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BUREAU OF MINES
INFORMATION CIRCULAR/1993

Fires in Abandoned Coal Mines and Waste Banks

By Ann G. Kim and Robert F. Chaiken

UNITED STATES DEPARTMENT OF THE INTERIOR

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This report includes information from a variety of sources, i.e., agencies of the federal government, state agencies, research reports, conference proceedings, product information and technical literature. This information has been collated into a comprehensive discussion of AML fire problems. Data on past fire control projects and on the estimated extent of the current problem have been compiled. Factors affecting the occurrence, propagation and extinguishment of AML fires are discussed. Conventional fire control methods are described, and and their probable effectiveness is evaluated.

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

Btu	British thermal unit
$Btu \cdot h \cdot ft^{-2} \cdot {}^{\circ}F^{-1} \cdot in^{-1}$	British thermal unit per hour per square foot per degree farenheit per inch
Btu/lb	British thermal unit per pound
°C	degree Celsius
cal/g	calorie per gram
$cal \cdot min \cdot m^{-2} \cdot {}^{\circ}C^{-1} \cdot cm^{-1}$	calorie per minute per square meter per degree celsius per centimeter
cm	centimeter
cm^2	square centimeter
cm^2/s	square centimeter per second
°F	degree Farenheit
ft	foot
ft^2	square foot
ft^3	cubic foot
g	gram
gal	gallon
gal/d	gallon per day
gal/h	gallon per hour
gpm	gallon per minute
g/s	gram per second
h	hour
hp	horsepower
Hz	hertz
in	inch
$in\text{-}H_2O$	inch of water
$J \cdot sec \cdot m^{-2} \cdot {}^{\circ}C^{-1} \cdot cm^{-1}$	joule per second per square meter per degree celsius per centimeter
kcal	kilocalorie
kcal/g	kilocalorie per gram
kcal/mole	kilocalorie per mole
kW	kilowatt
lb	pound
lb/ft^3	pound per cubic foot
MMBtu	million British thermal unit
MMgal	million gallon
MW	megawatt
ppm	part per million
psi	pound per square inch
s	second
st	short ton
V	volt

FIRES IN ABANDONED COAL MINES AND WASTE BANKS

By Ann G. Kim[1] and Robert F. Chaiken[2]

ABSTRACT

Fires that occur in abandoned coal mines, waste banks, and in coal outcrops constitute a serious health, safety, and environmental hazard. Toxic fumes, the deterioration of air quality, and subsidence constitute the greatest hazards from these fires. Although fires on abandoned mined land (AML) occur in every coal-producing state, the severity of the problem varies. Methods to extinguish or control AML fires, including excavation, fire barriers, and sealing, are generally expensive and have a relatively low probability of success.

This U.S. Bureau of Mines report includes information from a variety of sources, i.e., agencies of the Federal Government, State agencies, research reports, conference proceedings, product information, and technical literature. This information has been collated into a comprehensive discussion of AML fire problems. Data on past fire control projects and on the estimated extent of the current problem have been compiled. Factors affecting the occurrence, propagation, and extinguishment of AML fires are discussed. Conventional fire control methods are described, and their probable effectiveness is evaluated. Information on the hazards of AML fires and safety considerations is included. The status of current technology, recent improvements in fire control methods, and areas of current research are discussed.

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INTRODUCTION

The emission of toxic fumes, the deterioration of air quality, as well as subsidence from fires in abandoned coal mines and wastebanks cause problems that range from imminent danger to a decline in the quality of life. In addition to the health and safety hazard, such fires usually depress property values for affected land and for adjacent areas. AML fires occur in every coal-producing state, but the severity and extent of the problem varies. Depending on the type of fire and its location, the cost of controlling an AML fire may be between $100 thousand and $100 million. Even if funds are not a constraint, current methods of extinguishing or controlling AML fires are not routinely successful. The problems of AML fires are related to geology, past mining practice, and the limits of currently available technology.

Coal is defined as "a readily combustible rock.....of carbonaceous material" (*1*).[3] It is not a homogeneous substance. Most coals consist of varying amounts of visibly distinct macerals (*2*). The three maceral groups, vitrinite, exinite, and inertinite, exhibit different chemical compositions and are petrographically divided into macerals and submacerals. The origin of the various macerals is related to variations in the original material from which the coal was formed. Although the petrographic constituents vary with the rank of the coal, the rank as it relates to combustibility is generally defined by the percentage of fixed carbon and the heating value (*3*).

Because of its combustibility, coal can be readily converted to other forms of energy. This property has been essential to the economic and technical development of all Western cultures, particularly in the United States. Coal fired the industrial revolution and was essential to the development of the nationwide railroad system. At present, when other forms of energy such as oil, natural gas, and nuclear power are available, coal still supplies 24% of the U.S. total energy market (*4*); more than 765 million st of coal is burned annually to generate electricity (*5*).

Burning coal produces usable energy, but the uncontrolled burning of coal in place creates potentially lethal hazards and degrades the environment. Although fires in active mines (*6*) can be catastrophic, they are usually controlled by the mine operator in a relatively short period. In contrast, fires in abandoned mines and waste banks often affect people who had no connection with the original mining. They occur under different physical conditions and must be controlled or extinguished under a different set of institutional constraints.

This U.S. Bureau of Mines report focuses on the problems associated with fires in abandoned coal mines, outcrops, and waste banks. It includes a discussion of sources of ignition, factors influencing the propagation of such fires, currently available technology to control these fires, and current research in this area.

