A New (Geo)Logical Approach to Combating Mine Fires (Patent Pending)

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Abstract

The Office of Surface Mining Reclamation and Enforcement considers coal mine fires to be Priority 1 Hazards and in 2013 listed 98 active underground mine fires burning across 9 states. Many of these abandoned mine fires have been burning for decades, and in some cases, for more than a century, which contributes to the hazards they present; vents of hot combustion gases, toxic fumes, large surface cracks, fissures and other subsidence openings. Forcing even entire towns to be abandoned in some instances.

Although mine fires and attempts to extinguish them have existed for as long as coal mining, there has been no reliable practical method developed for extinguishing long-standing deep-seated mine fires in abandoned workings. Using previously documented results, whether successful or not, as reference while adopting more modern technology, and technology from other fields, to improve upon the results, a new method to extinguish mine fires in a reliable and economic fashion has been developed.

This new "foam slurry" method consists of mixing fire-fighting foam with noncombustible solids to create a slurry mixture which is then flushed into the mine openings, rubble zones, and fractures to extinguish a mine fire. When injected through boreholes into the mine workings in the area of the fire, the foam slurry will inundate the active fire with moisture, block ventilation and absorb heat. Nitrogen gas released as the bubbles pop and the foam dissipates will create an inert oxygen deficient atmosphere to inhibit combustion. And, the noncombustible solid particles suspended in the foam backfill the mine workings, rubble zones, burnt out areas, and fractures to permanently block ventilation after the foam dissipates. Thus, injection of foam slurry addresses all three legs of the fire triangle: heat is removed, oxygen is excluded, and the fuel is isolated, which increases the odds for success.

INTRODUCTION

The Office of Surface Mining Reclamation and Enforcement (OSMRE) considers underground coal mine fires to be Priority 1 Hazards, which is their highest hazard classification. According to the OSMRE Abandoned Mine Land Inventory System, there were a total of 98 active underground mine fires burning in 9 states in 2013, which is believed to be an underestimate. Many of these abandoned mine fires have been burning for decades, and in some cases, for more than a century, which contributes to the hazards presented. Mine fires create health hazards through venting of hot combustion gases, emission of toxic fumes, large surface cracks, fissures and other subsidence openings as the coal burns, and may trigger wildfires; forcing even entire towns to be abandoned in some instances (e.g. Centralia). The uncontrolled burning in mine fires creates a variety of environmental hazards; with emissions from such fires variously estimated at 2-3 percent of annual global greenhouse gas emissions (Stracher 2010).

Although mine fires and attempts to extinguish them have existed for as long as coal mining, there has thus far been no reliable practical method for extinguishing long-standing deep-seated mine fires in abandoned workings. Due to the high cost, difficulty, and low success rate of methods that have traditionally been applied in such instances, these fires are often left to burn unabated, and can burn for a considerable length of time.

The mine fire research and control efforts conducted by the US Department of Interior Bureau of Mines 1910 through 1996 as documented by McElroy (1938), Jolley and Russell, (1959), Griffith, et al (1960), Shellenberger and Donner, (1979), Chaiken, et al (1983), Kim and Chaiken (1993), and Kim (2012) provide useful reference for mine fire abatement techniques that have commonly or traditionally been applied. Using the insight and knowledge gained from these efforts, whether successful or not, as reference while adopting more modern technology, and technology from other fields, to improve upon the results, a new method to extinguish mine fires in a reliable and economic fashion has been developed. This new "foam slurry" method (patent pending) consists of mixing foam with mineral soil or other noncombustible solids to create a slurry mixture which is then flushed into the mine openings, rubble zones, and fractures to extinguish a mine fire.

When injected into the mine workings in the area of the fire, the foam slurry inundates the active fire with moisture, excludes oxygen, blocks ventilation and absorbs heat. Nitrogen gas released as the foam decays and the bubbles dissipate creates an inert oxygen deficient atmosphere to inhibit combustion. And, the noncombustible solid particles suspended in the foam fill the mine workings, rubble zones, burnt out areas, and fractures to surround and isolate the coal from oxygen and permanently block ventilation after the foam dissipates. Thus, injection of foam slurry addresses all three legs of the fire triangle: heat is removed, oxygen is excluded, and the fuel is isolated, which significantly increases the opportunity for success. Other benefits of the foam slurry approach include:

- Very little water is used
- Foam can be easily adjusted to control the viscosity or slump of the mixture
- The foam can be engineered to control placement of the noncombustible solids
- Potential for explosive steam and slurry eruptions is eliminated
- Aggregate size can be adjusted to suit the ground conditions
- High velocity turbulent flow is not required to maintain the solids in suspension
- Foam slurry readily flows and deposits noncombustible solids into nooks and crevices and other dead end areas
- Local materials otherwise normally considered waste can be used
- No cementitious binder is required
- Wider borehole spacing is possible

BACKGROUND

Coal Combustion

Understanding the coal combustion process is essential for evaluating and implementing fire control measures. On a very basic level, oxygen in the air reacts with carbon in the coal to produce carbon dioxide and heat in an exothermic process:

$$C + O_2 \rightarrow CO_2 + HEAT$$

The rate of heat generation is an exponential function of temperature while the rate of heat loss is a linear function of temperature; the reaction rate therefore increases faster than the heat loss increases as the temperature rises. If the heat produced is not dissipated, the coal will self-heat to the point of self-ignition, or spontaneous combustion. The self-heating tendency of coal varies with its porosity, moisture content, ventilation rate, and with the humidity of the ventilating air.

Spontaneous combustion is more likely when the coal is low quality with high volatile matter content and high pyrite content, and broken or crushed, as this increases the surface area per unit volume of coal. Poor ventilation and moisture are also contributing factors. These conditions are common in abandoned coal mines where the workings are generally collapsed and caved to some extent, and remnant coal pillars, roof coals, rider coals, and/or carbonaceous shales which eventually collapse into the mine openings are capable of initiating and sustaining combustion.

Studies have shown that self-heating leading to thermal runaway and spontaneous combustion can be initiated in sub-bituminous coal at temperatures starting as low as 85°F under the right conditions (Kuchta, et al, 1980; Smith and Lazarra, 1987; Miron, et al, 1990). The coal will continue to self-heat if there is a steady supply of oxygen and the heat being produced is not dissipated. Once initiated, heating can occur rapidly up to 212°F at which point the energy generated by oxidation is consumed to vaporize moisture in the coal. McElroy (1938) describes this process as "conditioning" of the coal, where the intense heat from a fire drives off water from the surrounding coal. Once the water is eliminated, the temperature can rise rapidly to the self-ignition point as oxidation continues and a vigorous fire can develop very quickly because of this preheating process. The self-ignition temperature may be as low as 350°F in some coal, and the coal can ignite without an external ignition source once this temperature is reached if sufficient oxygen is available.

