HEAT REMOVAL METHODS FOR CONTROL OF UNDERGROUND ABANDONED COAL MINE FIRES

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Abstract.--The Bureau of Mines is conducting research to determine the effectiveness of several related techniques for the removal of heat from underground fires in abandoned coal mines. Mine fires are notoriously difficult and dangerous to extinguish because the heat becomes deeply seated in the coal and in the surrounding rock strata, and there can be potentially explosive gases near the heated material. Fire control methods which attempt to deprive the combustion zone of oxygen are ineffective, as the fuel can smolder indefinitely at <2 pct oxygen concentrations. Methods that excavate the coal seam produce extensive and expensive surface disruption affecting the landscape and surface structures. The Bureau has developed heat removal methods to remotely extract thermal energy from the underground fuel and adjacent heated rock strata. The mine then cools below the temperature needed to sustain combustion and negative effects on the surface are minimized. The Bureau techniques draw heated underground gases to the surface with an exhaust fan attached to a borehole into the mine. Water, detergent foams, or cryogenically liquified inert gases injected into the mine can enhance the energy-absorbing capacity of the subsurface gases. Two completed field trials have used water, injected as a spray or in a stream. A current project will use one or more foams to carry water and other chemicals to the burning material. Future activities may use cryogenic gases to both cool directly and remove heat indirectly via the exhaust fan.

INTRODUCTION

Small fires that occur at, or near, an outcrop of coal, if unnoticed or ignored, can become deeply seated fires in abandoned underground coal mines. The old mine usually is too dangerous to enter, so fire-fighting must be done from the surface. One option is careful and total excavation, with the attendant disruptions to the environment in the vicinity of the mine. The excavator must contend with hot, flammable material and potentially explosive gases. Another conventional technique attempts oxygen deprivation by surface sealing. This goal is difficult to attain because of the many pathways for air to enter the workings; the seal is practically impossible to maintain over the long periods of time necessary for cooling of fuel and rock to below self-heating temperatures of 40 - 70° C (104 - 158° F) as obtained in laboratory studies of spontaneous combustion susceptibility of Pittsburgh seam and other coals (Kuchta et al. 1980, Smith and Lazzara 1987).

Bureau of Mines research into remote fighting of fires in abandoned underground coal mines has focused on removing the thermal energy from the

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combustion system. (Even in the total excavation method, the hot strata must be cooled before the materials can be stowed anywhere.) The basic problems are to find inexpensive substances with good heat-absorbing properties that can be conveyed easily into and through the subterranean environment and subsequently returned to the surface without damaging the surface environment. The research to date has identified some likely candidates and some positive and negative attributes associated with use of these materials to achieve mine fire extinction by remote means. This report briefly discusses recent field studies and summarizes the overall findings to date. Also described are new approaches to heat removal that are under consideration for field trial.

BASIS OF HEAT REMOVAL TECHNIQUES

In any fire situation, extinguishing the combustion can be accomplished by removing any of the three necessary components: oxygen, fuel, and thermal energy (heat). Oxygen deprivation by sealing the earth above a burning underground mine, even if there are no surface structures or other impediments, is difficult and expensive to implement and may not be successful. If the "sealed" mine is normally an active coal-producing one, methane often will desorb from the coal and displace most of the oxygen not consumed by the fire. Nonetheless, O_2 concentrations below 2 pct can sustain smoldering combustion (Smith and Lazzara 1987). Moreover, a fire in an abandoned coal mine is often ignited at the outcrop years after the mine has ceased operation, and after essentially all the methane has desorbed and been lost. Therefore, in a surface-sealed abandoned mine, only combustion products would be available to displace the air that had been drawn into the mine by convection currents created by the burning and by atmospheric pressure changes. Sealing the surface and the thousands of strata fractures is exceedingly difficult, especially where there are buildings on the surface or subsidence over the entries. With shallow mines, it is impossible in practice to sufficiently reduce the oxygen level in the air available to the carbonaceous fuel for the long time periods (5 - 10 yr) needed while the materials cool to below reignition temperature (40 - 70° C or 104 - 158° F). Injection of inert gas, as conventionally implemented to displace oxygen, also requires long time periods and expensive quantities of the gas to achieve cooling.