ACKNOWLEDGMENTS

This report includes information from extensive data that has been accumulated on AML fires over the past 40 years. U.S. Bureau of Mines' projects and methods were documented by M. O. Magnuson, supervisory mining engineer, in the Eastern United States and by F. H. Shellenberger, mining engineer, and D. L. Donner, mining engineer, in the Western United States. The factors affecting AML fires and the status of such fires in Colorado were summarized by P. Rushworth, reclamation specialist, Colorado Geological Survey. L. Roberts, chief, AML Reclamation, OSMRE's Washington Office and B. Maynard, hydrologist, OSMRE's Eastern Technical Center provided information of the AML Inventory and the Federal Reclamation Program. The authors also wish to acknowledge the many State and Federal officials who responded to our request for information, and those members of the Bureau's AML Advisory Panel who offered suggestions and support for this work.

NATURE OF ABANDONED MINED LAND FIRES

AML fires, also called wasted coal fires, generally occur as smoldering fires in the low oxygen environment of an abandoned mine or waste bank. Outcrop fires, either related to a mine fire or in unmined coal, are also considered within this category. They occur in most coal-bearing areas of the United States (fig. 1), and were contemporaneous with mining in the east and predated mining in the west. In 1765, soldiers from Fort Pitt, who were digging coal from the outcrop, lit a fire near the base of the Pittsburgh seam. The fire propagated into the coal seam and could not be extinguished. Visitors to the area

[3] Italic numbers in parentheses refer to items in the list of references at the end of this report.

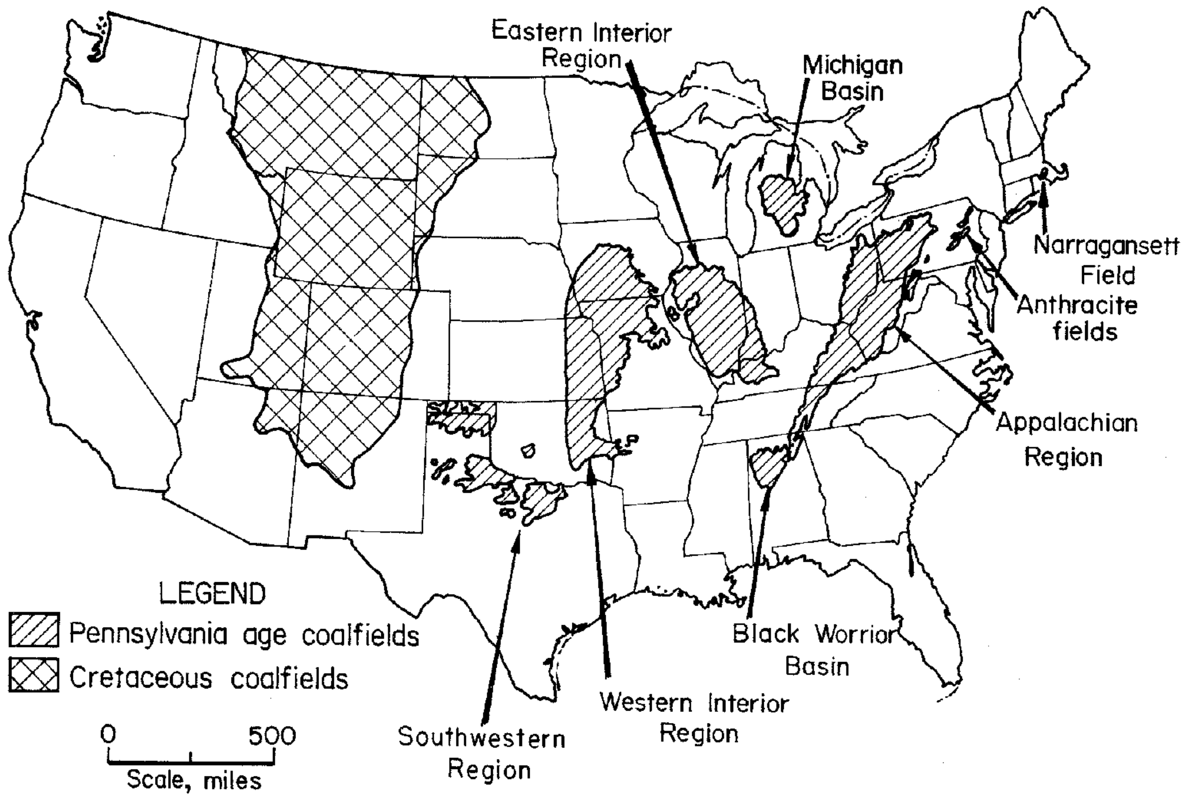


Figure 1.—Coalfields of United States.

gave an accurate description of the effects of a fire under shallow cover (*10-11*). The fire was active until at least 1846.

In the Western United States, coal outcrop fires were a natural feature of the landscape. In 1805, Lewis and Clark, in their exploration of the Missouri River, reported that coal seams were plainly visible in the bluffs along the river and that some of the veins were burning, ignited by spontaneous combustion or by grass fires (*12-13*).

AML fires or wasted coal fires occur in abandoned underground mines, abandoned surface mines, waste banks, and in coal outcrops. Many of these fires can be categorized according to the area in which they occur (fig. 2). For example, most underground mine fires are in the eastern coal-producing States. The characteristics of eastern fires also vary depending upon whether they are in bituminous or anthracite seams. Waste bank fires occur in the eastern and central States where the majority of coal preparation plants were located. Outcrop fires are more prevalent in the Western United States. These fires may or may not be related to mining. A mine fire may spread into the barrier outcrop or it may ignite coals stratigraphically above the mine fire. Lightning and brush fires can ignite the outcrop of unmined coal seams. Under current regulations, only fires related to past mining are considered AML fires.