Fire Propagation and Discontinuous Fire Zones

Once ignited, heat and rising combustion gases create low pressure in the area of a fire that draws in more air. The mine fire will commonly burn toward this source of airflow in the oxygen-constrained environment rather than 'down wind' as in a wildfire where virtually unlimited oxygen is present and the fire is generally fuel-constrained. Unless the area is very well ventilated, the fire will consume much of the available oxygen in the immediate vicinity of the fire. Therefore, the highest oxygen concentrations will be where the air enters the fire zone and the fire advances in that direction. A fire near the outcrop or at shallow depth of a dipping bed can draw air from within the mine, causing the fire to descend and propagate down dip. McElroy (1938) indicates that in some instances, fires in steeply dipping mines were drawn down onto lower levels or lifts as many as three or four times by air flow breaking through from the lower level workings.

Rising combustion gases can also induce large convective air flows, which can circulate air and combustion gases throughout the mine. The circulation of hot combustion gases underground can transfer heat from the fire to other areas of the mine, which can in turn ignite, often a considerable distance from the original fire site. As the ventilation patterns change, the movement of hot gases can cause the fire to propagate from one area to the next. This process is believed to be responsible for the discontinuous fire zones encountered at a number of abandoned mine fires where active combustion is observed in scattered locations with no apparent propagation pathway (Kim and Chaiken, 1993). This process is described as a heat-spread mechanism of fire propagation in which ignition of the coal can occur well removed from active combustion in the fire zone. At the Centralia mine fire, temperature data showed that active fire zones were separated by cool regions which would not be the case if the fire had spread by direct flames and conductive heat transfer (Chaiken, et al, 1983).

Sinha and Singh (2005) indicate that in the Jharia coalfield it is common for fires to move between closely spaced coal seams due to the circulation of hot gases through caved zones and tunnels, and is known to have caused fires to descend to lower coal seams. Bokum, et al, (2005) report that mine fires in the Wuda coalfield of China often occur in disparate locations due to spontaneous combustion as the heat spreads and the self-ignition temperature of the coal is reached in different areas. Convection currents induced by the rising heat and exhaust of the combustion gases from these hot spots increase oxygen inflow which further fuels the system, allowing large combustion centers to develop.

In the New Castle coalfield of New South Wales, it is common to encounter numerous small mobile hot spots rather than a continuous fire front, with fire centers often 100 meters or more from each other or exhaust vents (McNally, et al, 1996). Because of the dip of the coal seams, air enters the mine workings at low elevation and is drawn up dip by convection before being exhausted through chimney-like vents along the hilltops. Fueled by the airflow from convection currents, the fires follow zones of broken coal along open manways or roadways.

Heat Retention

As early as 1875, it was documented that the area of a mine on fire must be hermetically sealed for a long enough period of time for the heated coal to cool sufficiently to prevent re-ignition when air was reintroduced (Rothwell, 1875). Fires which have been sealed off and fully extinguished can re-ignite when oxygen is reintroduced, even after considerable periods of time. McElroy (1938) reports of mine fires quickly becoming very active by ventilation provided through new fissures or a break in a seal, despite having been entirely dormant for 15 to 25 years after being declared extinguished.

Rushworth, et al (1989) indicate that unless the temperature is brought to below 200°F a fire may be considered likely to re-ignite. Kim and Chaiken (1993) note that a breach in a seal before the coal and surrounding rock have cooled below a temperature of 212ºF will probably reactivate the fire due to the conditioning effect. They estimate that it could take 20 to 30 years for stored heat from a fire to be lost by direct transfer of the heat energy through the solid overburden, i.e. conduction.

The time to cool a fire zone by thermal conduction through the overburden can be approximated by the following equation:

$$t = x^2/k$$

where;
t is the time,
x is the overburden thickness, and
k is the thermal diffusivity of the overburden

Published values of the thermal diffusivity of common coalfield rocks (Robertson, 1988) as presented in Table 1 can be used with this equation to provide a crude estimate of the time for heat transfer to occur through the overburden by conduction relative to the type of overburden and its thickness. Figure 1 provides a graphical representation of the estimated time for heat transfer by conduction versus overburden thickness using the data presented in Table 1. As indicated by these results, fires burning beneath more than 50 feet or so of cover may require several decades to cool. At depths of 200 feet or more, the heat may be retained more or less indefinitely.

Material Type	Thermal Diffusivity (10^{-3} cm^2/sec)
Sandstone	0.013
Limestone	0.011
Shale	0.008
Clay	0.005

Table 1 - Thermal Diffusivity of some Common Coalfield Rocks

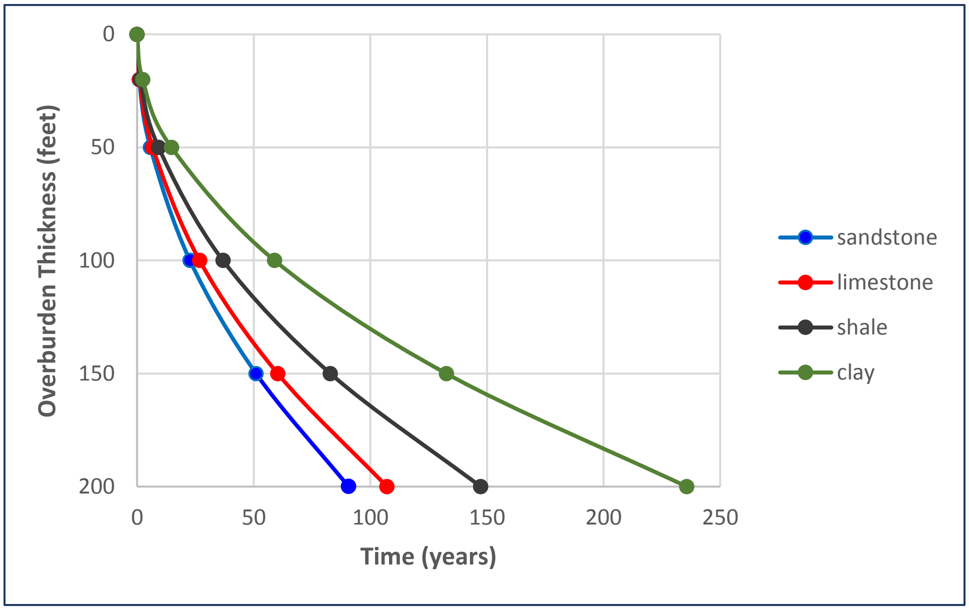

Figure 1 – Heat Loss by Conduction

Geologic Factors affecting Mine Fires

Fracturing of the overburden is an inevitable consequence of an underground coal mine fire as the fire consumes a portion of the coal, removing support from the overlying strata which then fracture and cave into the mine void. The character and extent of the fracturing and subsidence features that may result depend upon many factors, such as the depth to the mine workings and the competence of intervening rock units, however the subsidence process can often generate cracks and openings that have direct communication to the surface and are capable of supplying large quantities of air to a fire. Even in the absence of observable subsidence, micro-fracturing and fissuring of the overburden is likely to have occurred as the rock mass strains and deforms in response to the coal that was removed by mining, as well as the coal consumed by the fire. Timbers that may have been used to provide ground support during mining are obviously consumed in the early stages of a mine fire, which further contributes to caving and collapse.

