig. 4).

In some extreme cases, tunneling or re-mining of coal underground has been proposed as a means of isolating a fire[22]. The costs and associated safety risks of this approach are quite high and will not be feasible in most cases.

Inundation with water

Efforts to quench a mine fire directly and cool the surrounding rock mass with water by flooding the mine have been successful in limited instances where complete inundation could be achieved, such as mines which are below the water table and were dewatered for mining. Considerable efforts have been made to flood mines on fire by creating dams and seals and filling the workings with water by pumping. However, these have generally been unsuccessful due to leakage of the water and inability to completely inundate the upper portions

Fig. 4 South Canyon West coal mine fire, Colorado (USA) during snow. The coal bearing strata and mine workings plunge to the left at about 50 degrees and would be impossible to isolate.

of the fire. In some cases, fires have been extinguished by completely flooding the mine with water for months; only to re-ignite due to residual heat and spontaneous combustion in damp coal dust, fines and rubble once the water is drained, and in some case even in areas where the fire didn't previously exist[3,23,24].

Attempts to extinguish a fire with water percolated into the mine from surface application, infiltration from ponding (Fig. 5), or by injection through boreholes, has also been attempted at many mine fires, with little success. Since the flow of water through the rock and mine workings is uncontrolled, it follows the path of least resistance down gradient, thus almost assuring that portions of the fire or heated rock mass will be bypassed by the water and remain unquenched. Attempts to overcome this drawback of the method include the use of closely spaced injection borings to disperse the water more uniformly, and the use of steam or mist injection. Slightly better results can be achieved in this fashion, but not reliably so, and at significantly increased cost due to the large number of injection borings required. The US Bureau of Mines conducted a number of water inundation fire-control projects on both active and inactive mines, with a success rate of just 21 out of 41 attempts (51%)[4,19,20].

When injecting water into the high-temperature environment of an underground coal mine fire, geyser-like eruptions of steam and hot water have been known to occur[25]. When injected into superheated areas of the mine fire, hydrolysis of the water into an explosive mixture of hydrogen and carbon monoxide or 'water gas' may also occur under the extreme temperatures.

Surface seals

Surface seals are commonly constructed by placing a four- to ten-foot-thick layer of compacted soil or pulverized rock over a coal seam or mine fire area to exclude air from the fire. Surface seals smother a fire by inhibiting ventilation of the fire zone; denying oxygen and causing combustion gases to accumulate in order to smother the fire. The seal material must contain sufficient fine-grained particles to prevent ventilation and exclude oxygen. In some cases, seals constructed using pulverized rock were too porous such that the fire could easily breathe throughout the entire slope and the fire spread. If too much fine-grained clay-rich material is present, the seal may crack due to shrinkage as it loses moisture and dries, compromising the integrity of the seal.

Seasonal climatic cycles, changing weather patterns, and barometric pressure variations all place stress on a seal that may compromise its integrity. Freeze/thaw cycles can induce movement of rocks within the seal material by 'frost jacking' which has been attributed as the apparent cause of vent pathways at some sites[21]. Subsidence induced fracturing or erosion of a surface seal also allow air to enter.

Pressure differences between the confined space of the mine workings and open atmosphere create a gradient that can cause leaks in seals and allow air exchange and a renewed supply of oxygen. Chaiken et al.[26] indicate that leaks in sealed areas can develop as a result of rising hot combustion gases which create convection currents that draw in more fresh air. These leaks provide natural ventilation to circulate air and vent combustion gases that can reignite a fire which has been inactive for a long time due to the amount of heat retained in the rock mass. Studies have shown that coal can smolder indefinitely at 2% oxygen concentrations[27] such that even slight leakage can sustain a fire indefinitely.

Kim & Chaiken[28] suggest that a surface seal must be maintained for a period of 10 to 20 years while the stored heat dissipates in order to extinguish a fire. However, in practice this is often difficult to achieve and surface seals frequently fail due to settling, drying, shrinkage, subsidence, erosion, slope failure, or increased fire activity (Fig. 6).

Once a breach in the surface seal occurs, the fire can regenerate quickly if maintenance of the seal is not performed. Timely inspection and repair of damaged seals is often difficult to accomplish in practice and many surface seals ultimately prove ineffective at controlling the fire. Because surface seals disrupt ventilation patterns, the altered flow and circulation of hot

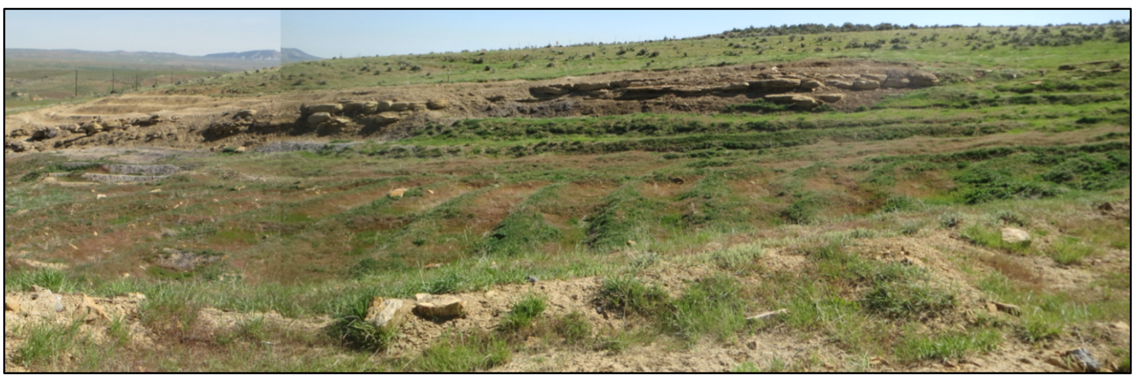

Fig. 5 Surface water infiltration basins over a shallow mine fire.

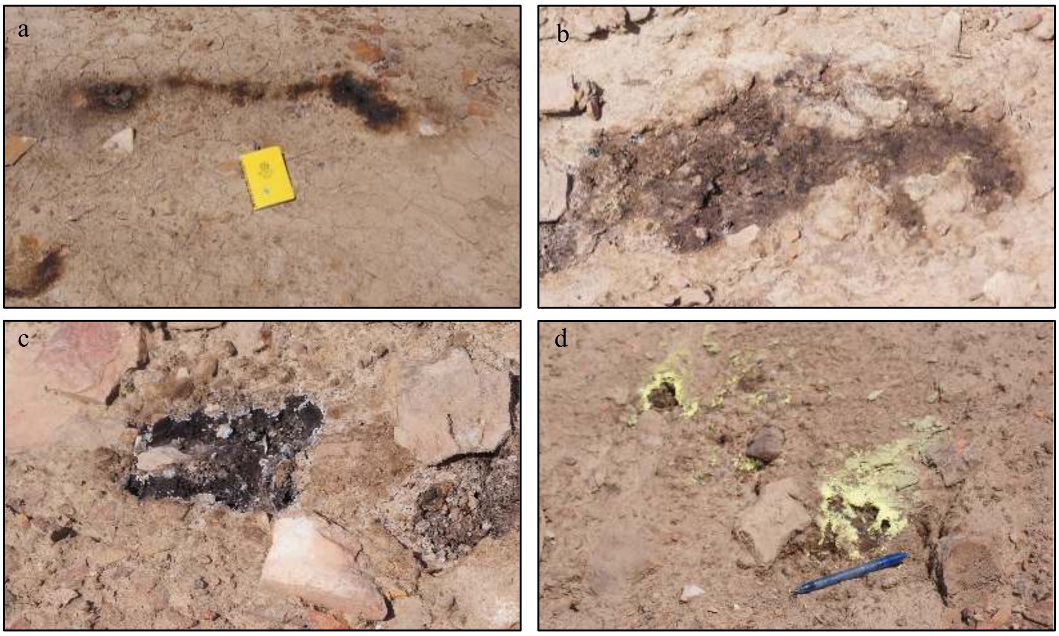

Fig. 6 Examples of mine fires venting hot combustion gases through soil cover. (a) Coal tar residue condensed from gases upon venting through soil desiccation cracks; (b) and (c) Hydrocarbon and coal tar residues from venting through rocky cover material; (d) Sulphur crystals from H_2S emissions through rocky cover soil.

combustion gases underground may also cause the fire to ignite in other areas of the mine. As the ventilation patterns change, the movement of hot gases can cause the fire to propagate from one area to the next in a discontinuous fashion.