A second alternative for fire extinguishment is removal of the fuel. Fire extinguishment is certain if all the fuel is removed and treated correctly. However, this activity is expensive, causes extensive disruption of the surface terrain, and consequently has both concurrent and lasting environmental effects on the surrounding area. Hot material is dangerous to transport and must be cooled and mixed with incombustible material before it can be redeposited at the mine site or elsewhere. There is always the possibility of continued burning if total excavation is not done (Magnuson 1974).

Removal of the third constituent in the fire triangle, heat energy, is an extension of natural processes occurring in abandoned coal mines without fire. No burning will occur if (a) the thermal energy produced by natural oxidation and wetting is removed quickly enough to prevent energy storage leading to sustained, rapid exothermic reactions, and (b) there are no other external inputs of energy into the fuel. In theory, large quantities of ordinary air rapidly passed over the hot surfaces should remove the heat. In practice, it is difficult to sustain both high air volumes and high airspeeds through the rubble in collapsed mine entries. Forced flow of plain air generally accelerates combustion; this also can be considered as a method of removing fuel and is the basis of controlled burnout (Chaiken 1980).

The Bureau's heat removal concepts address these practical concerns by using air, which is an inexpensive, plentiful fluid, as a carrier for other substances that have larger heat capacities. In this context, it is necessary that the flow direction be controlled. This is accomplished by:

1. Use of an exhaust fan connected to the underground mine network through a cased borehole, and
2. Injection of cooling or heat-absorbing compounds into the subsurface flows induced by the fan's suction.

In these applications, the fan generates a vacuum which induces underground gas flow along the pressure gradient to the surface.

TESTING OF HEAT REMOVAL TECHNIQUES

The earliest use of a heat removal technique was at the conclusion of <u>in situ</u> combustion simulation experiments in a surface trench in which coal or coal wastes had been burning for several days (Chaiken et al. 1981). During the experiments, a fan drew air through the hot material to supply oxygen and sustain accelerated combustion under controlled conditions. At the end of the study and with the fan operating, water sprayed onto the top of the bed of carbonaceous material percolated down and quickly quenched the combustion reactions so that the bed could be dissected for analyses. The fan pulled any quantities of carbon monoxide, hydrogen, and other products of low-temperature combustion of coal generated during the cooling and quenching process through the bed into an incinerator. Maintaining a negative pressure on the fuel bed also reduced the possibility of explosions from concentrations of heated flammable gases.

FIELD TEST OF WATER INJECTION WITH FUME EXHAUSTION, CALAMITY HOLLOW

Based on successful application of the technique under laboratory conditions, a trial quenching was done at the end of the first field evaluation of the Bureau's Burnout Control technique at an abandoned underground coal mine at Calamity Hollow, PA. The Burnout Control process had produced exhaust gases with an average temperature of 600° C (1,112° F) for most of the 4-month activity. Burning had been extended to a radius of 36 - 42 m (120 - 140 ft) from the exhaust manifold. Excavation of the site was scheduled to furnish data about the effects of the controlled combustion on the mine entries and surrounding strata.

Prior to excavation, the heat removal process was tested at the site. To implement the quenching trial using the Water Injection with Fume Exhaustion (WIFE) technique, a water distribution network was connected to all the air inlet boreholes on the site. Streams of water saturated the hot material at the bottoms of the boreholes and generated steam in the process; the exhaust fan drew the steam and other hot gases out of the mine. The high heat capacity of the water and its energy absorption in the latent heat of vaporization during the phase change removed thermal energy from the fuel and lowered temperatures. Although water continued to be sprayed onto strata surfaces exposed during the excavation (as an extra safety precaution), the highest measured temperature in the solid materials upon exposure was about 150° C (302° F). It was estimated that about 50 pct of the burning carbonaceous material was extinguished during 30 days of water injection. By extrapolation from the data, total extinguishment might have occurred in about another 20 days (Chaiken et al. 1984).