Kuenzer and Stracher (2012) indicate that in all coal fire areas they have visited, coal fires lead to the formation of new geomorphic features and changes in the landscape. The extreme temperatures of a coal mine fire cause the rock overlying the combustion zone to dehydrate, alter, expand and contract, thereby creating fissures and subsidence cracks, and ultimately collapse, that allow increased air flow to the fire. Wolf and Bruining (2006) indicate that fracturing and fissuring from drying and shrinking in the overburden can extend several hundred meters above the fire, and the entire slope may act as a highly permeable breathing zone. Koveva (2013) suggests that "*It is reasonable to assume that ambient fissures and the combustion fissures are connected by heavily fractured and / or subsidence induced void regions* *lying atop burning coal seams. This network of fractures and voids in the subsurface suggests that high volumes of air can feed the combustion zone.*"

Recent studies of combustion gas emissions from burning underground coal fires by the USGS (Engle et al 2012) have shown that these gases can be emitted by diffusion through the soil as much as by venting through cracks and fissures, even in areas where the ground was not hot and there were no obvious signs of the underlying fire. Diffused emissions are very evident at many fire sites where creosote, tar, and other minerals from venting combustion gases have been deposited on the surface of the soil where no exhaust vent is discernable. If a fire can vent exhaust gases through the surficial soil cover, then it is equally likely the fire can breathe in oxygen just as well, although this may be virtually impossible to detect or measure due to low unit inflow rates over any one specific area.

McElroy (1938) observed that "*Even though the caved ground and soil surface appear to be compact, they are essentially porous as far as allowing air to pass through is concerned, and large openings exist in the broken strata. All fires….therefore, have what amounts to an open top*".

EXTINGUISHMENT METHODS

Traditional Control Measures

Although mine fires and attempts to extinguish them have existed for as long as coal mining, there has thus far been no reliable practical method developed for extinguishing a mine fire that has been burning for a long time under deep cover. A fire which has been burning in an abandoned underground coal mine for any appreciable length of time represents a highly complex three dimensional geological problem. The extinguishment methods currently in use to combat such fires are generally expensive and not routinely successful.

In order to extinguish a fire it is necessary to prevent the fire triangle; heat, fuel, and oxygen combination from occurring. One or more of these three components must be removed or eliminated by some means in order to extinguish a fire. Singh (2013) provides a useful summary of the current methods and techniques that are in general use throughout the world to extinguish coal mine fires; a list that includes:

- Application of steam or water mist
- Application of a surface coating or sealant material to prevent oxidation
- Dynamic pressure balancing, ventilation control
- Inertization through Nitrogen or Carbon Dioxide gas injection
- Cryogenic Injection
- Injection of hydrogel in coal mass
- Application of fire-fighting chemicals
- High-expansion foam
- Excavation

- Isolation
- Inundation with water
- Surface seals
- Noncombustible Barriers
- Underground Sealing with stoppings or bulkheads
- Grouting
- Hydraulic Backfilling or 'Flushing'
- Pneumatic stowing

Many of these methods are commonly employed for combating fires in active coal mines and are not applicable for long-standing abandoned mine fires. Chemical fire suppressants, inert gas, high-expansion foam, hydrogel, or foamed gel injection all have a short effective life. In the case of a fire that has been burning for a long time, the fire will re-ignite once the foam, gel, or other chemical treatment dissipates as a result of the large amount of residual heat present. For this reason, fire control methods that only serve to temporarily remove oxygen from the combustion zone are unlikely to be effective for well-established mine fires.

US Bureau of Mines Experience

The US Department of Interior Bureau of Mines conducted mine fire research and control efforts from 1910 up until 1996 when it was closed by Congress. Originally created in 1910 to reduce accidents and improve safety in operating coal mines, the Bureau of Mines was also authorized for researching and combating fires in abandoned mines from 1948 up until 1977 when Congress passed the Surface Mining Control and Reclamation Act State and OSMRE was formed and given jurisdiction. After 1949 when it began documenting fire-control projects, extinguishment methods and costs, the Bureau of Mines performed control or extinguishment efforts on approximately 347 mine fires (Kim 2012)

Table 2 summarizes the US Bureau of Mines experience with various extinguishment methods on mine fire control projects for which such data are available. Based on the Bureau of Mines experience, excavation was found to be the most effective control method, but it was also the most expensive. Surface seals were considered the only viable approach for a well-established fire under deep cover and were used more often than other methods as this approach was the least costly, but was only moderately effective. Although its overall success rate was low, flushing was considered effective, but only for small fires in flat coal beds.

		Method				
		Excavation	Surface seal	Flushing	Seal or Barrier	Flooding or Infiltration
Location	Eastern Anthracite	80% (8 of 10)	50% (1 of 2)	43% (6 of 14)		
	Eastern Bituminous	70% (40 of 57)	42% (36 of 86)	27% (7 of 27)	24% (6 of 25)	0% (0 of 3)
	Active Mines			50% (12 of 24)	21% (5 of 24)	59% (17 of 29)
	Colorado	100% (2 of 2)	49% (18 of 37)		40% (2 of 5)	
	Summary	72% (50 of 69)	44% (55 of 125)	32% (25 of 65)	24% (13 of 54)	53% (17 of 32)

Table 2 – US Bureau of Mines Experience with Various Fire Control Measures

Based on the data summarized in Table 2, the overall success rate on fire control projects using these typical approaches for controlling abandoned mine fires is less than 50 percent (138 successful out of 292 attempts). Excluding excavation, the overall success rate on Bureau fire control projects was only around 39 percent (88 out of 223 attempts). Unfortunately going forward, the success rates using these same methods are likely to be similar or lower considering that the mine fires that have continued to burn unabated thus far are likely larger more complex fires, or the mine fires which do remain will become larger and more complex with time.

Detailed documentation of the Bureau of Mines fire control efforts by McElroy (1938), Jolley and Russell (1959), Griffith, et al (1960), Magnuson (1974), Shellenberger and Donner (1979), Chaiken, et al (1983), Kim and Chaiken (1993), and Kim (2012) provide useful reference for instances or situations in which the various mine fire abatement techniques employed have been successful. Equally as important, these reports also provide detailed description of the reasons or cause for failure in situations and conditions for which the techniques used were unsuccessful. Following is a more detailed overview of the relative strengths and weaknesses of some of these more common extinguishment methods used for fires in abandoned mines, based largely on the excellent documentation of the extensive Bureau of Mines experience.