Surface seals have been the primary abatement approach used in the western United States due to the relative ease and low cost of the method, and lack of water at most sites[29,30]. However, Renner[31] reports that of the 20 sites in Colorado where surface seals were implemented for extinguishing mine fires from 1952 through 1974 by the Bureau of Mines, only eight appeared to be dormant in 2005, a success rate of only 40%. Overall, Rushworth et al.[21] report a 43% success rate for 37 surface seal mine fire control efforts conducted in Colorado (USA).

Similarly, Magnuson[20] reports an overall success rate of 42% for surface seals constructed at 86 eastern bituminous mine fires. Surface seals were used more often than other methods for eastern bituminous mine fires as this approach was the least costly and was considered the only viable approach for a well-established fire under deep cover. Surface seals may best be used in conjunction with backfill methods such as flushing, grouting, etc. or other approaches.

Underground seals

Since the workings in an inactive mine generally cannot be safely accessed, there has been a considerable amount of research over the years into suitable means and methods for placing a variety of seals and barriers remotely underground from the surface[23,32]. Invariably problems creating an adequate seal have been encountered and further study recommended. In a more recent report summarizing full scale testing of remotely placed grout seals, Gray et al.[33] concluded that attempting to place a reliable seal in a blind fashion without an observation borehole is virtually impossible, even then it is very difficult.

Construction of underground seals remotely also requires locating intact tunnels in which to place the seal, which can be a challenge in an abandoned mine. Often coal pillars would be robbed during secondary retreat mining to increase recovery of the coal, resulting in extensive collapse and caving of the mine workings. Under such conditions, suitable locations in which to place a seal can be quite limited and effectively impossible to locate remotely in a blind fashion from the surface using drill holes. As the number of seals required increases, so does the complexity.

Numerous case histories have shown that when seals and barriers are incomplete and only partially effective, changes to the ventilation patterns often result in spread of the fire. If the flow of air and combustion gases through the mine are simply re-routed as a result of localized seals or barriers and sufficient heat remains underground, the fire will likely re-ignite elsewhere and spread. Chaiken et al.[26] caution that there is little evidence that isolated tunnel barriers are successful at containing fires, and may only serve to retard and change the direction of fire propagation. Similarly, Rushworth et al.[21] suggest that 'abatement activities .... might alter the circulation of air and fumes to the extent that the fire spreads or starts in an unexpected location', and in fact this has happened all too often in practice.

Thus, placement of underground seals to control or extinguish a fire in abandoned mine workings is not a practical or reliable approach, and may actually complicate the fire and extinguishment efforts that are ultimately then required.

Noncombustible barriers

Placing wide fire-proof barriers of noncombustible material underground to isolate a mine fire has been attempted on many occasions, but with limited success on a historical basis in an inactive mine. In an inactive mine, construction of the barrier must be conducted remotely through boreholes, and in a blind fashion. Experience has shown this is an extremely difficult way to ensure a complete and sufficient barrier is adequately and suitably constructed to provide the necessary isolation. As often as not, isolation barriers have failed by being placed in the wrong location due to inadequate characterization of a fire to begin with, and failure to identify discontinuous fire zones or changes that occur in the fire during, or caused by, the construction activities.

Magnuson[20] reported a low success rate of just seven out of 27 attempts at using underground barriers in the eastern bituminous coal fields (USA). These unsuccessful attempts to install noncombustible barriers include multiple efforts at the now infamous mine fire at Centralia, Pennsylvania (USA) which ultimately forced evacuation of the entire town. Failure of the isolation barriers in the case of Centralia can be attributed to underestimating the extent of the fire initially, a lack of sufficient funding to complete effective barriers, ineffective material placement and poor construction oversight. Unfortunately, these issues appear to be all too common occurrences when it comes to historical reports of attempts to extinguish abandoned mine fires.

Invariably it is also impossible to construct an isolation barrier without having un-mined coal in the form of boundary pillars, floor or roof coal, or a rider coal seam or carbonaceous shale that penetrates the barrier and provides the fire with a fuel path through the barrier. This method also has the disadvantage in that the fire is generally left to burn unabated behind the isolation barrier, with the potential for associated health and safety issues to continue for a considerable amount of time before the fire eventually burns itself out.

Hydraulic backfilling or 'flushing'

Using water to wash or 'flush' material into mine workings hydraulically to extinguish a fire by backfilling the workings is essentially a method of permanently flooding it, but with solid material instead of water. Very large volumes of backfill material can be injected into underground workings quite economically as a hydraulic slurry composed of soil or sand and water, but it is difficult to control final placement of the solids.

The hydraulic flushing method is believed to have been devised by a Catholic priest in the 1860s in the anthracite coalfields of Pennsylvania (USA) and then implemented by the mining company to protect his church against subsidence[34]. The method was also used historically to fight mine fires in the anthracite field from the late 1800s until decline of the district in the 1940s. Davis[35] describes the process of flushing culm (coal waste) into anthracite mines with water, where it was determined that the smaller the particles were, the better the hydraulic backfill worked at filling cracks and crevices to provide support. The smaller particles also required less water to transport, with material ranging from 'rice- to dust-sized particles' working best. Davis concluded that mine fires could be extinguished by backfilling the chambers surrounding the fire with fine culm by flushing.

McElroy[4] indicated that hydraulic backfilling with fine culm, which he terms slushing, was a great deal more effective for controlling mine fires than placing underground seals, having extinguished the fire in 50% of the instances (12 of 24) in which it was tried. McElroy suggests that 'by filling a large part of the voids in what is a partly sealed fire area, flow of air is greatly retarded and inflow by "breathing" [sic] likewise. Slushing therefore appears to offer an ideal method of retarding the progress of fires and, where its placement is under sufficient control, offers probably the most effective method of making a seal in broken ground and inaccessible openings'. However, McElroy indicates that the cost for using this approach circa 1938 was prohibitive except for small fire areas. Griffith et al.[23] also cautioned that the size of the fire and the area to be backfilled using this method may be prohibitively large unless the backfill material and water can be obtained at reasonable cost.

Chaiken et al.[26] considered hydraulic backfilling to be generally more effective than sealing in steep anthracite mine fires and the most effective method in broken ground or when conducted remotely. However, these authors note that in hydraulic flushing, fractures above the caved strata are often not filled, and it is difficult to create a complete seal in rubble-filled caved areas and in steeply dipping seams; the tendency being for the flow of water to carry material down dip to some unknown point. Chaiken et al.[26] indicate hydraulic flushing to be most effective when deposition can be controlled or contained such that the injected material remains in place.

Philbin & Holbrook[19] reported that blind flushing through boreholes using hydraulic methods had an overall success rate of six out of 14 attempts at controlling or extinguishing coal mine fires historically. These authors concluded that the hydraulic flushing generally does not provide a tight enough seal to preclude ventilation of the fire area and will flow to the low points in steeply inclined workings. Philbin & Holbrook also reported that flushing with sand had proven successful at extinguishing mine fires in three of five situations in which it had been attempted. They theorize that because sand is heavier than other particles commonly used for flushing, like coal refuse and fly ash, it settles in place more readily, packs more tightly, and consolidates less over time to allow oxygen pathways. Although its overall success rate was low, hydraulic flushing was considered effective for small fires in flat coal beds.