FIELD TEST OF WATER INJECTION WITH FUME EXHAUSTION, RENTON, PA

A subsequent field study that attempted to extinguish combustion in several parts of another abandoned coal mine in southwestern Pennsylvania demonstrated some of the problems that can be encountered using this Water Injection with Fume Exhaustion (WIFE) technique. There were three thermally separate heated zones on the perimeter of the >24-ha (60-acre) site of another abandoned, turn-of-the-century mine in the Pittsburgh Coal Seam. The locations of the zones and the direction of movement of the combustion fronts had been determined by the Bureau's mine fire diagnostics technique (Chaiken 1984). As expected, no borehole was drilled into an actively burning area although some of the holes did become chimneys for hot gases that contained a lot of water vapor. Measured initial temperatures did not exceed about 80° C (176° F), but temperature is very deceptive because it is very localized (Kim 1986). Time-dependent monitoring indicated continuing significant combustion, however, and provided the information needed for placing additional boreholes to intercept the three combustion fronts.

A gravity-fed distribution system supplied water to the boreholes; there, the water was conveyed in small-diameter tubes to spray nozzles placed at the bottoms of the casings. Typically, the exhaust fans were operated about 6 h/day for 5 days/week with concurrent waterflow of about 0.04 - 0.06 L/S (0.6 - 1.0 gal/min) per borehole. The WIFE systems operated on the subsites for about 6 months including some hiatuses for data analyses and distribution system modifications.

Because there was concern that some of the borehole casing depth data were incorrect and that burning was occurring above the casing openings, the injection tubes were reinstalled outside the casings and about 0.30 - 0.61 m (1 - 2 ft) below the surface. The idea was to saturate the borehole surface so that any subsurface gases drawn through the wet strata would also become saturated with water vapor, and any fuel heating around the steel casing would be cooled by water flowing down the borehole surface. All boreholes served as the locations for temperature and pressure monitoring and gas sampling. Although some data indicated that thermal energy was being removed in the air and water vapor extracted by the fans, other data proved that combustion was being accelerated near some boreholes. The overall result was that general extinguishment did not occur. The probable cause was that insufficient quantities of water were carried by the induced airflows to all hot areas to overcome heat release by oxidation. The heated areas least likely to be exposed to adequate quantities of water (liquid or vapor) and most likely to be on fire would be in the roof strata. If the combustion is primarily in the carbonaceous roof strata and those strata are highly fractured, getting liquid water to those areas is particularly difficult due to the effects of agglomeration and gravity on the water flow. Without the latent heat of vaporization, air (with or without water vapor) may not absorb enough heat energy to counter the effects of enhanced oxygen availability when the fume exhaustion technique is applied. Discussion of these difficulties led to consideration of ways of enhancing the conveying of water to all parts of mine entries, whether collapsed or intact.

CURRENT RESEARCH USING FOAM INJECTION

As an outgrowth of the field tests using the Water Injection with Fume Exhaustion technique, current Bureau research is focused on development of a related heat removal technique using foam. Foams are, basically, large agglomerations of water films containing gases. Additives modify and strengthen the films so that foams having bubbles of specific size distributions can be formed and made to flow like a liquid or like a gas. As such, the use of foams for transporting water to heated zones in an underground mine fire may overcome the water flow problems observed at Renton. In concept, foams having different properties could be generated so as to:

(a) carry water to large void sections of mine entries, and to maintain those sections with a long-lasting supply of cooling water.
(b) fill small cracks and fissures in the roof area.

Contact between foam and heated fuel would cause the foam to break down structurally and deposit the water film on the solid surface where evaporative cooling and other reactions would occur.

Assuming the water were converted to steam, the increase in local gas pressure along with the injection pressure of the foam would move the steam elsewhere in the mine. A cooler downstream location would condense the steam and allow the thermal energy to be absorbed there; the effect could be to spread the heating farther into the mine. However, if in conjunction with foam injection, an exhaust fan appropriately located on the surface were put into operation, the suction would induce underground gas flows to a known vent. Additionally, the foam would be drawn along the same flow paths to maintain the heat removal from the entire flow network as the upstream segments cooled. As in operation of the WIFE system, continuing gas sampling and analysis would provide the necessary information about the progress of the extinguishment activity. The physical presence of foam, as with steam, would exclude oxygen, thus reducing the exothermic activity and slowing the rate of temperature increase.