Excavation

For fires in active mines or shallow abandoned mine workings direct attack of the fire by excavation and quenching the burning coal with water is the most reliable method for extinguishing the fire. However, for a deep-seated fire in an abandoned mine this approach quickly becomes cost prohibitive as the fire cannot be attacked directly to excavate and quench the burning coal within normal economic constraints.

Isolation

Excavating a continuous trench around an underground mine fire has been used to create a noncombustible zone to isolate the burning coal and keep the fire from spreading. For relatively shallow mine fires this is an excellent approach to create a continuous barrier across which the fire cannot spread. However, within 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. As the depth to the fire increases, the cost of this method increases exponentially, quickly becoming prohibitive in most instances.

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

Inundation with Water

Efforts to quench a mine fire directly and cool the coal and surrounding rock mass with water by flooding the mine have been successful in limited instances where complete inundation could be achieved, such as for mines which are below the water table and were dewatered for mining. Attempts to flood a mine by creating dams and seals and filling the workings with water by pumping have generally been unsuccessful due to leakage of the water and inability to completely inundate the fire. In some cases, fires have been extinguished by completely flooding the mine with water; 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 areas where they didn't exist previously (Rothwell 1875; Griffith, et al, 1960).

Attempts to extinguish a fire with water percolated into the mine from surface application, infiltration from ponding, or by injection through boreholes, has also been attempted at many mine fires, with very 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 by-passed 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. 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.

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; accumulating combustion gases and denying oxygen to smother the fire.

Subsidence induced fracturing or erosion of a surface seal can allow air to enter and reignite an inactive fire due to the amount of heat retained in the rock mass. Kim and Chaiken (1993) suggest that a surface seal must be maintained for a period of 10 to 20 years while all the stored heat dissipates in order to extinguish a fire. However, in practice this is difficult to achieve and surface seals frequently fail due to settling, drying, shrinkage, subsidence, slope failure, or increased fire activity.

Freeze/thaw cycles can induce movement of rocks within the seal material and has been attributed as the apparent cause of vent pathways at some sites (Rushworth, et al 1989). Seasonal and climatic cycles, barometric pressure changes, and weather patterns all place stress on a seal and may compromise its integrity. Pressure differences between the confined space of the mine workings and open atmosphere creates a gradient across seals that can cause leaks and allow air exchange and a renewed supply of oxygen. Chaiken, et al, (1983) indicate that convection currents can develop in sealed areas through leaks as a result of the heat from the fire and resulting variations in gas density. These leaks provide natural ventilation to circulate air and exhaust combustion gases. Studies have shown that coal can smolder indefinitely at 2 percent oxygen concentrations (Dalverny, 1988) such that even slight leakage can sustain a fire indefinitely.

Once a breach in the seal occurs, the fire can regenerate and other vents develop 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 in controlling the fire. Because surface seals disrupt ventilation patterns, the altered flow and circulation of air and hot combustion gases underground may also cause the fire to propagate to other areas of the mine.

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. However, Renner (2005) reports that of the 20 sites in Colorado where surface seals were implemented by the USBM from 1952 through 1974 for extinguishing mine fires, only 8 appeared to be dormant, while 12 were at the time active in 2005, a success rate of only 40 percent.

Similarly, Magnuson (1974) reports that for eastern bituminous mine fires an overall success rate of 42 percent out of 86 attempts, as indicated in Table 2. 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.

<u>Noncombustible Barriers</u>

Placing noncombustible material underground to create a fire-proof barrier in order to isolate a mine fire has been used on many occasions, but with limited success on a historical basis.

In an abandoned mine, construction of the barrier must be conducted remotely through boreholes, which experience has shown is an extremely difficult way to ensure a complete and sufficient barrier is adequately constructed to provide the necessary isolation. As often as not, isolation barriers have failed by being placed in the wrong location due to changes in the fire during, or caused by, the construction activities or inadequate characterization of a discontinuous fire to begin with.

Unsuccessful attempts to install noncombustible barriers include multiple efforts at the now infamous mine fire at Centralia, Pennsylvania which ultimately forced evacuation of the entire town. Failure of the isolation barriers in the case of Centralia can be attributed to the lack of sufficient funding to complete effective barriers, ineffective material placement, poor construction oversight, and underestimating the extent of the fire initially. 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 is akin to leaving a portion of intact coal in a cut-off trench. 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 quite some time before the fire eventually burns itself out.

Underground Seals

Placement of bulkheads and stoppings underground to plug or seal off a fire from the rest of the mine to prevent ventilation and exclude oxygen is common practice in active operating mines where the workings are readily accessible. In this manner mining may continue uninterrupted in one area of a mine while a fire continues to burn in another area.

Since the workings in an abandoned mine generally cannot be safely accessed, there has been a considerable amount of research over the years on suitable means and methods for placing a variety of seals and barriers remotely underground from the surface (e.g. Griffith, et al, 1960, and Nagy, et al 1964). Invariably problems effecting 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 (2006) conclude that attempting to place a reliable seal in a blind fashion without an observation borehole is virtually impossible.

Construction of underground seals remotely also requires locating intact tunnels in which to place the seal, which can be a challenge in of itself 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.

To further complicate sealing efforts, many abandoned mines have numerous ventilation openings that can serve to provide air to the fire. Since a major difficulty in early coal mining was the ability to maintain adequate air flow to the active work area, multiple openings were commonly developed at different levels of the mine to create a natural draft of air to ventilate the workings. Trying to understand the complex ventilation patterns that have resulted, and installing a number of effective seals at the proper locations to prevent ventilation of the fire, is a daunting task.

Rothwell (1875) notes that it is very difficult to make perfectly tight seals as the cover rock is generally broken up to the surface and the fire in an abandoned mine can obtain air through innumerable unnoticed fissures. In a detailed study of 177 fires in the anthracite coal mines of the eastern US, McElroy (1938) reports that underground seals were generally not successful due to the extent of fracturing present and indicates a poor success rate (5 of 24 attempts) in these active mine situations. McElroy reports that fracturing of the rock mass above the fire allowed the fire to breathe to great depth through natural ventilation driven by convection currents.

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 (1983) 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 (1989) 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*".

Thus placement of underground seals to control or extinguish a long-standing 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.

<u>Grouting</u>

Griffith, et al (1960) reports that grouting can be a very effective method to fill voids and exclude air from a fire. The grout extinguishes the fire, stabilizes the ground, and reduces the possibility of re-ignition. Void-fill grouting 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 spots' due to the high cost of the grout.

The high temperature environment of a mine fire can cause flash setting in cementitious grouts which can compromise grout placement by preventing adequate grout takes and suitable distribution of the grout. Shrinkage of grout as it sets can cause cracking and allow air transmission. When heated above a temperature of 212ºF, water entrained in the grout aggregate will convert to steam and expand, which can cause also cracking of the grout.