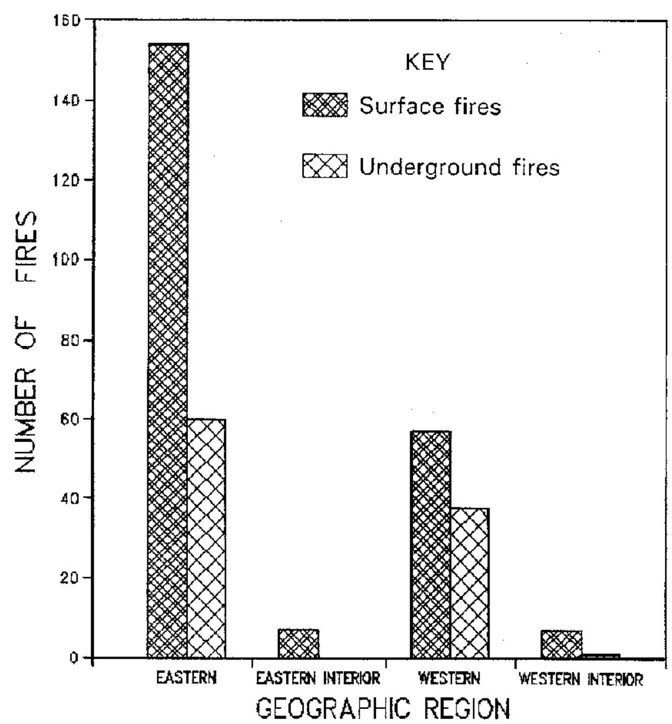


Figure 2.—Geographic distribution of AML fires. (Eastern geographic region includes Appalachian region and anthracite fields.)

In underground mines that used a room-and-pillar mining system, a relatively large proportion (30% to 50%) of the coal is left in place. Roof coals and carbonaceous shales also may have been left in place. The tonnage of combustible material left in the mine, therefore, may exceed that extracted during mining. Older mines had several entries at the outcrop for drainage, ventilation, and access. Fires usually started at the outcrop and propagated along the outcrop or through the interconnected workings. Heat moved by convection through the mine or by conduction into the overburden. The overburden serves as an insulator, preventing the transfer of heat away from the combustible material. As the overburden became warmer or as the coal pillars failed, the overburden subsided, creating a system of cracks and fractures through which smoke and fumes left the mine and fresh air entered the mine (fig. 3). Under these conditions, most abandoned mine fires exhibit smoldering combustion, involving relatively small amounts of coal at any given time, with little visible flame and capable of burning with as little as 2% oxygen (*14*). Such fires can continue to burn for extended periods (10 to 80 years) and are difficult to extinguish.

In abandoned surface mines, the coal outcrop may be left exposed when stripping operations are terminated, or coal refuse may be left in contact with the outcrop. In either case, fires are not unusual. If the stripping operation involved the barrier pillar of an abandoned mine, it is possible for a fire to propagate into the mine.

Surface disposal of coal waste, from mines and from preparation plants, is an AML problem. Approximately 25% of the coal removed from the mine in the United States is rejected and disposed of on the surface (*15*). Over the past 200 years, more than 3 billion st of refuse has accumulated in 3,000 to 5,000 active and abandoned waste piles (fig. 4) and impoundments in the eastern coalfields alone. It has been estimated that a billion cubic yard of anthracite waste (fig. 5) has been disposed of in surface piles in the anthracite region. The refuse consists of waste coal, slate, carbonaceous shales, pyritic shales, and clay associated with the coal seam. The combustible content of this material averages between 2,000 to 6,000 Btu/lb. Material with a combustible content above 1,500 Btu/lb will support combustion (*16-17*).

Construction standards for active piles are intended to prevent combustion and to reduce the infiltration of surface water that produces acid drainage (*18*). Older waste piles, gob piles, or slate dumps were built wherever there was sufficient land and where transportation costs could be minimized. Usually, no attempt was made to stabilize the slopes, prevent combustion, or reduce the production of acid drainage. Many of these piles burned, producing acrid smoke and toxic fumes. The burnt material, known as "red dog," is considered a good construction aggregate, and was not considered a waste problem. Because of past indiscriminate dumping, there is no accurate estimate of the number of abandoned coal waste piles. Those piles that appear on inventories are generally those that produce enough acid drainage to negatively affect the water quality of nearby streams, and those that are on fire and because of suburban spreading are now causing safety and environmental problems in populated areas.