Foam injection with fume exhaustion (FIFE) makes feasible the introduction of compounds other than water into the subsurface environment. The gas encapsulated in the water films can be an inert one, for example. The water additives that enable foam formation could be some that would coat the exposed carbonaceous surfaces and inhibit various chemical and biochemical reactions and processes. Evaluation of bactericides, such as some against Thiobacillus ferrooxidans which accelerates mine acid production, could be accomplished as a concurrent activity. In-mine application of bactericides is difficult to do for reasons including access to the workings and controlled release of the chemicals; much of the research has been done on surface coal and refuse piles (Erickson et al. 1985). Introduction of chemicals that retard surface oxidation may minimize the possibility of reignition while mitigating acid production. It could be possible to solve two environmental problems - fire effects and acid mine drainage.

Field testing of the FIFE technique is planned for the near future at another abandoned mine in the Pittsburgh Coal Seam, where the fire has been burning for at least 10 years. The two main objectives are:

1. Getting inexpensive water, with its especially high heat capacity (relative to gaseous N_2 or CO_2), to the heated fuel and adjacent rock; and
2. Extinguishing the combustion with minimal effects to the environment.

Again, the boreholes and the exhaust fan would be in place following the mine fire diagnostics necessary to delineate the combustion zones.

FUTURE RESEARCH USING CRYOGENIC FLUID

The advantages inherent in using an exhaust fan connected to a mine through a borehole within a set of instrumented holes have been proposed for use with an inert cryogenically liquified gas or gas mixture as the primary fire-suppressing and cooling medium. As with the foams, the cryogenic fluid would be injected into the underground network under pressure; at this stage, the fluid would be in the liquid phase so as to enhance its effective heat capacity. Upon exiting the bottom of the borehole casing, the liquid would vaporize as it absorbed thermal energy from the heated surroundings. While similar in this regard to water, the revaporized cryogenic fluid has a greater advantage over water for diluting or inerting the mine atmosphere to reduce the quantity of oxygen available for combustion reactions. The exhaust fan would draw the warmed gas out of the mine; there also would be additional cooling of heated surfaces downstream from the injection point. Balancing injected gas flow with exhaust fan flow should minimize influx of atmospheric air to the mine, thereby maximizing oxygen exclusion from the fuel.

In comparison to water, the usual inert cryogenic gases (nitrogen and carbon dioxide) have both smaller heat capacities and latent heat of evaporation effects during liquid to gas phase change, but the gases do not conduct thermal energy back to cooler surfaces as rapidly as does condensing steam. The very low initial temperatures of the gas vaporizing from the cryogenic liquid will cause a large temperature gradient that will promote thermal energy transfer. This alternative extinguishing system should have a minimal environmental impact and should be especially useful at abandoned mine fire locations that lack water. Combining an exhaust fan with the cryogenic fluid injection may increase the overall efficiency of the method so as to lower material costs that are normally quite high for conventional cryogenic fluid injection.

CONCLUSIONS

Three methods to effect removal of heat energy from fires in abandoned coal mines have been discussed. All involve using an exhaust fan to produce an underground pressure gradient that will cause heated gases and vapor to be drawn from the mine through a borehole connected to the fan. The other necessary component of the methods is the injection into the mine of substances that will (1) absorb thermal energy from the heated fuel, (2) move into all mine spaces (especially the carbonaceous roof strata) so as to make contact with all the fuel, (3) exclude as much oxygen as possible from the mine network, and (4) remain in the gas or vapor phase and flow to the outside atmosphere via the exhaust fan.

Plain water works quite well as a cooling medium, and particularly so when the injection boreholes are placed directly into burning material. Large heat capacity, latent heat of vaporization energy absorption, low cost, and general availability are its positive attributes for fire extinguishing. Its deficiencies in this application are that any steam generated can condense and release its absorbed energy to a cooler location, and the liquid phase coalesces and collects by gravity, flowing away to the floor of the mine.

Foams can carry water to all parts of the underground environment when the foams are properly formulated and injected. Similarly, cryogenically cooled inert gases will flow to the heated fuel and rock strata surfaces to absorb thermal energy and then be removed without transferring that energy to previously unaffected portions of the mine. Both foams and inert gases can exclude oxygen or dilute its concentration in the mine workings so as to reduce the rate of exothermic reactions and decrease the overall temperature. These methods are intended to be implemented with a minimal disruption to the surface environment, thereby reducing project costs.

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