Feiler and Colaizzi (1996) describe a method for suppressing a mine fire using a hybrid grout to overcome some of the concerns with high temperature performance by mixing foam with cement grout to create cellular concrete. However, the material costs remain high, and attempts to extinguish mine fires by this and other grouting approaches generally involve relatively small grout volumes (less than 5,000 cubic yards) and localized target grouting of the active combustion zone or small fires.

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 (e.g. IHI No. 3 in Colorado, Maclean in Utah, etc.). Grouting 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 (e.g. Cray, 2010; Malin, 2012). Even when a fire is locally contained or extinguished by grouting, the super-heated conditions that exist underground from a fire that has been burning for a long time will cause the coal to re-ignite where oxygen is still present or becomes reintroduced. This can occur years, or even decades later, as oxygen inevitably re-enters through the formation of new cracks and fissures.

However, to grout the entire underground mine area that exceeds the thermal runaway temperature of the coal at most historic mine fires would be impossible within reasonable funding limits. Therefore, due to cost limitations, grouting is generally unlikely to be successful for all but the smallest, relatively young fires, and alternative methods are required to combat long-standing mine fires.

Hydraulic Backfilling or 'Flushing'

The practice of placing large volumes of backfill material into underground workings by means of water is called "flushing". Using water to wash or 'flush' backfill into mine workings hydraulically to extinguish a fire is essentially a method of flooding it, but with solid material instead of water. Flushing can be used as a much more economical alternative to grouting for placing solid material.

The hydraulic backfill, or flushing, method is believed to have originated in the anthracite coalfields beginning as early as 1864 with efforts to protect a church against subsidence (Walker, 1993). 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 (1898) 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 flushing the chambers surrounding the fire with fine culm.

Griffith and Connor (1912) present a study of methods to prevent surface subsidence due to mining beneath Scranton, Pennsylvania and concluded that the only method that combined the necessary strength, ease of application, and reasonable cost was filling the workings with culm, sand, crushed rock, and other fine material that could be washed into the mines with water. Extensive culm piles around Scranton were subsequently placed underground using the flushing method to backfill the extensive mine workings beneath the city. Griffith and Connor report that the method was also widely adopted in Europe where it had been extended and amplified to effect total extraction by flushing the workings with crushed rock, sand, gravel and soil obtained from quarries expressly for that purpose.

McElroy (1938) indicates that hydraulic backfilling with fine culm , which he terms slushing, was a great deal more effective for controlling mine fires than placing seals, having extinguished the fire in 50 percent 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 slushing is prohibitive except for small fire areas. Griffith, et al (1960) also caution that the size of the fire and the area to be backfilled may be prohibitively large unless the backfill material and water can be obtained at reasonable cost.

Chaiken, et al (1983) 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 water flow to carry material down dip to some unknown point. Chaiken, et al (1983) indicte hydraulic flushing to be most effective when deposition can be controlled such that the injected material remains in place.

Philbin and Holbrook (1988) report that flushing with sand had proven successful at extinguishing mine fires in 3 of 3 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. Unfortunately, Philbin and Holbrook also report that blind flushing through boreholes using hydraulic methods has only had about a 50 percent success rate at controlling or extinguishing coal mine fires historically.

Although hydraulic backfilling, or flushing, has been successfully employed to combat mine subsidence and mine fires on occasion in the past, there are several distinct drawbacks to the method, including:

- Hydraulic flushing requires very large volumes of water to be injected with the backfill material.
- For remote sites with limited access, the cost for developing an adequate water supply capable of providing a sufficient flow of water for hydraulic flushing can be prohibitive.

- The slurried backfill material, and water liberated once the solid particles settle from suspension, moves through the mine workings uncontrolled. The water can cause significant deterioration where the mine floor or roof are weak, and in some instances, is reported to have triggered surface subsidence.

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

- Hydraulic deposition of granular materials often results in segregation of the noncombustible material into coarse and fine fractions which can lead to stratification and zones or layers which are permeable to air.

Devers (1908) 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 in this manner required extensive effort to construct elaborate underground bulkheads in workings sloping at 45 degrees and what was estimated to be over a billion gallons of water to flush the clay into the mine. Similarly, Lynde (1909) reports that culm injected by flushing through a number of 6-in diameter boreholes to extinguish a fire that had been burning for more than 50 years was estimated to require 2 billion gallons of water and at a total cost of $2 million (at the time).

Pneumatic Stowing

Pneumatic stowing is a dry process in which compressed air is used to transport and place backfill material in mine workings. This eliminates some of the difficulties with hydraulic methods. Walker (1993) reports that pneumatic stowing was first applied in Germany in 1924, and became the preferred backfilling method there. Dutt (1950) 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 or filling behind tunnel liners.

Heavilon, Barton, and Jones (1967) 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. The technique can also be extended to include the same approach applied to the fire directly for extinguishing. Pneumatic stowing offers better control over 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 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 (Chaiken, et al, 1983).

Other Extinguishment Methods

Multi-Phase Foam

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 rubble. A fire that had been burning for a long time is likely to re-ignite when the foam dissipates due to the amount of latent heat present. Research to overcome this limitation for combating coal mine fires includes the use of multi-phase foam-gel mixtures to improve the stability and viscosity of the foam.

A multi-phase foam composed of foaming agent, water, fly ash, and compound additives has been used successfully in China to combat mine fires (Zhang and Botao, 2014). The fine solids suspended in the foam reportedly coat and seal the coal, effectively hindering the coal from absorbing oxygen, and preventing oxidation of the coal, even after the foam dissipates.

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. However, these approaches have thus far not been extensively tested or proven, or have significant drawbacks, limitation or weakness that have prevented widespread adoption. These include:

- Forced Ventilation Burn-out Control
- Blasting
- Methane Capture
- Slurry Wall
- Polyurethane grout (w/ sodium silicate)
- Chemical Fire-retardant agents

DEVELOPMENT OF A NEW EXTINGUISHMENT METHOD

Requirements

In the case of long-standing fires in abandoned mines, the rock mass has been exposed to intense heat for long periods of time, often many decades. Since the remaining coal and surrounding rock mass is already heated, it must be isolated from air until the temperature reduces to a level below which re-ignition will not occur. For a fire in an abandoned mine which started by spontaneous combustion, residual heat somewhere in the system could easily lead to re-ignition if sufficient oxygen becomes available.

Therefore, ventilation of the mine workings and associated rubble and fracture zones where temperatures are elevated above the thermal runaway temperature of the coal must be prevented to avoid exposing heated coal to oxygen, or spreading and circulating heat to other areas of the mine where oxygen is present. This approach is similar to typical excavation and quench mine fire extinguishing practices where all coal exceeding a minimum temperature of 150ºF (65°C), or even as low as 100ºF (38°C), is excavated, then quenched and cooled with water to prevent re-ignition.