Another fire problem indigenous to western States is the outcrop fire, which can be either the surface expression of an abandoned mine fire or in unmined formations. Depending upon their location, these fires can

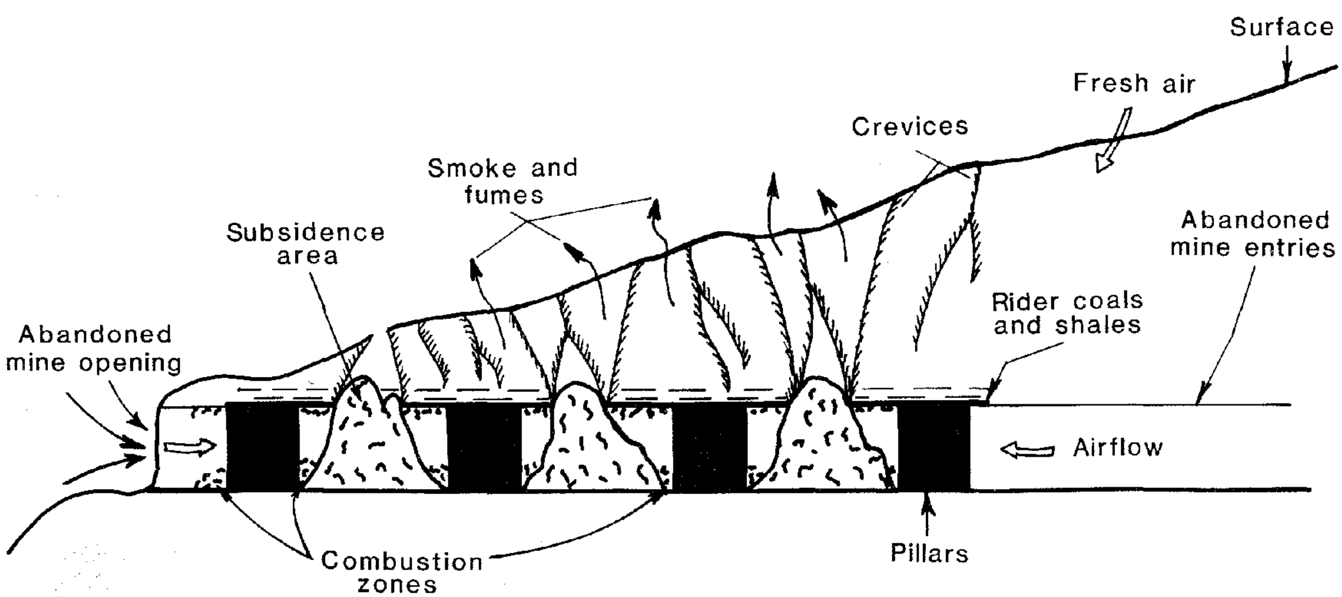


Figure 3.—Fire(s) in abandoned mine.

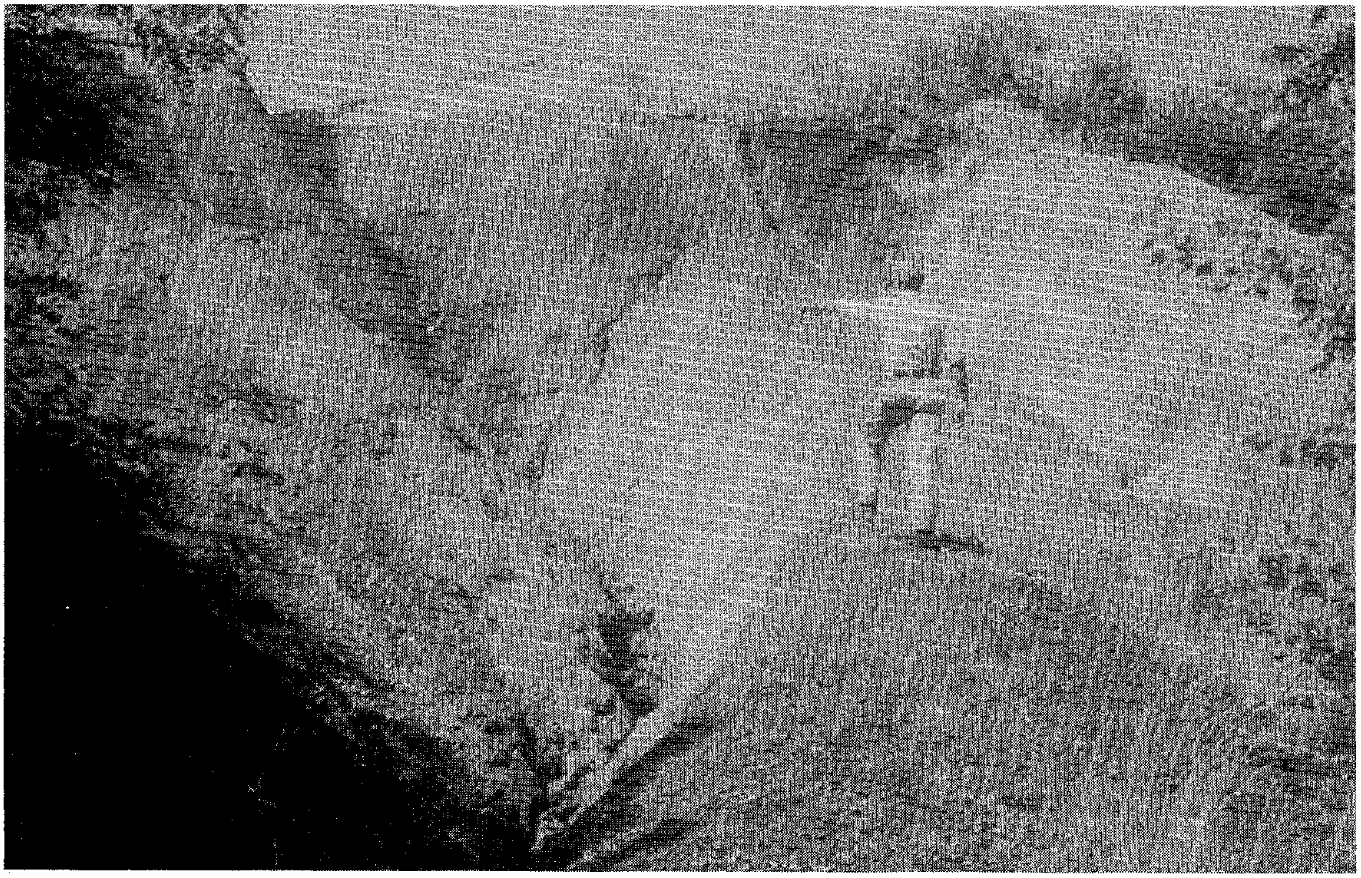


Figure 4.—Bituminous waste bank, Albright, WV.