In the Wuda area of China, attempts to extinguish mine fires incorporated localized injection of a mixture of water, ash, and colloids, essentially a mud slurry, under high pressure to fill up cavities and fractures underground, and then covering the burning areas with loess, gravel, and rock in efforts to deplete the fire of oxygen. Studies conducted between 2004 and 2010 indicated that the total number of fires was decreased from 18 to 6 as a result of these extinguishment efforts, but unfortunately the total area affected by the fires increased from approximately 160 to 227 hectares[36]. Since mud slurry is heavy it will flow to the lowest portions of the mine and may not fully reach the roof in all areas. As the slurry dries, it will also shrink and develop mud cracks that can allow air entry (Fig. 7).

One of the key benefits of hydraulic backfilling are that it is an economical means for placing a large volume of backfill underground. The method is also suitable for a wide range of materials which helps to reduce costs. However, there are several distinct drawbacks to the method, including:

• Hydraulic flushing requires very large volumes of water to be injected with the backfill material.

• Turbulent flow is required to maintain the solids in suspension and a minimum flow velocity must be maintained, usually several feet per second at least. This makes it virtually impossible to deposit noncombustible solid backfill materials tight to the roof of openings or into dead end nooks and crevices where flow cannot occur.

• High velocity turbulent flow often erodes channels in previously deposited material thereby preventing an adequate seal.

• There have been cases where hydraulic flushing has resulted in large volumes of steam and water being explosively

Fig. 7 Large shrinkage or 'mud' cracks in fine grained sediments upon drying.

ejected from boreholes creating a safety hazard as the water contacted the super-heated fire zone.

Devers[37] presents a fascinating account of a successful 4-year effort to extinguish an anthracite fire in the Red Ash Company's Jersey Mine by washing clay into the workings using water. However, the efforts to surround and inundate the fire zone with noncombustible material required extensive effort to construct elaborate underground bulkheads and what was estimated to be over a billion gallons of water to flush the clay into the mine. Similarly, Lynde[38] reports that injecting culm by flushing through 6-in diameter boreholes to extinguish a fire burning for more than 50 years required 2 billion gallons of water at a total cost of $2 million circa 1909.

Pneumatic stowing

Pneumatic stowing is a dry process in which compressed air is used to transport and place backfill material in mine workings, either directly or through boreholes. This eliminates some of the difficulties associated with the large volumes of water required for hydraulic flushing methods[37,38]. Walker[39] reports that pneumatic stowing was first applied in Germany in 1924, and became the preferred backfilling method there. Dutt[40] describes stowing methods in use in India, indicating the method can be used to avoid most of the dangers arising from fires or subsidence due to coal mining. Pneumatic stowing is not widely practiced in the United States; typically, its use being limited to small-scale applications like building seals in active mines or filling behind tunnel liners.

Heavilon et al.[41] describe a method and apparatus for pneumatically stowing fly ash or other granular material in mine workings to support the overburden and create a noncombustible barrier to prevent or hinder advance of a fire. Pneumatic stowing offers better control over the final placement of backfill material than hydraulic flushing. However, the pneumatic placement method has the disadvantage of introducing additional air into the fire, requires more closely spaced injection points than hydraulic flushing, and is unable to penetrate fractures or rubble effectively.

Inert gas can be used in lieu of air in the pneumatic injection process with the added benefit of excluding oxygen from the fire zone, but at increased cost. Additionally, fly ash is used extensively in construction as a concrete additive and for soil treatment, and may not be readily available or inexpensive. Some of the noncombustible barriers at Centralia were constructed by pneumatic injection of fly ash, involving 122,556 tons of fly ash placed through 1,600 boreholes, but were ultimately breached by the mine fire[20].

Grouting

Griffith et al.[23] reports that grouting can be a very effective method to fill voids and exclude air from a fire. Grout is injected into the mine workings and collapse zones (gob) remotely through boreholes from the surface (Fig. 8) to extinguish the fire, stabilize the ground, and prevent ventilation to reduce the possibility of re-ignition. Void-fill grout injection with sand-cement-fly ash mixtures traditionally adopted for mine subsidence control can be used to extinguish coal mine fires provided a high percentage of the mine voids and also fractures in the surrounding rock mass can be infilled. However, this method of treatment is very expensive and grouting has generally been limited to seals and barriers, or small fires and treatment of localized active combustion 'hot spot' due to the high cost of the grout.

The high temperature environment of a mine fire can cause flash setting in cementitious grouts. This can compromise grout placement by preventing adequate grout takes and suitable distribution of the grout from each injection point. Shrinkage of grout as it sets can also cause cracking that allows air transmission.

Thermal degradation of Portland cement begins to occur around a temperature of 65–90 °C. For this reason, the American Concrete Institute code for concrete construction specifies a maximum temperature limit of 71 °C to ensure predictable concrete behavior[42]. When heated above a temperature of 100 °C, water entrained in the grout aggregate will convert to steam and expand, which can also cause cracking of the grout. At a temperature of 400 °C the cement paste dehydrates and shrinks in volume while siliceous aggregates expand, causing the grout to crack. As the temperature approaches 500 °C, Portland cement paste undergoes chemical changes and decomposes, which causes significant shrinkage and cracking and an increase in porosity[43]. With temperatures inside a coal fire able to reach 800–1,200 °C or more, the

Fig. 8 Grout injection holes venting combustion gases at the Scotch Hill mine fire, Newburg, West Virginia, USA.

use of normal Portland cement-based grouts for combating a mine fire may be compromised and ineffective at creating an adequate seal. The high temperature performance of grout can be improved through the use of refractory calcium sulfo-aluminate cement, but at a higher cost.

Many efforts to extinguish larger underground fires by isolating the fire with targeted grouting have initially been effective at decreasing the fire following treatment, but then ultimately resulted in spread of the fire. Grouting in this manner to extinguish a long-standing mine fire has been likened to a frustrating and very expensive version of the 'whack-a-mole' arcade game where the fire is suppressed or extinguished at one location only to pop up somewhere else, often a considerable distance away[44,45]. The stored heat energy that persists underground from a fire that has been burning for a long time causes the coal to ignite in other areas where oxygen is present or later becomes reintroduced. This can occur years, or even decades later, as fresh air is able to enter through the formation of new cracks and fissures.

To prevent re-ignition by injecting enough grout to treat the entire underground mine area at most historic mine fires would be impossible within reasonable funding limits. Therefore, due to cost limitations, grouting may be unsuccessful for all but the smallest, relatively young fires, and alternative methods are likely necessary to combat large long-standing coal mine fires.

Recent extinguishment method developments

As previously indicated, high-expansion foam has been successfully employed for extinguishing mine fires in active mines, however, this type of foam is relatively fragile and will break down quickly, particularly when in contact with rough surfaces in porous media like gob/rubble in collapsed areas. A fire that has been burning for a long time is likely to re-ignite when the foam dissipates due to the amount of latent heat energy stored in the surrounding rock mass. Research to overcome this limitation for combating coal mine fires includes the use of multi-phase foam and hydrogel mixtures to improve the stability and performance of foam, and the addition of foam to grouting materials.

Multi-phase foam

Michaylov[46] describes what he terms 'Foam Pulp Technology' or FPT for controlling spontaneous combustion in gob areas of Bulgarian coal mines during active mining. The 'pulp' in this case consists of fly ash, water, and foaming agent. Foam is produced by injecting compressed gas under pressure into a highly turbulent stream of the liquid pulp flowing through a foam generator to create 'foamed pulp'. This material is then injected into caved gob through pipes preinstalled behind long-wall panels a short distance beyond the edge of the mechanized supports soon after advance.