Factors which must be considered when evaluating extinguishment options include the large amount of latent heat present in the rock mass and fracturing and alteration of the overburden which allows the fire to breath. The mine fire abatement method must consider the open top nature of most (all?) mine fire sites and remain functional long enough for heat to dissipate below the re-ignition temperature of the coal. In order to meet these requirements, permanently backfilling the zone that has been heated above the thermal runaway threshold temperature of the coal with noncombustible material is essentially necessary to prevent ventilation and re-ignition long-term.

It is not necessary to entirely fill the mine workings with noncombustible material provided sufficiently high injection volumes are achieved such that remaining mine voids, rubble, cracks, and crevices are not interconnected to a significant degree, and ventilation through the area is effectively prevented. Backfilling should be done in a reliable, efficient, and economic fashion such that a large enough area can be treated to be effective over the entire zone where elevated temperatures are present. Possible backfill methods include:

> **Hydraulic flushing** – has been successfully employed to place large volumes of mine backfill very economically but the method is not very reliable for mine fires.
>
> **Pneumatic injection** – offers better placement control of noncombustible solids than hydraulic flushing but cannot effectively penetrate rubble and is not reliable for mine fires.
>
> **Grouting** – very reliable method for controlled placement of noncombustible solids and filling mine voids but prohibitively expensive for all but the smallest mine fires.

Paste – used extensively in metal mining for economic underground backfill using mine tailings. Requires noncombustible solids with a very specific grain size distribution, sensitive to changes in material grain size distribution, unproven for mine fires.

Foaming Mud Cement – developed in the mid-1990s using foam blended with local soils and cement to create a lower cost grout with better thermal properties. Used successfully to suppress several fires but did not extinguish them. Costs remain too high for large volume injection.

Masloff and Palladino (2008) describe the use of a foam-aggregate mixture to place crushed rock backfill for mitigating potential collapse and surface subsidence effects in a limestone mine located beneath an active landfill in Kansas City, Kansas. The mined void was between five and twenty-five feet high, at a depth of 250 to 300 feet, with a total volume of approximately 150,000 cubic yards, which affected approximately thirty acres on the surface. The backfill material consisted of crusher fines from a limestone quarry which was developed locally in large quantity at little cost. The crusher fines were transported and placed underground using a biodegradable foam as the transport medium rather than water.

The Colorado Division of Reclamation Mining and Safety used a similar foam-aggregate mixture to place sand backfill for subsidence control in coal mine workings beneath a residential neighborhood in Colorado Springs, Colorado (Amundson, et al 2009). For this demonstration project 267 cubic yards of standard ASTM C-33 concrete sand were placed through a single 4-inch diameter borehole using gravity flow to backfill 230 feet of haulage tunnel. Video observation through a second borehole showed the foam-sand slurry mixture behaved as a self-leveling fill conforming tightly into irregularities along the tunnel.

<u>New Geological Approach (Patent Pending)</u>

Modifying the economical foam slurry backfilling approach described by Masloff and Palladino (2008) and Amundson, et al (2009) specifically for use with mine fires to prevent ventilation of the area which has been heated by the fire, provides a new means and method of combating mine fires which offers distinct advantages relative to the approaches that have been traditionally been adopted. The foam slurry approach involves mixing noncombustible solids with nitrogen-enhanced foam to create a slurry suitable for flushing backfill into the mine openings to permanently extinguish a mine fire. When injected into the mine workings in the area of the fire, the foam slurry will block air flow, inundate the active fire with moisture, and absorb heat; inert nitrogen gas released as the foam dissipates creates an oxygen deficient atmosphere; and the noncombustible solid particles suspended in the foam fill the mine workings, rubble zones, burnt out areas, and fractures to surround and isolate the coal and permanently block ventilation after the foam decays. In this manner, injection of foam slurry addresses all three legs of the fire triangle: heat is removed, oxygen is excluded, and the fuel is isolated. As a result, the method provides the greatest opportunity for success; in an economical fashion and at reduced risk for spreading and complicating the fire.

The rheology of the foam slurry mixture allows flushing of non-combustible solids to backfill the zone which has been heated by the fire much effectively and at significantly reduced cost relative to other more conventional approaches; including hydraulic flushing, pneumatic stowing, or grouting. Cost advantages of the foam slurry flushing approach include the ability to use a wide range of low-cost noncombustible materials derived from on-site sources or waste from other industries, low water consumption, and wider borehole spacing.

Backfill Material

Cost advantages provided by the method are due, in part, to the ability to use very low cost noncombustible backfill material. The rheology of the foam slurry mixture is very flexible, thereby allowing a broad range of noncombustible flushing materials to be used. Locally available materials commonly considered waste such as mine tailings, wash plant or crusher fines, slag, dredge sediment, noncombustible spoil, etc. are all excellent sources of material for use with the method that can normally be provided to the project at little to no cost. Waste material often found in conjunction with abandoned coal mines may be used directly, or can be crushed and screened to appropriate size if necessary, for the dual benefit of getting rid of these waste piles as well as providing foam slurry backfill material. Local unconsolidated soil deposits, alluvium, decomposed or weathered bedrock, etc. can often be used directly as pit run material, or screened or crushed as necessary at relatively little cost to provide suitably sized material with an appropriate gradation.

The noncombustible material must contain sufficient fine-grained solids or fines to reduce the transmission of air below what is required to sustain combustion, which varies by coal type and class, and the oxygen content of the air. Generally material with 15 to 50 percent material by weight finer than 0.074 mm (No. 200 sieve size) should be suitable for use with the foam slurry method. The noncombustible material should be well-graded to provide good flow characteristics.

The noncombustible solids must contain sufficient coarse particles of such density that the material consolidates under self-weight as the foam degrades to prevent retention of an open porous structure that is permeable to air. Similarly, the noncombustible material must not set or cure to a hardened state due to the presence of cementitious materials in the mixture to the point where consolidation and collapse of the bubble structure that could allow air flow is prevented. Material which exhibits sufficient soil plasticity to sustain an open crack long-term, or material which will consolidate excessively after deposition, should not be used.

The grain size and grain size distribution of the noncombustible material can be adjusted to match the condition of the mine workings, whether intact or largely caved and rubble filled. Coarse particles up to approximately 1.5-inch in diameter can be placed with the method where open intact mine workings or large voids exist, or anywhere rapid settling is desired. Fine-grained solids can be used for injection into rubble or fractures where additional travel time and penetration are desired.

Foam

Besides the noncombustible material, a non-flammable liquid (usually water), a foaming agent, a foam generator, and a mixing device are all that are required to create the foam slurry mixture.

Foam consists of a continuous liquid phase that forms a cellular bubble structure which surrounds and contains a dispersed gas phase. Surfactant added to the liquid is used as a foaming agent to capture the gas phase and control the properties of the foam. Essentially all surface active agents with the capability of producing a dense, stable, fine-textured foam can be used. The use of water and bio-degradable aqueous foaming agents and additives is generally preferred because of their economy and ease of use. Stabilizers and other additives can be included in the mixture to adjust the viscosity or strength properties of the foam. Additives such as chemical fire retardants, fly ash, or rock dust, can also be added to the foam slurry to further enhance the fire-fighting properties.