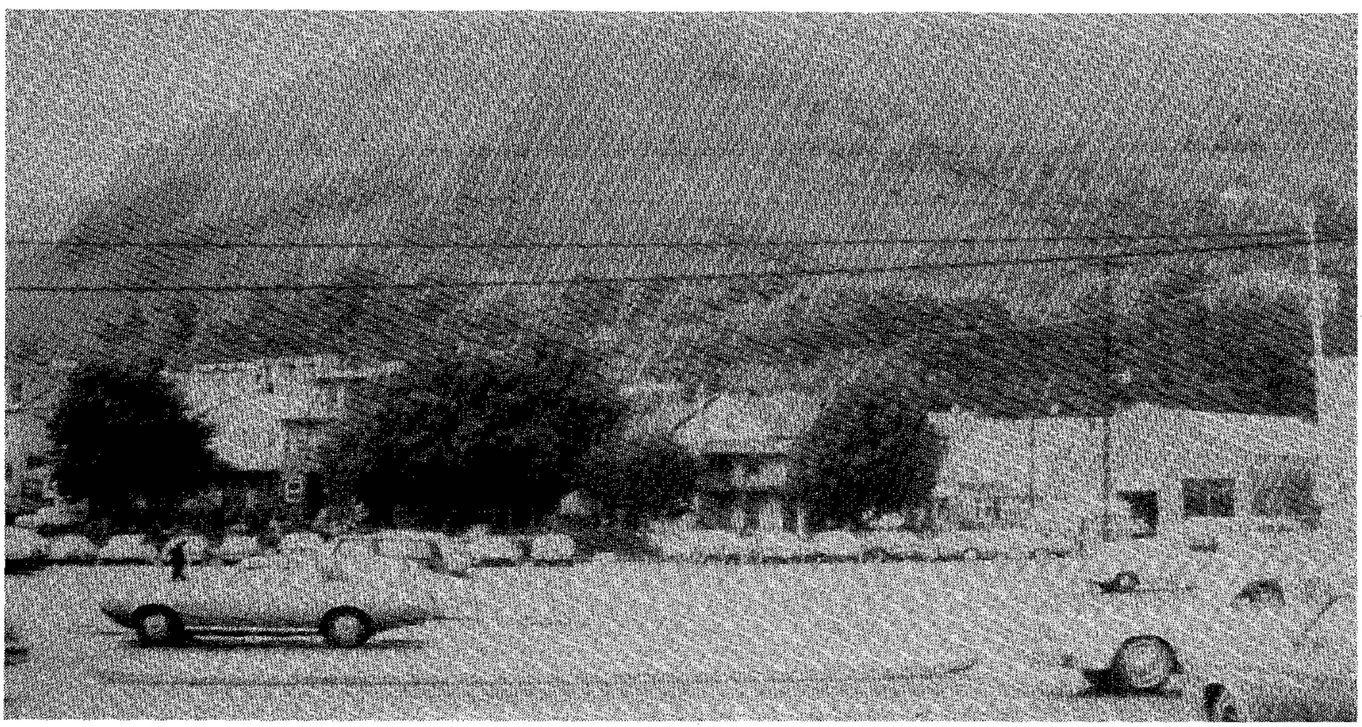


Figure 5.—Anthracite waste bank, Shamokin, PA.

threaten coal reserves, degrade environmental quality, and present a hazard to wildlife, grazing animals, and unwary humans. These fires frequently occur in lower rank coals, the high-volatile bituminous coals and lignites that are prone to spontaneous combustion. In general, an outcrop fire spreads initially along the outcrop, under thin cover, where oxygen is relatively plentiful. It may slowly spread into the solid coal under deeper cover if the overburden is naturally fractured or if subsidence promotes the development of cracks and fractures. The rate and direction of fire propagation are determined by the availability of oxygen.

Any given AML fire may include more than one type of fire. For example, waste banks may be in contact with an outcrop and involve both waste bank and subsurface fires. Fires that begin in the outcrop can spread to underground workings. Fires that appear to be related to past mining may actually be in virgin seams above the seam that was mined. Generally, fires are classified as surface (waste bank and outcrop) and underground; however, the classifications are somewhat arbitrary and not always accurate.

INITIATION AND PROPAGATION OF ABANDONED MINED LAND FIRES

As with any fire, wasted coal fires require three elements: fuel, oxygen, and an ignition source (fig. 6). In coal combustion, the fuel is the carbon in the coal. If combustion is considered the exothermic reaction of carbon and oxygen to form carbon dioxide, written as:

$$C + O_2 \text{ ----> } CO_2 + \text{heat},$$

the amount of heat liberated is 93.7 kcal/mole. The amount of heat liberated by the reaction of 12 g of carbon with 16 g of oxygen is enough energy to raise the temperature of a liter of water 100° C. However, coal is not composed of elemental carbon. On a dry, mineral matter free basis, coal contains between 60% and 90% carbon. The rest of the coal molecule is composed of hydrogen, oxygen, nitrogen, and sulfur. For example, the stoichiometric combustion of coal can be written as *(19)*:

$$CH_{1.18}N_{0.15}O_{0.35}S_{0.005} + 1.120_2 + 4.15\ N_2 \text{ ---> }$$

$$CO_2 + 0.58H_2O + .005SO_2 + 4.157N_2 + 138.4\ \text{kcal}.$$

Combustion reactions are exothermic, producing more energy than consumed, from 5 to 7 kcal/g of coal. Depending on the rank of the coal, combustion of coal produces between 6,000 and 16,000 Btu/lb on a dry, mineral matter free basis (fig. 7).