This approach was adopted to take advantage of the three main methods being used to control mine fires in Bulgaria at the time; fly ash slurry, foam injection and inerting with nitrogen, while eliminating or counteracting the disadvantages of each. The three components of the FPT approach each fulfill a different role in combining to prevent or extinguish a gob fire:

• Foam: cools the coal, inhibits oxygen, wets the rock surface.

• Nitrogen: creates an inert environment in the neighboring area as the foam decays.

• Fly ash: increases stability of the foam and forms a lasting coating on the surface of the coal to inhibit oxidation.

Michaylov reports that the costs of using FPT are 60% to 70% lower than for gob inerting with nitrogen alone when mining thick seams. However, the costs are indicated to be 80% higher than fly ash slurry injection for average seam thicknesses[46].

Zhou et. al.[47] used this same multi-phased foam approach to extinguish an 'extraordinarily serious' mine fire in an active coal mine in China. Because of the size of the fire and numerous gas explosions, the entire mine had been sealed and the exact position of the fire could not be located. Therefore, large quantities of a three-phase foam mixture were injected into the underground fire through dill holes over a broad area. The three-phase foam was composed of a dilute slurry of fly ash and foaming agent in water was infused with nitrogen to an expansion ratio of 30 to 1. Each of 11 drill holes was injected with the three-phase foam continuously for 2 to 5 d. A combined total of approximately 718,031 m^3 of the mixture was used to extinguish the fire and allowed the mine to go back into full production within a year following the fire.

Three-phase foam was also used to combat more than 22 hectares of fire in abandoned room and pillar workings at the Anjialing mine in China[48]. The three-phase foam was composed of water and loess rather than fly ash, mixed at a low solids-to-water ratio of 1:4. This pulp mixture was then infused with foaming agent and expanded at a ratio of 20 to 30:1 using nitrogen and injected through boreholes drilled at 8 m spacing. The three-phase foam was highly flowable and effective at reaching into loose coal and rock rubble in the upper portions of caved areas. However, the three-phase foam material used did not build up or stack upon itself well enough to completely fill large openings and water-mist injection was subsequently used for extinguishment in these instances.

Other research includes the use of metal and metal oxides, and silica nanoparticles to improve foam properties[49,50]. Reduced to nano size increases the specific surface of the particles which increases their reactivity. The nanoparticles improves the stability of fire-extinguishing foams and extinguishing efficiency

Although the nanoparticles, loess or fly ash stabilizes the high-expansion foam and mproves effectiveness, the three-phase foam still has a relatively short effective life. Thus, this approach is probably better suited for use in combination with other methods, relatively recent fires in active mines, outcrop fires, and for preventing gob fires.

Hydrogel

Hydrogel, or simply gel, attempts to overcome some of the drawbacks and limitations of both high-expansion foam and water or slurry injection. Foam is self-stacking and will not drain away, but it has a short effective life measured in terms of a limited number of days[51,52]. Conversely when water or hydraulic flushing is being used for extinguishing a fire, a large portion may leak away through lower-level mine workings, open fractures and cracks due to gravity, thus leaving upper areas untreated. Gel on the other hand is very liquid when injected and will easily penetrate small openings, but becomes highly viscous following injection, causing the material to set and remain for a much longer period of time in the high-temperature zone of a mine fire.

Initially a slurry is prepared using local materials such as finely crushed rock, sand, loess or fly ash, mixed with water and other additives. A small amount of gelling agent is added immediately before pumping the mixture into the ground near the fire site, where it congeals or gels in the cracks and voids to prevent air flow and eventually extinguish the fire. The gel forms an impervious seal on the coal surface and in broken coal that reportedly lasts for at least 12 to 15 months[53], extending the effective life of fire prevention relative to high-expansion foam or water alone. As the gel dehydrates and dries it will crack, ultimately crumble and fall apart.

A composite gel consisting of gelatinizer, loess or fly ash, and water is widely used for fighting coal fires in China[54]. The ratio of solids to water used is from 1:1 to 2:1 with gelatinizer content less than 0.1% of the total water by weight. Deng et al.[55] describes the use of large volumes of thickening gel to extinguish outcrop coal fires in the southern Sichuan Province of China.

Although hydrogel should be effective at extinguishing mine fires, the long-term protection provided against possible re-ignition remains uncertain due to the large amount of stored heat energy present and great length of time the material must remain effective. The use of gels for control of coal fires is probably best limited to relatively recent or young fires, control of spontaneous combustion and fires in active mining situations, or when used in conjunction with other methods due to its limited effective life.

Foamed gel

In practice it is difficult to inject polymer gel material throughout a large mass of gob to extinguish a large fire due to the generally limited range of the mixtures prior to gelling once injected. Foam on the other hand is able to penetrate for great distances, but does not cure or set and therefore has a much shorter effective life. To overcome each of these deficiencies, foamed gel has been used in China to prevent the spontaneous combustion of coal[56]. The foamed gel combines the enhanced firefighting properties of gel with the improved flowability characteristics of foam to significantly enhance the fire prevention and extinguishing capabilities.

A multi-phase foamed gel composed of foamed gel combined with fly ash, has been used successfully in China to combat mine fires[57,58]. It makes use of the combined capability of gel, foam, fly ash injection, and chemical inhibitors to prevent mine fires. This method blends the properties of gel with multi-phased foam to increase the long-term effectiveness. The fine solids suspended in the mixture coats the coal, effectively hindering the coal from absorbing oxygen and preventing oxidation of the coal, even after the foam and gel dissipate.

Because of the large amount of stored heat energy present and great length of time the material must remain effective the long-term protection provided against re-ignition by multi-phased foamed gel remains uncertain. Thus the use of foamed gels for control of coal fires is probably best limited to relatively recent or young fires, control of spontaneous combustion and fires in active mining situations, or when used in conjunction with other methods due to its limited effective life.

Cellular grout/foamed concrete

Feiler & Colaizzi[59] described a method for suppressing a mine fire using a hybrid foam-grout mixture to overcome some of the concerns with high temperature performance of grout by mixing foam with cement grout to create cellular grout. Colaizzi[60] introduced foamed grout fire control technology called Thermocell®, which is composed of sand, cement, water and a high proportion of fly ash, to which pre-generated air-entrained foam is added. The grout is highly flowable and extremely heat resistant due to the air entrained in the foam; it can be applied directly to hot coal in a fire, maintaining flowability without flash setting. The foamed grout removes heat, encapsulates the burning fuel, and fills void spaces to block oxygen[61]. This approach was used for the IHI mine fire in Colorado, USA (Fig. 9) and several mine fires on the Southern Ute Indian Reservation (USA). However, the Portland cement-based grout still suffered from thermal breakdown through sustained exposure to high temperature[61].

Szurgacz et al.[62] describe using a fly ash-water slurry with anti-pyrogenic foam made using CO_2 to disrupt spontaneous combustion during long-wall coal mining. Self-cementing fly ashes which contain calcium oxide (CaO) are used for the mixture which is injected into the goaf (i.e. gob, rubble, etc.) behind the long-wall panel. The mixture penetrates well and seals the goaf to restrict ventilation of the zone being treated, while CO_2 from the foam helps inert the area.