Foaming of the fluid mixture is provided by dispersing a gas into the fluid; commonly nitrogen, carbon dioxide, fire combustion gases, or ambient air. Foam is considered to be dry or wet, depending on the gas content. If the foam quality is less than about 50 percent gas, a water phase may form, resulting in 'wet' foam with spherical bubbles and liquid between the bubbles. Above about 75 percent gas, the foam is considered 'dry' and the bubbles are packed together closely and deform each other into polyhedral shapes. If the foam quality is higher than about ninety percent, a separate gas phase may form. The life of gas-enhanced foam is highly dependent on the quality of the foam; "wet" foam has a shorter life (from a few minutes to a few hours) while "dry" foam may last as long as several days.

Bubble size in the foam typically ranges from 0.1 to 3 millimeters, with the foam referred to as either fine- or coarse-textured depending on bubble size. Fine foam texture denotes a high level of bubble dispersion characterized by many small bubbles with a narrow size distribution and a high specific surface area. Coarse foam texture denotes larger bubbles with a broad size distribution and a lower specific surface area. Fine-textured foam tends to have a longer life and greater solids carrying capacity than coarse-textured foam.

The strength and texture of the foam can be adjusted to control suspension time, transport distance, and placement depth of the foam slurry before decay and collapse of the foam structure occurs by varying the type of foaming agent used and adjusting its dilution ratio in the mixture. Similarly, the foam-to-solids ratio is typically adjusted during injection to control the viscosity of the mixture based on field observation and slump testing. This aspect of using foam as the carrier medium allows the placement and movement of the material underground to be controlled which provides distinct advantages relative to hydraulic flushing that relies on high velocity turbulent flow.

Mixing

The foam slurry can be mixed using any method that achieves uniform blending of the noncombustible material, foam, and any additives, to produce a slurry-like consistency; e.g.

drum mixer, paddle mixer, auger conveyor, cement truck, pug mill, etc. The foam slurry can be mixed continuously or in batches, and can be mixed directly at the injection point or at an on-site or off-site batch plant. Because there is no cementitious binder used, foam slurry generated in batches can be held for long periods of time prior to injection if necessary. If the foam begins to degrade, additional foam can be added and the material re-agitated and re-mixed to maintain proper flow characteristics of the slurry.

Injecting

When placing noncombustible material along the perimeter of the treatment area, a high-viscosity, low-slump mix using weak, coarse-textured foam that allows the solids to settle rapidly from suspension near the injection point can be used to limit excursion of the material outside the prescribed area. A de-foaming agent can also be injected simultaneously with the foam slurry to destroy the bubble structure in the foam upon entry and cause the solid particles to deposit rapidly near the injection point. When placing noncombustible material within a large treatment area, a low-viscosity, high-mobility slurry using a stronge, durable, fine-textured foam that allows greater travel distance can be used in order to minimize the number of injection boreholes required. Because high-velocity turbulent flow is not required to maintain suspension of the solid particles as with hydraulic flushing, the foam slurry flows and deposits noncombustible solids around obstructions and obstacles such as pillars or rubble piles, and into hard to reach cracks and crevices, which could otherwise serve as air conduits. This aspect of the foam slurry method allows for much better field control over noncombustible material placement relative to hydraulic flushing.

The foam slurry is injected into cased boreholes drilled into the area to be treated, under gravity flow or by pumping, until predetermined refusal or acceptance criteria are achieved. Typically a grid pattern would be used for the initial injection, followed by additional drilling and slurry injection in areas where the initial amount of slurry injected was low, or loss outside of the treatment area is suspected. Because the foam slurry has high mobility and doesn't harden and set once injected, very large volumes can be injected into a single borehole over a long period that may easily span several days. With grout containing cement or fly ash binder, the material often hardens in a matter of hours and will typically harden around the injection point and inside of injection pipes between shifts, blocking injection of additional grout. As a result, it is a key feature of the foam slurry method that a much wider injection pattern is possible than with conventional cement-based grout.

Borehole Spacing

For mine subsidence grouting using void-filling techniques with traditional sand-cement-fly ash grout mixes, a borehole grid spacing of 25 to 30 feet is commonly employed. With the foam slurry method, borehole spacing may be readily increased to 40 or 50 feet or more. By simply increasing borehole spacing from 30 feet to 40 feet, the number of injection drill holes required is reduced by 40 percent. Increasing the spacing from 25 feet to 50 feet reduces the number of drill holes required by 75 percent. Since the cost of the injection borings usually represents a significant portion of the costs for remote underground backfilling, a significant cost benefit can be realized just in terms of the number of injection borings required and the associated logistics to provide suitable drill rig access.

Practical Application of the Foam Slurry Approach

The foam slurry approach is particularly well suited for long-standing deep-seated underground mine fires in abandoned workings where other methods have generally proven ineffective or cost-prohibitive to implement. Since the foam slurry consolidates under self-weight as the foam decays and the noncombustible solids settle, the method is well suited for mine fires in inclined coal seams. This includes the steeply dipping coal seams of the Eastern anthracite belt and some Western coal districts such as the Grand Hogback in Colorado which have heretofore represented major challenges.

Under the complicated three-dimension geologic conditions associated with a well-established fire under deep cover, residual heat in the system can cause a fire to re-ignite years or even decades later if oxygen is re-introduced through new cracks or fissures, particularly for mine fires which initially started through spontaneous combustion. The foam slurry flushing approach is particularly well suited for mine fires in such situations since the large heated area associated with a long-standing fire can be backfilled to prevent ventilation much more economically than with previously identified methods.

Flat lying mine workings which are filled rapidly with large volumes of foam slurry may require "topping off" with additional slurry in a multi-stage process or by pressure injection with traditional grout to adequately block ventilation. This will still be much more economic than grouting alone as ventilation though the bulk of the workings is prevented by the much lower cost foam slurry material. In some situations, the mine workings may require placement of a down dip barrier of grout or quick settling material comprised of coarse solids and weak foam to prevent excessive excursion of foam slurry outside of the zone to be treated.

Open subsidence cracks or voids, loose ash-filled combustion zones, rubble, etc. can also be injected with foam slurry to block ventilation to a fire from occurring through these features. The foam slurry method may also be applied to other types of mine fires and to coal seam and outcrop fires.

It is not necessary to entirely fill the mine workings with noncombustible material provided sufficiently high injection volumes are achieved such that remaining mine voids, rubble, cracks, and crevices are not interconnected to a significant degree, and ventilation through the area is effectively prevented.

Summary and Conclusions

To permanently extinguish a large long-standing coal mine fire and isolate the heated area of the mine that could re-ignite, ventilation must be prevented throughout the area where the thermal runaway temperature for the coal is exceeded. Flushing low permeability backfill using foam slurry to fill the mine workings and prevent ventilation of the heated area provides a reliable means for extinguishing a deep-seated mine fire at reduced cost, and at reduced risk of spreading and complicating the fire.