Oxidation of coal occurs constantly. The temperature of the coal is a function of the rate of heat generation versus the rate of heat loss. When these processes occur at the same rate, the temperature of the coal remains constant. When the rate of heat generation is greater than the rate of heat loss, the temperature of the reacting system increases. Since the rate of heat generation is an exponential function of temperature and the rate of heat loss is a linear function of temperature (fig. 8), as the temperature increases, the reaction rate increases faster than the heat loss *(20)*. Ignition is a function of the *amount* of energy released by a reaction and the *rate* at which it is released, as well as the *rate* at which energy is transferred from the reacting mass to the surroundings. The reaction rate is a function of the concentration of reactants, carbon and oxygen, the surface area, particle size, temperature, and activation energy.

There are two types of ignition, forced and spontaneous. In forced ignition, energy is added to the system to increase the rate of reaction to the self-sustaining point. In spontaneous ignition, there is no external heat source; natural reactions supply sufficient energy to sustain combustion. For AML fires, forced ignition sources include lightning, brush and forest fires, improperly controlled camp fires and spontaneous combustion in adjacent materials. There are no statistics on the number of AML fires started by forced versus spontaneous ignition. It is generally considered that lightning and other surface fires are probably prevalent sources of ignition in the western outcrop fires. In the Eastern United States, trash fires in areas where the coal outcrop has been stripped are considered the most common source of ignition.

Spontaneous combustion in the coal or coal refuse is related to the oxidation of the coal to form carbon dioxide,

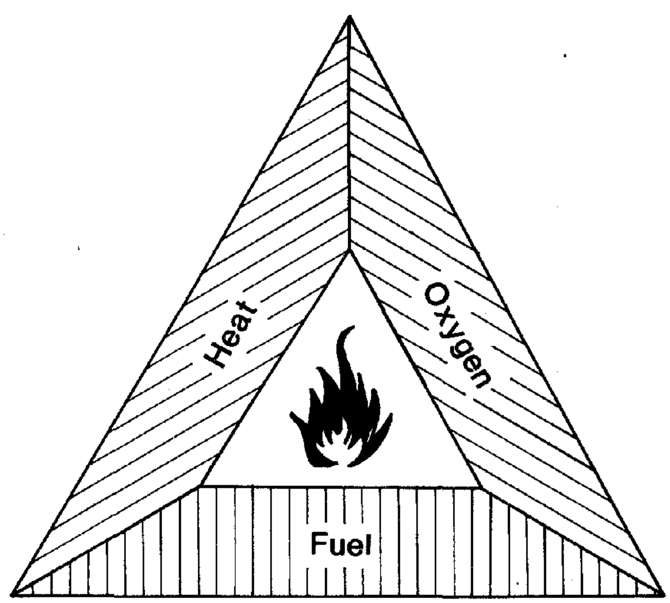
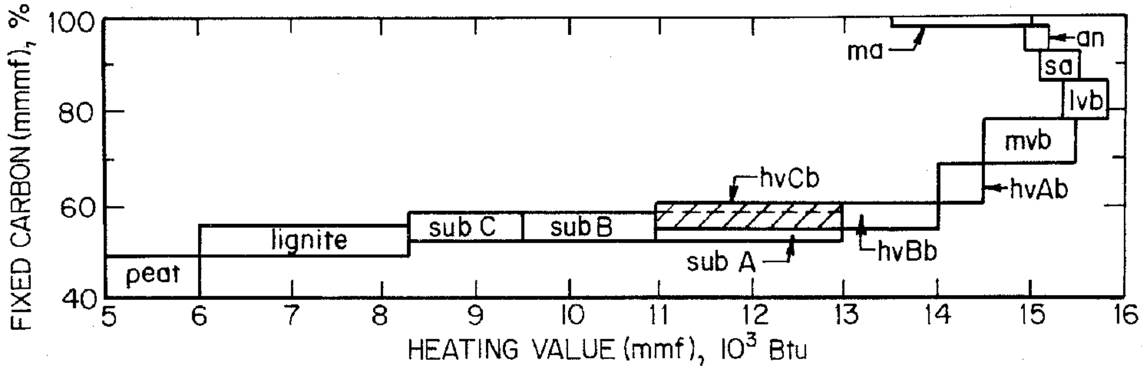


Figure 6.—Fire triangle.



KEY

sub A	Subbituminous A	lvb	Low volatile bituminous
sub B	Subbituminous B	sa	Semianthracite
sub C	Subbituminous C	an	Anthracite
hvAb	High-volatile A bituminous	ma	Metaanthracite
hvBb	High-volatile B bituminous	mmf	Mineral matter free
hvCb	High-volatile C bituminous	mmmf	Moisture, mineral matter free
mvb	Medium volatile bituminous		

Figure 7.—Heat of combustion versus rank of coal.

carbon monoxide, and water. The oxidation of pyrite and the adsorption of water on the coal surface also are exothermic or heat generating reactions that increase the probability of spontaneous combustion (*21*). Thermophilic bacteria also may contribute to raising the temperature of the coal. In waste banks, most of the oxygen diffusing from the surface is consumed by bacterial activity within a few feet. However, enough oxygen is available at depth to support combustion.