Other researchers have investigated the use of foamed cement with different additives for improving performance or

Fig. 9 IHI No.3 coal mine fire, Colorado (USA) which continues to burn vigorously despite multiple extinguishment efforts that included surface sealing, grouting and excavation.

reducing cost for controlling spontaneous combustion and mine fires. For example, Qin & Lu[63] investigated the addition of various amounts of cellulose to the performance of foamed concrete which they call 'inorganic solidified foam'. Similarly, Wen et al.[64] investigated the use of inorganic solidified foam using various amounts of calcium sulpho-aluminate cement added in an effort to improve the performance and reduce the cost of the material. This research showed that as the amount of sulpho-aluminate cement increased, both the initial and final setting times shortened and the compressive strengths for different ages gradually increased, so to however does the cost since sulpho-aluminate cement is more expensive than ordinary Portland cement.

Yuan et al.[65] developed a quick-solidifying foamed concrete for sealing large spaces of a mine to prevent coal fires. The mixture consists of cement, fly ash, water and foam with powdered gypsum added as a solidifying agent to achieve a set time of 15 min to 2 h, depending on the various material proportions. For filling and sealing large underground spaces the foamed concrete mixture is optimized so that its water bleeding and foam collapse rates are low, and it can solidify quickly.

Xi et al.[66] present the results of tests on mixtures of 'cement-based foam material' using different types of surfactants and organic polymer to optimize solidified foam with high stability and water-retention characteristics. Xu et al.[67] studied the mechanical behavior properties of a cemented 'composite foam slurry material' for mine plugging when using various activators.

Each of these studies attempts to optimize some aspect of the foam-cement mixtures; such as strength, fluidity, set time, simplicity, cost, etc. primarily for use in controlling spontaneous combustion in active mines. Since there is no aggregate, the thermal performance of this type of foamed concrete material should be better than Thermocell® grout. However, for use in a high temperature mine fire that has been burning long enough to create a large amount of stored heat energy, solidified foam created using calcium sulpho-aluminate refractory cement is likely to perform better than Portland cement since it is not subject to thermal degradation. However, this type of cement is more expensive than Portland cement and may be cost-prohibitive for large gob areas or mine fires.

Experimental approaches

A number of experimental approaches for extinguishing fires in abandoned mines have been tried or attempted that appear to offer potential, at least under some specific situations, either singly or in combination with other methods. However, these approaches have thus far not been extensively tested or proven. These methods include:

- Methane capture;
- Foam-transported backfilling.

Methane capture

All coal contains some methane, formed during the gradual transformation of organic plant material into coal. The amount of methane varies by grade of coal and depth. Higher grade coal such as anthracite contains more methane than low grade coal such as lignite. The deeper the coal, the higher the amount of methane in coal of the same grade or rank. Methane is released from the coal seam when the coalbed is disturbed by mining, caving and subsidence, or when heated by spontaneous combustion. The gas collects in openings, fractures and fissures and can migrate to the surface through cracks in the strata overlying the coal mine, leading to uncontrolled methane seeps.

The role of methane may be significant in sustaining and intensifying some coal mine fires. As methane seeps into the active combustion zone, it can sustain or intensify a coal fire, possibly even trigger explosions.

At the North Coal mine fire on the Southern Ute Indian Reservation in Southern Colorado (USA), studies indicated that the fire was fueled not only by coal, but also by a large amount of naturally seeping methane flowing into the combustion zone from unburnt coal[68]. A string of 28 wells located downdip of the coal fire was used to intercept and capture the methane before it reached the fire. The system was operated from 2009 through 2016 capturing approximately 13 million cubic feet of methane[69] that was prevented from fueling the fire and represented more than 333,000 tons of CO_2 equivalent[70] that was prevented from being released to the atmosphere. However, the fire continues to burn[71] and it is unclear how much the methane capture system diminished the fire activity, if at all.

It appears unlikely that methane capture alone will be sufficient to effect extinguishment of most coal fires, but it may be useful when employed in conjunction with other methods to reduce the intensity of the fire. If the flow of methane can be intercepted and captured before it reaches the fire, it may be possible to significantly diminish and stress fires in gassy mines to where they can be more easily extinguished by other means. This approach has the added benefit of being able to use the methane for alternative energy sources and reducing greenhouse gases for carbon capture credits.

Foam-transported backfill

In addition to being able to transport moisture and fire-fighting chemicals into the active combustion zone, foam can be used to convey solid particles to effect backfilling and thereby permanently block ventilation. Hallman[72] describes a novel approach for injecting a slurry-like mixture of foam and non-combustible backfill to combat coal mine fires. Mechanically generated foam is mixed with moist sand or other non-combustible backfill to create a slurry mixture (Fig. 10) that is injected through boreholes to fill voids and block fractures. The foam decays as deposition of the backfill occurs such that more and more backfill can be placed, thereby completely filling large openings, voids, and fissures with the backfill material. The foam serves only as the transport medium and provides no long-term presence.

Injection of foamed backfill addresses all three legs of the fire triangle: heat is removed, oxygen is excluded, and the fuel is isolated. The foam-transported backfilling method combines the benefits of multi-phase foam, compressed-nitrogen foam, cellular grout/foamed concrete and hydraulic flushing which should enhance extinguishment capabilities. For combating coal mine fires these benefits include:

- The foam-transported backfill is self-stacking and will smother the fire, absorb heat and block air flow (Fig. 11) like multi-phase foam or foamed gel, but is permanent due to the much higher solids concentration in the foamed backfill material and complete backfilling the method provides.
- When nitrogen gas is used to generate the foam, an inert oxygen-deficient atmosphere is created as the foam decays.

Fig. 10 Starting with pit run sand, water is added to raise the moisture content to 1%−2% below field moisture content, then preformed foam is added to about 30% vol/vol solids to produce a highly flowable, pumpable slurry mixture.

• The foam-backfill slurry can be injected under pressure to penetrate fissures and rubble in order to permanently block ventilation and prevent subsidence similar to grout, but at lower cost than grout and with better thermal performance. Foam-transported backfill is not subject to flash setting or chemical degradation at elevated temperatures.

• Similar to hydraulic flushing, large volumes of a wide variety of backfill materials can be placed at low cost, but with much better control over backfill placement, while reducing water requirements

Several field demonstration pilot projects have been conducted using the foam-transported backfill method in partially collapsed, abandoned, albeit non-burning, room-and-pillar coal mine workings to control surface subsidence[73,74]. Verification results confirmed that large voids had been filled tight to the crown or roof with compact backfill sand (Fig. 12) and narrow fissures or voids between blocks of collapsed overburden were also tightly infilled.

Conclusions

The extinguishment method or combination of methods that offer the best opportunity for success at each coal mine fire will be a function of the specific site conditions; how long the fire has been burning, its depth, number of coal seams present, extent of mining, site geology, surface topography/development, access, material availability, etc.

Fig. 11 Foam transported sand backfill being placed in a room and pillar coal mine.

Extinguishment methods commonly in use to combat coal mine fires are not regularly successful and are also generally expensive. Based on the published results of the extensive extinguishment efforts by the US Bureau of Mines, the overall success rate on 347 Bureau of Mines fire control projects using these common approaches was 47%. Excluding 78 excavation projects, the overall success rate on the remaining 269 Bureau of Mines fire control projects was only 39%.

Implementing these established fire extinguishment approaches is likely to result in similarly low rates of success on future projects. As such, it is important to consider a number of factors to increase the odds for success when selecting a suitable mine fire extinguishment strategy. Is the mine active or inactive? Fully-mechanized or room and pillar? Is the fire deep or shallow? How long has the fire been active? Each mine fire is unique and the extinguishment method or combination of methods that offer the best opportunity for success will depend on the specific fire conditions. Table 1 summarizes the main characteristics of the extinguishment methods discussed.

For a relatively shallow coal seam or mine fire beneath a non-sensitive area, excavation has generally been the preferred method due to a much higher rate of success. Conversely, excavation would not be a suitable method for a coal fire at large depth, or beneath a developed area, sensitive environment or rugged terrain. A well-established fire burning under deep cover in an abandoned underground coal mine for an extended period of time represents a particularly difficult problem. There has been no practical reliable method developed for extinguishment in these cases due to the large amount of stored heat energy generated by the fire, and a new approach is sorely needed in these instances.