By attacking all three legs of the fire triangle simultaneously, flushing noncombustible solids using foam slurry increases the likelihood of success. The method is relatively simple and very flexible with regard to the precise details of the implementation, which is part of its economic benefit. Essentially a permanent underground soil seal is created to isolate the coal and prevent ventilation throughout the area of the mine affected by the fire.

The foam slurry method overcomes many of the difficulties and problems associated with hydraulic flushing and is much more economical than grouting for combating mine fires. Benefits of using the foam slurry approach relative to hydraulic flushing or grouting methods to isolate and extinguish a mine fire include, but are not limited to:

- Very little water is used to generate the foam which reduces the cost and logistics. Only about 20 gallons of water are required to generate enough foam to move 1 cubic yard of material versus 400 gallons or more for conventional hydraulic flushing, a 95 percent reduction.

- The amount of foam added to the slurry can be easily adjusted to control the viscosity or slump of the mixture over a much wider workable range than is possible with hydraulic flushing.

- The strength of the foam can be engineered to degrade after a certain period of time (minutes, hours, days) to control placement of the noncombustible solids. With hydraulic flushing, deposition occurs only when and where the velocity happens to slow sufficiently following injection.

- The potential for explosive steam and slurry eruptions caused by large volumes of water or water based grout when contacting the fire is eliminated.

- The aggregate size can be readily adjusted to suit the ground conditions encountered. Coarser aggregate can be used for open intact mine workings or perimeter areas where rapid settling from suspension is desired. Conversely, finer grained solids can be used for injection into rubble or fractures where additional travel time and penetration distance are desired.

- Since turbulent flow is not required to maintain the solids in suspension, the foamed slurry readily flows into nooks and crevices and other dead end areas to deposit noncombustible solids. Because the material stays mobile for as long as the foam persists, the self-weight of the foam slurry forces the material deep into these areas as the foam degrades and deposition occurs.

- No cementitious binder material is required which greatly reduces the material cost.

- Since the foam slurry material doesn't harden or set, a much wider borehole spacing is possible than with grouting. Since the drilling cost are often a significant portion of the cost on projects of this nature, these savings can be significant.

- The foam slurry method makes use of local materials otherwise normally considered as waste, such as mine tailings, wash plant or crusher fines, culm, slag, non-combustible spoil, etc., which can normally be provided to the project at little or no cost.

These and other benefits of using the foam slurry approach provide an efficient means of permanently blocking ventilation in a cost-effective manner to enable a large enough area of the mine to be treated for the fire to be reliably extinguished, as well as to prevent long-term re-ignition.

McElroy (1938) reports that the greatest costs for combating mine fires is for situations in which the initial measures were ineffective and the fire subsequently increased or became more complex which led to prolonged and expensive efforts. Of the case histories examined by McElroy, the costs to combat 22 fire re-occurrences amounted to more than 50 percent of the total cost of all efforts, although they represented only 12 percent of the total number of projects.

Chaiken, et al (1983) indicate that the average amount spent on successful anthracite mine fire projects completed since 1950 was 5 times more than on those projects which failed. Projects which were started with insufficient funds required repeated efforts during which the fire often spread and became more difficult and costly to control. Kim and Chaiken (1993) report that repeat projects that prove successful are 2 to 10 times more expensive than the original unsuccessful project. Experience with fires where initial efforts resulted in spread of the fire and further more costly efforts include now infamous sites such as Centralia and Laurels Run in Pennsylvania, and more recently in the case of grouting, the Axial and IHI No. 3 mine fires in Colorado, and the Maclean mine fire in Utah, among many others.

These data suggest that a complete and thorough approach initially will best minimize the overall long-term mine fire abatement efforts and associated costs. The economy and ease of use of the foam slurry method provides such an opportunity. Compared with using sand-cement-fly ash grout to effectively treat a large area, foam slurry should easily provide a 50 percent decrease in the number of borings and a 90 percent decrease in the backfill material costs versus grout. Depending on the specific situation, the cost savings may well be even greater.

Definition of Terms

coarse-grained – material with a particle diameter greater than 0.074 mm (No. 200 US Standard Sieve size)

crusher fines – sand and silt-sized rock fragments resulting from rock crushing operations culm – waste from anthracite coal mines, inferior anthracite coal. Waste rock and fragments of coal that are uneconomical to separate from the waste. Often used as synonymous with gob.

dip or dipping – pitching or inclined, as in an inclined coal seam

fine-grained – material with a particle diameter smaller than 0.074 mm (No. 200 US Standard Sieve size)

fines – synonymous with fine-grained

foam - consists of a liquid phase, forming a cellular bubble structure, that surrounds and contains a gas phase dispersed in a liquid such that the gas comprises between 50 and 97 percent of the volume occupied by the mixture.

foam slurry – a mixture of foam and noncombustible solid material wherein the solid particles contain sufficient coarse fraction of sufficient density to settle from suspension under self-weight and gravity as the foam decays.

gangway – level tunnel used in coal mining for transporting coal, serving as a manway for access to the mine and providing ventilation.

gob – loose waste material stored inside a coal mine, often packed or stowed into openings to support the roof. Waste rock and fragments of coal that are uneconomical to separate from the waste. Often used as synonymous with culm.

gravity flow – the movement of liquid from one place to another due to the force of the earth's gravity field.

manway – tunnel or opening allowing for movement of miners between different parts of the mine underground.

mine tailings – residual solid waste resulting from mineral processing, generally consisting of finely ground rock particles

mine workings – collective system of adits, tunnels, shafts, stopes, rooms, pillars, gangways and manways that comprise the underground mine excavation

pillar – portion of coal that is not mined in order to provide local roof support or separation between different parts of a mine.

quench, quenching – use of water to extinguish and cool burning or heated coal

rider coal – a thin layer of generally non-economic coal located in the rock layers above the primary coal seam(s).

rock dust – very finely ground rock particles

room – mined out production area in a room and pillar mine

rubble – loose material which has caved as a result of coal mining.

slushing or flushing – high-volume placement of solids into mine workings, generally by using hydraulic slurry methods.

spalling – surface failure in which a chunk, slab, flake, or piece or rock breaks loose and falls free, generally in response to weathering or pressure

spontaneous combustion – self-heating to the point of ignition caused by oxidation of coal

stoppings – barriers placed underground in the mine workings to prevent or direct ventilation through a portion of the mine.

stowing - placing waste materials in a mine opening, commonly using hand packing or pneumatic injection.

surfactant - compounds that lower the surface tension (or interfacial tension) between two liquids or between a liquid and a solid.

USGS – United States Geological Survey

well-graded – material with a smooth grain size distribution curve covering a broad range of grain sizes

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