The normal ignition temperature for coal is between 400° and 500° C. In laboratory experiments, the minimum temperature at which a coal will self-heat under adiabatic conditions (all heat generated is retained in the sample) was 35° to 140° C (*22*). Normal underground temperatures are 11° C or less, and ambient air temperatures are usually below 35° C. To reach temperatures at which combustion is self-sustaining, heat generation must be greater than heat loss. In most abandoned mines and waste piles, conditions favor the retention of heat. As listed above, there are several exothermic reactions that release energy. Heat is lost by convection or conduction. Since abandoned mines and waste piles have an essentially stagnant atmosphere, convection accounts for very little heat loss. Most heat transfer is probably by conduction to surrounding strata, but rocks tend to be good insulators, keeping heat within the mine or waste bank. Temperature and the factors that increase temperature are one element in starting and sustaining a wasted coal fire.

In addition to a physical environment that favors the accumulation of heat, other factors influence the propagation of wasted coal fires, i.e., geologic setting, previous mining, the rank of the coal and environmental conditions.

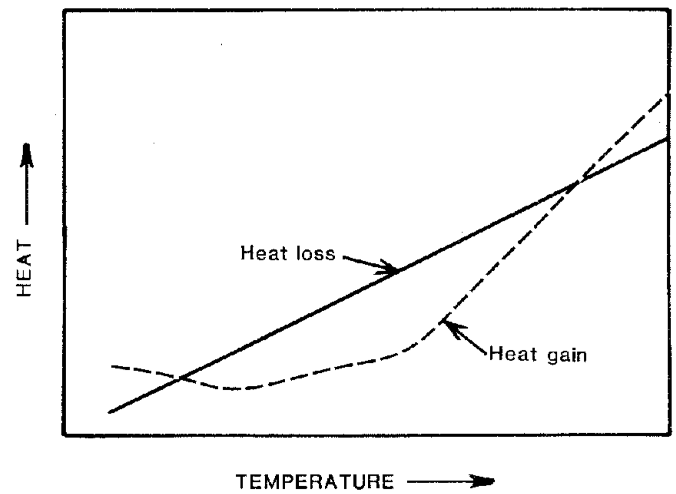


Figure 8.—Rate of heat loss and rate of heat gain versus temperature.

The geologic factors that affect the propagation of mine fires vary depending upon the geologic setting. In bituminous coalfields, the depth of overburden, the degree of fracturing and the nature of the overlying strata are the primary geologic factors. Mines under shallow cover are usually under more permeable strata and above the water table; shallow strata tend to be more highly fractured. Fires propagate toward the source of oxygen, and in shallow beds and in areas near the outcrop, the concentration of oxygen tends to be higher. However, wasted coal fires can smolder in atmospheres with less than 3% oxygen (*23-25*). Where the overburden is fractured, barometric pressure changes cause the mine to *breathe*, exhausting combustion products and bringing in fresh air. Under these conditions, fires spread very slowly, but continue to burn for very long periods.

In anthracite mines and in some western mines, the dip or pitch of the beds also influences the propagation of fires. In anthracite areas, the intense folding and faulting have contributed to subsidence fractures extending from the coalbed to the surface. On steep pitches, differences in temperature and elevation are sufficient to control the circulation of oxygen and fumes. A fire near the outcrop of a steeply dipping bed can draw air from within the mine, propagating the fire downdip. The movement of hot gases can transfer heat to other areas (fig. 9). The distance between coalbeds determines the transfer of heat between beds and the possibility of propagation of a fire from the source bed to adjacent beds.

In abandoned mines, the extent of previous mining is a factor in the spread of fires. The amount and condition of carbonaceous material left underground determines the extent of the fuel supply. Roof coals, rider coals, and/or carbonaceous shales, which eventually collapse into the mine, are capable of initiating and sustaining combustion (*17*). Coal that spalls from ribs and pillars as well as carbonaceous material in gob areas add to the fuel volume. Because the broken coal has a larger surface area than solid coal, it is more combustible. Main entries appear to be high oxygen areas along which a fire may propagate. A fire can establish a natural ventilation pattern in which combustion gases are exhausted at one point and fresh air drawn in at another. The number of openings in the outcrop, the number of ventilation shafts, the competency of the overlying strata, and the prevalence of subsidence-induced fractures are other factors that contribute to the prolonged propagation of abandoned mine fires. The condition of the mine determines the amount and surface area of fuel and the availability of oxygen, which determine the direction and rate of propagation of the fire.

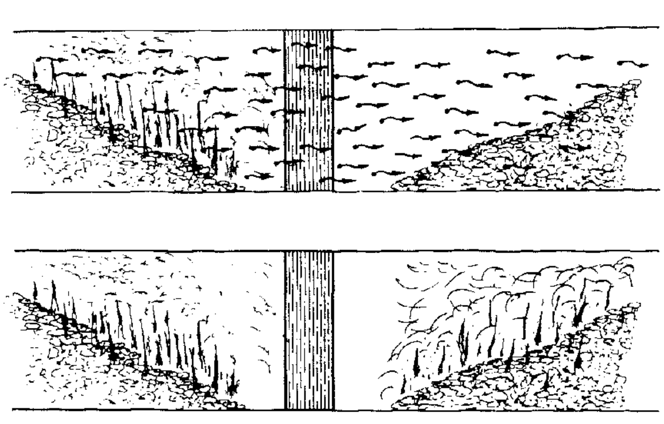


Figure 9.—Transmission of heat by movement of hot gases.