The various formulations and types of cemented foam have been reported effective at reducing or inhibiting spontaneous

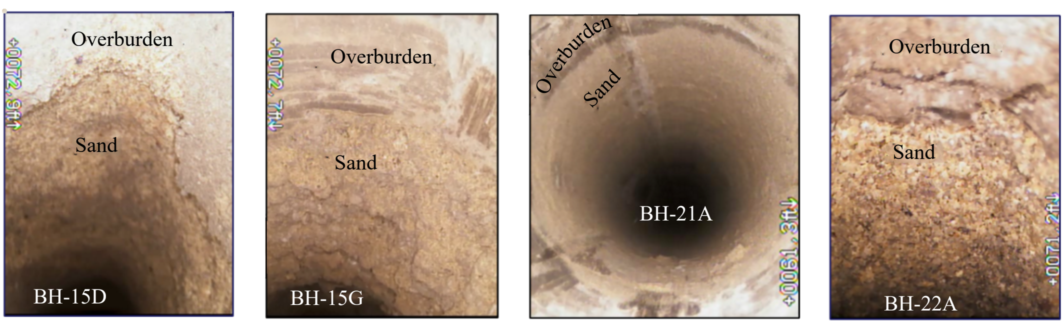

Fig. 12 Verification boring results showing tight contact between the final sand backfill and the roof or crown of the underground void opening.

Table 1. Summary of mine fire control methods.

Method	Mine condition		Depth	Surface Impact	Relative cost	Comments
	Active	Abandoned				
Bulkheads and stoppings	Yes	No	Any	None	Low	Good for reducing spontaneous combustion and recent fires in active mines; used with inerting
Inerting	Yes	No	Any	Little to none	Low to moderate	Good for reducing spontaneous combustion and recent fires in active mines; leakage an issue
Ventilation control*	Yes	No	Any	None	Low	Requires active ventilation system
Surface treatment**	Yes	No	Any	None	Low	Primary use is to inhibit spontaneous combustion
High-expansion foam	Yes	Limited	Any	Little to none	Low	Good for recent fires in active mines
Excavation	Limited	Yes	Shallow	Very high	Very high	Can't be used for developed areas, rugged terrain or deep fires
Isolation	No	Yes	Shallow	High	High	Fire is left to burn indefinitely
Surface seal	No	No	Any	High	Low	Low cost but also low effectiveness
Remote seal	Yes	No	Shallow	Little to none	Low	Ineffective
Barriers	Limited	Yes	Any	Little to none	Moderate	Largely ineffective
Hydraulic backfill	No	Limited	Any	Little to some	Moderate	Effective for small mines in flat seams; large volumes of water required
Pneumatic stowing	Limited	Limited	Any	Some to none	Low	Limited applicability except in active mines; primarily used for subsidence control. Beneficial use of waste.
Grouting	Limited	Yes	Any	Little to some	High	Grout is subject to flash setting and thermal degradation
Multi-phase Foam and gel***	Yes	Yes	Any	Little to none	Moderate	Material dehydrates and cracks with time, limited duration of protection
Cellular Grout****	Yes	Yes	Any	Little to some	High	Good for spontaneous combustion in active mines; Portland cement prone to break down under sustained high temperature
Foam-transported backfill	No	Yes	Any	Little to some	Moderate	Wide range of backfill materials possible, less cost than grout, un-tested on a coal fire

* Includes dynamic pressure balancing as well as reversal. ** Includes chemicals, powders or other coatings. *** Includes foamed gel, and foam stabilized with fly ash, nanoparticles, etc. **** Cellular concrete, foamed concrete, inorganic solidified foam (ISF), inorganic curing foam (ICF) and cement-based foam material (CBFM).

combustion and blocking airflow. These are relatively recent implementations and their long-term effectiveness against a deep seated mine fire has not been demonstrated.

The foam-transported backfilling method also appears to offer promise as the method addresses all three legs of the 'fire triangle' to increase the odds for successful extinguishment. This method combines the benefits of multi-phase foam, compressed-nitrogen foam, cellular grout/foamed concrete and hydraulic flushing, while eliminating many of the draw-backs. However, this approach would not be suitable for controlling spontaneous combustion during modern fully-mechanized mining due to the flowability of the material.

Author contributions

The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.

Data availability

The datasets analyzed during this study are available from the corresponding author on reasonable request.

Conflict of interest

The author declares that there is no conflict of interest.

Dates

Received 4 November 2023; Revised 27 January 2024; Accepted 29 February 2024; Published online 7 April 2024

References

1. Kim AG. 2011. *United States Bureau of Mines: study and control of fires in abandoned mines and waste banks*. In *Coal and Peat Fires: A Global Perspective. Coal - Geology and Combustion*, eds. Stracher GB, Prakash A, Sokol EV. Vol 1. Oxford, UK: Elsevier. pp. 267–305. https://doi.org/10.1016/B978-0-444-52858-2.00016-5
2. Singh RVK. 2013. Spontaneous heating and fire in coal mines. *Procedia Engineering* 62:78–90
3. Rothwell RP. 1875. Fires in mines: their causes, and the means of extinguishing them. *Transactions of the American Institute of Mining* 4:54–76
4. McElroy GE. 1938. *Some Observations on the Causes, Behavior, and Control of Fires in Steep-Pitch Anthracite Mines*. U.S. Bureau of Mines Information Circular IC-7025. Washington, D.C.: U.S. Department of the Interior, Bureau of Mines. pp. 36.
5. Ray SK, Zutshi A, Bhowmick BC, Sahay N, Singh RP. 2000. Fighting mine fires using gases with particular reference to nitrogen. *Journal of the South African Institute of Mining and Metallurgy* 100(4):265–72
6. Ide ST. 2011. *Anatomy of Subsurface Coal Fires: A Case Study of a Coal Fire on the Southern Ute Indian Reservation*. PhD dissertation. Stanford University, US. pp. 190.
7. Calizaya F, Nelson MG, Bateman C, Jha A. 2016. Pressure Balancing Techniques to Control Spontaneous Combustion. *2016 SME Annual Conference and Expo: the future for Mining in a Data-Driven World, Phoenix, Arizona, USA, 2016*. Englewood, Colorado, USA: Society for Mining, Metallurgy and Exploration Inc. pp. 261–64.
8. Lolon SA, Brune JF. 2018. Barometric-induced gob breathing: root cause, effect and recommended best practices. *Proceeding of the Society for Mining, Metallurgy & Exploration Annual Meeting, Minneapolis, Minnesota, USA, 25-28 February, 2018*. Paper 18-12. Englewood, US: Society for Mining, Metallurgy and Exploration (SME). pp. 59–64. www.proceedings.com/content/039/039209webtoc.pdf

9. Rath D. 2012. *Application of inhibitors to prevent spontaneous heating of coal*. Thesis. Department of Mining Engineering, National Institute of Technology Rourkela, Odisha, India. pp. 47. http://ethesis.nitrkl.ac.in/3782/1/Debasis_Rath_108MN036_B.Tech_Mining_Engg._2012.pdf
10. Gusek J, Masloff B, Fodor J. 2012. Engineered Pumpable pHoam™: A new innovative method for mitigating ARD. *2012 Annual Meeting of the West Virginia Surface Mine Drainage Task Force, Morgantown, WV, USA. March 27-28*. US: West Virginia Mine Drainage Task Force. https://wvmdtaskforce.com/past-symposium-papers/2012-symposium-papers/
11. Sloss LL. 2015. *Assessing and Managing Spontaneous Combustion of Coal*. London, UK: IEA Clean Coal Centre.
12. Ozdogan MV, Turan G, Karakus D, Onur AH, Konak G, et al. 2018. Prevention of spontaneous combustion in coal drifts using a lining material: a case study of the Tuncbilek Omerler underground mine, Turkey. *Journal of the Southern African Institute of Mining and Metallurgy* 188(2):149−56
13. Smith AC, Mucho TP, Trevits MA, Cummins M. 2005. The Use of Nitrogen-Enhanced Foam at the Pinnacle Mine Fire. *Proceeding of National Coal Show, Pittsburgh, Pennsylvania, 2015*. pp. 1−15.
14. LaFosse L, Cummins M. 2011. Modern-Foam-Injection Technology for Extinguishing Coal Fires. In *Coal and Peat Fires: A Global Perspective. Coal–Geology and Combustion*, eds. Stracher GB, Prakash A, Sokol EV. Vol. 1. Elsevier. pp. 327−33. https://doi.org/10.1016/B978-0-444-52858-2.00019-0
15. Morton MC. 2012. *Hot as Hell: Firefighting foam heats up coal fire debate in Centralia, Pa*. Earth Magazine. www.earthmagazine.org/article/hot-hell-firefighting-foam-heats-coal-fire-debate-centralia-pa
16. Cummins M. 2016. *Houston CAFS Problems?* Firehouse Forums. https://forums.firehouse.com/forum/emergency-vehicles-operation/apparatus-innovation/31056-houston-cafs-problems
17. Chakraborty B. 2021. *Toxic foam used to put out Illinois coal mine fire, records show*. www.washingtonexaminer.com/news/2633320/toxic-foam-used-to-put-out-illinois-coal-mine-fire-records-show/
18. Associated Press. 2022. *Illinois Sues Mine Over Use of Toxic Foam to Control Fire*. US News and World Report. https://apnews.com/article/business-environment-illinois-5839ed55173c9ad737dbad723a68af64
19. Philbin DR, Holbrook JA II. 1988. Progress toward abatement of mine fires in the anthracite coal fields. *Proceeding of Mine Drainage and Surface Mine Reclamation, US Bureau of Mines Information Circular IC 9184*. Washington DC, USA: US Government Printing Office. pp. 330-36.
20. Magnuson MO. 1974. *Control of fires in abandoned mines in the Eastern Bituminous region of the United States. US Bureau of Mines Supplement to Bulletin 590*. Technical Report. US Government Printing Office, Washington DC. pp. 53. www.osti.gov/biblio/5418089
21. Rushworth P, Haefner BD, Hynes JL, Streufert RK. 1989. *Reconnaissance study of coal fires in inactive colorado coal mines (No. 26)*. Colorado Geological Survey, Department of Natural Resources, Denver, Colorado. pp. 60.
22. Sinha A. 2018. *BCCl to mine coal under DC line to douse raging inferno*. The Pioneer, Ranchi, India.
23. Griffith FE, Magnuson MO, Toothman GJR. 1960. *Control of Fires in Inactive Coal Formations in the United States (No. BM-BULL-590)*. Technical Report. Bureau of Mines, Pittsburgh, PA (USA). Health and Safety Research Testing Center. www.osti.gov/biblio/7312760
24. Mitchell DW, Bruhn RW, Winschel LJ, Michalski SR. 1984. Interpreting the state of fires in abandoned underground mines. *Proceeding of Workshops on Combating Mine Fires, US Bureau of Mines, Pittsburg Research Center, Pittsburg, PA, 1984*. Washington DC, USA: US Government Printing Office.
25. Zhang X, Xu J, Xi G, Deng J, Wen H. 2008. Model and control of high-temperature coal fires. *Proceeding of Spontaneous Coal Seam Fires: Mitigating a Global Disaster, ERSEC Ecological Book Series, UNESCO, Beijing, China*. vol. 4. China: Tsinghua University Press. pp. 544−53. https://unesdoc.unesco.org/ark:/48223/pf0000159538
26. Chaiken RF, Brennan RJ, Heisey BS, Kim AG, Malenka WT, et al. 1983. *Problems in the control of Anthracite Mine Fires: a case study of the Centralia Mine Fire (August 1980). Report of Investigations RI 8799*. US Government Printing Office, Washington DC. pp. 93.
27. Dalverny LE. 1988. Heat Removal Methods for Control of Underground Abandoned Coal Mine Fires. *Proc. Mine Drainage and Surface Mine Reclamation Conference, Pittsburg. PA, April 17−22*. Washington DC, USA: Office of Surface Mining Reclamation and Enforcement, US Government Printing Office. pp. 343−47.
28. Kim AG, Chaiken RF. 1993. *Fires in abandoned coal mines and waste banks. US Bureau of Mines Information Circular IC 9352*. Washington DC: US Department of the Interior, Bureau of Mines. pp. 58.
29. Jolley TR, Russell HW. 1959. *Control of Fires in Inactive Coal Deposits in Western United States, Including Alaska, 1948−1958 (No. BM-IC-7932)*.BureauofMines,WashingtonDC,USA.https://dggs.alaska.gov/webpubs/usbm/ic/text/ic7932.pdf
30. Shellenberger FH, Donner DL. 1979. *Controlling fires in unmined coal deposits and abandoned coal mines in the Western United States and Alaska. US Bureau of Mines Progress Report 10047*. US Government Printing Office, Washington DC. pp. 150.
31. Renner S. 2005. *Report on the status of fires at abandoned underground coal mines in Colorado*. Report. State of Colorado, Department of Natural Resources, Division of Minerals of Geology, Denver, Colorado.
32. Nagy J, Mitchell DW, Murphy EM. 1964. *Sealing a Coal-mine Passageway through a Borehole: a Progress Report. US Bureau of Mines Report of Investigations RI 6453*. Technical Report. US Government Printing Office, Washington DC.
33. Gray TA, Glogowski P, Crayne LM, Trevits MA, Smith AC. (Eds.) 2006. Evaluation of remotely installed mine seals for mine fire control. *Proceedings of the 11th US/North American Mine Ventilation Symposium. 5-7 June 2006, University Park Pennsylvania, USA*, eds. Mutmansky JM, Ramani RV. London, UK: Taylor & Francis Publishing. pp. 367−72. www.cdc.gov/niosh/mining/works/coversheet1035.html
34. Ashmead DC. 1927. Mining of thin coal beds in the Anthracite Region of Pennsylvania. Bulletin 245. Washing DC, US: US Bureau of Mines, US Government Printing Office. pp. 113.
35. Davis JB. 1897. *The method and cost of flushing culm into anthracite mines*. Letter report. Anthracite Coal Operators Association presented in Report of the Bureau of Mines of the Department of Internal Affairs of Pennsylvania. State Printer of Pennsylvania, Harrisburg, Pennsylvania, USA. 10: xxxv−li
36. Kuenzer C, Zhang J, Sun Y, Jia Y, Dech S. 2012. Coal fires revisited: the Wuda Coal Field in the aftermath of extensive coal fire research and accelerating extinguishing activities. *International Journal of Coal Geology* 102:75−86
37. Devers PH. 1908. Fighting fire in an Anthracite Coal Mine. *Engineering and Mining Journal* 86:86−89
38. Lynde F. 1909. Fighting a coal mine fire. *Engineering and Mining Journal* 88(12):565
39. Walker JS. 1993. *State of the Art Techniques for Backfilling Abandoned Mine Voids*. Vol. 9359. US: Department of the Interior, Bureau of Mines.
40. Dutt AB. 1950. Sand-stowing. *Proceedings of the National Institute of Sciences of India* 16(6):513−20
41. Heavilon JL, Barton TA, Jones DA. 1967. *U.S. method for mine fire control*. U.S. Patent No. 3, 421, 587.
42. McCall WC. 2011. The new ACI 301, specifications for structural concrete. *Concrete International* 33(4):66−69
43. Hagar I. 2013. Behaviour of cement concrete at high temperature. *Bulletin of the Polish Academy of Sciences Technical Sciences* 61(1):145−54
44. Cray D. 2010. *Deep Underground, miles of hidden wildfires rage*. Time Magazine. www.schwartzreport.net/2010/07/29/deep-underground-miles-of-hidden-wildfires-rage/

45. Malin L. 2012. 2012 Abandoned Mine Reclamation Awards, Nomination, Maclean 3 Project. Spring Canyon, Carbon County, Utah: National Association of Abandoned Mine Land Programs. https://vdocuments.mx/maclean-3-project-utah-division-of-oil-award-nomination-utah-abandoned-mine-reclamation.html?page=1
46. Michaylov M. 1995. Preventing and Fighting Spontaneous Combustion by Foam Pulp in Bobov Dol Coal Field. *Proceeding of 7th US Mine Ventilation Symposium, Lexington, KY (United States), 5–7 June 1995*. Littleton, Colorado USA: Society for Mining, Metallurgy and Exploration. pp. 185–90. www.osti.gov/biblio/269223
47. Zhou F, Ren W, Wang D, Song T, Li X, et al. 2006. Application of three-phase foam to fight an extraordinarily serious coal mine fire. *International Journal of Coal Geology* 67:95–100
48. Shao Z, Wang D, Wang Y, Zhong X, Tang X, et al. 2015. Controlling coal fires using the three-phase foam and water mist techniques in the Anjialing Open Pit Mine, China. *Natural Hazards* 75(2):1833–52
49. Vinogradov AV, Kuprin DS, Abduragimov IM, Kuprin GN, Serebriyakov E, at al. 2016. Silica foams for fire prevention and firefighting. *ACS Applied Materials & Interfaces* 8(1):294–301
50. Rabajczyk A, Zielecka M, Gniazdowska J. 2022. Application of nanotechnology in extinguishing agents. *Materials* 15:8876
51. Trevits MA, Smith AC, Mucho TP, Ozment A, Walsh JB, et al. 2006. Mine fires – measuring the efficacy of gas-enhanced foam. *Proceeding of the 11th US/North American Mine Ventilation Symposium, Pennsylvania, USA, 5–7 June, 2006*, eds. Mutmansky JM and Ramani RV. London, UK: CRC Press. pp. 309–16. https://doi.org/10.1201/9781439833391
52. Chasko LL, Conti RS, Derick RL, Krump MR, Lazzara CP. 2010. In-mine study of high-expansion firefighting foam. *Transactions of the Society for Mining, Metallurgy, and Exploration*. 328(1):507-16. www.cdc.gov/niosh/mining%5C/UserFiles/works/pdfs/imsohe.pdf
53. Miron Y. 1995. Gel sealants for the mitigation of spontaneous heatings in coal mines. Report. No. PB-96-131966/XAB; BUMINES-RI-9585. Pittsburgh, PA, US: Bureau of Mines, Pittsburgh Research Center.
54. Song Z, Kuenzer C. 2014. Coal fires in China over the last decade: a comprehensive review. *International Journal of Coal Geology* 133(1):72–99
55. Deng J, Xiao Y, Lu J, Wen H, Jin Y. 2015. Application of composite fly ash gel to extinguish outcrop coal fires in China. *Natural Hazards* 79(2):881–98
56. Zhang L, Qin B. 2014. Study on the gelation of foamed gel for preventing the spontaneous combustion of coal. *Journal of Spectroscopy* 2014:163742
57. Zhang L, Qin B. 2014. Development of a new material for mine fire control. *Combustion Science and Technology* 186(7):928–42
58. Zhang L, Shi B, Qin B, Li Y, Wu Q. 2015. Research of the formation of foamed gel with fly ash. *Chemical Engineering Transactions* 46:61–6
59. Feiler JJ, Colaizzi GJ. 1996. I*HI Mine Fire Control Project Utilizing Foamed Grout Technology, Rifle, Colorado*. Technical Report. U.S. Bureau of Mines, U.S. Department of the Interior Research Contract Report 14320395H0002, Goodson and Associates, Inc., Colorado.
60. Colaizzi GJ. 2004. Prevention, control and/or extinguishment of coal seam fires using cellular grout. *International Journal of Coal Geology* 59(1-2):75–81
61. Stracher G, Stracher GB, Prakash A, Sokol EV. (Eds.) 2012. Coal Fires of the United States. In *Coal and Peat Fires: A Global Perspective*. vol. 2. Netherlands: Elsevier. pp. 441-528. https://doi.org/10.1016/B978-0-444-59412-9.00023-5
62. Szurgacz D, Tutak M, Brodny J, Sobik L, Zhironkina O. 2020. The method of combating coal spontaneous combustion hazard in goafs – a case study. *Energies* 13(17):4538
63. Qin BT, Lu Y. 2013. Experimental research on inorganic solidified foam for sealing air leakage in coal mines. *International Journal of Mining Science and Technology* 23(1):151–55
64. Wen H, Zhang D, Yu Z, Zheng X, Fan S, et al. 2017. Experimental study and application of inorganic solidified foam filling material for coal mines. *Advances in Materials Science and Engineering* 2017:3419801
65. Yuan K, Gong Y, Fu S, Xu S, Liu K, et al. 2020. Development of quick-solidifying foamed concrete for mine fires extinguishment and the basic performances tests. *Frontiers in Materials* 7:587998
66. Xi X, Jiang S, Yin C, Wu Z. 2021. Experimental investigation on cement-based foam developed to prevent spontaneous combustion of coal by plugging air leakage. *Fuel* 301(23):121091
67. Xu Y, Qin B, Shi Q, Hao M, Shao X, et. al. 2023. Study on the adsorption of cement particles on surfactant and its effect on the characteristics of inorganic curing foam for prevention of coal spontaneous combustion in a goaf. *Fuel* 333(2):126407
68. Ide ST, Orr FM Jr. 2011. Comparison of methods to estimate the rate of CO_2 emissions and coal consumption from a coal fire near Durango, CO. *International Journal of Coal Geology* 86(1):95–107
69. Thompson J. 2015. Could fugitive methane help out remote communities?. High Country News, Paonia, Colorado. www.hcn.org/articles/bridging-science-and-solutions/
70. Spray K. 2017. *Southern Ute Indian tribe westside CBM seep capture and use project*. Monitoring Report #6. Southern Ute Indian Tribe Growth Fund, Department of Energy, US. http://externalassets.cooleffect.org/lib/content/wp-content/uploads/2018/05/03001653/Southern-Ute-CBM-MONIT_REP_937_01JAN2016_TO_30NOV2016.pdf
71. Colorado Department of Natural Resources, Division. 2019. *Colorado Underground Coal Mine Fires 2018*. Inventory Report.
72. Hallman DS. 2022. Foamed Backfilling for Combatting Mine Fires. *Environmental Geotechnics* 9(5):310–17
73. Hallman DS. 2018. Foamed sand backfilling for subsidence mitigation at Glenrock, Wyoming. *Proc. Rocky Mountain Geo-Conference 2018, Golden, Colorado, November 2, 2018*. US: American Society of Civil Engineers, Geotechnical Practice Publication No. 12. pp. 151-67. https://doi.org/10.1061/9780784481936.012
74. Breiner J, Hallman DS, Wagner E. 2021. Foam transported sand backfill for subsidence mitigation at Noonan, N.D. *41th Annual Conference of the National Association of Abandoned Mine Land Programs, September 13, online*.