The rank of a coal is apparently not a primary factor in the incidence of AML fires (fig. 10). Although the lower rank coals (lignite and subbituminous) tend to be more susceptible to spontaneous combustion, the incidence of AML fires in these coals is no greater than in higher rank coals (bituminous and anthracite). Moisture in the coalbed or waste bank has both positive and negative effects on fire propagation. If water is present on the surface of the coal, heat generated by oxidation is dissipated by the evaporation of the surface water. Prolonged drying of the coal allows for increased sorption of oxygen. The sorption of water vapor on dried coal is also an exothermic processes that raises the temperature of the coal, increasing the probability of ignition.

If wasted coal fires were propagated by a flame spread mechanism, coal adjacent to the burning mass would be heated by conduction or radiation to its ignition temperature (*26*). Propagation of the fire would follow a continuous pathway. However, in many AML fires, fire zones are discontinuous, with no apparent propagation pathway (*8, 27-29*). In these fires, the movement of hot gases is believed to be a factor in propagation. The fire induces circulating air currents, which carry fumes and heat into nonadjacent areas. The effective ambient temperature of a large area of the mine is slowly increased. As the temperature of the coal increases, normal bed moisture is lost and the rate of oxidation reactions increases. If the heat is not dissipated, the temperature of the coal continues to rise until spontaneous ignition occurs.

In a discussion of factors influencing the initiation and propagation of wasted coal fires, it is apparent that all factors are related to the three elements, fuel, oxygen, and energy. The amount of combustible material, its particle size, surface area, and tendency to spontaneous combustion are fuel related factors. The presence of fractures through which air can be drawn into the fire zone, circulation caused by the fire, and changes in barometric pressure control the amount of available oxygen. The rate of heat generation versus the rate of heat loss, the heat-generating reactions (oxidation of coal, oxidation of pyrite, surface adsorption of water vapor, bacterial activity), and the insulation provided by adjacent strata control the amount of energy within the system.

Natural barriers to subsurface fire propagation basically affect the availability of fuel and the generation and/or the

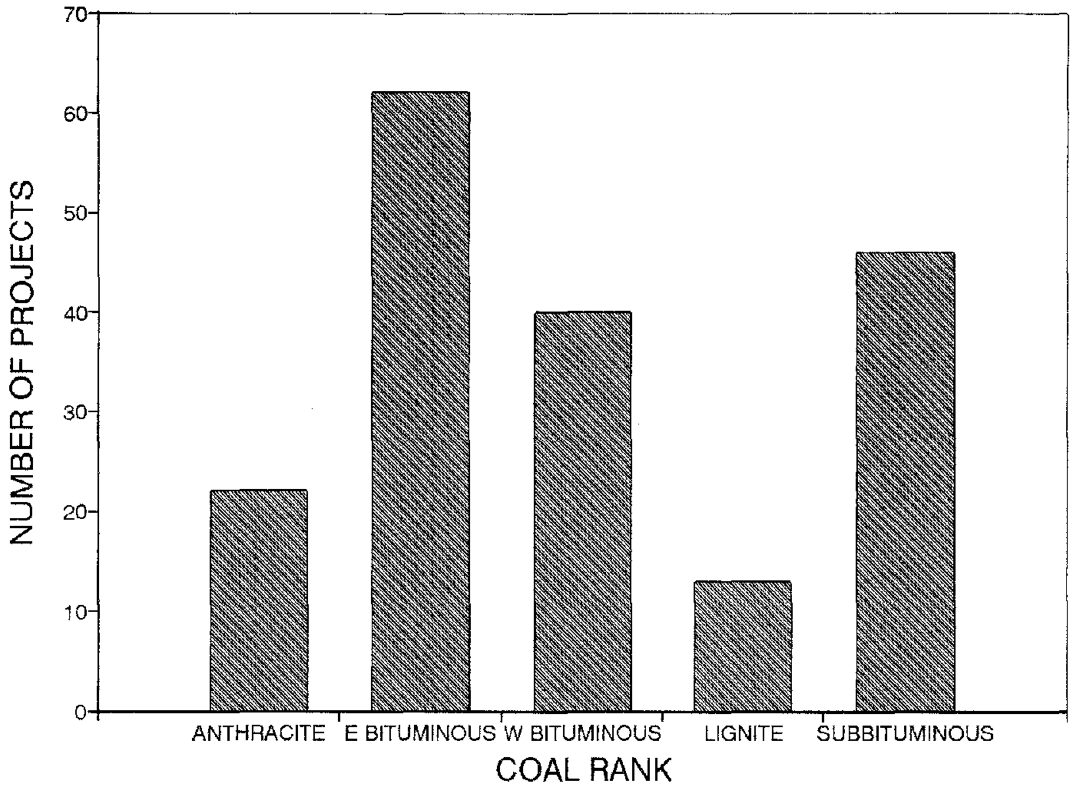


Figure 10.—Distribution of AML fire control projects by rank. (E Bituminous - eastern bituminous; W Bituminous - western bituminous.)

retention of heat. Faults with vertical displacement may disrupt the continuity of the coalbed and limit the amount of fuel. Interior boundary pillars between mines are considered natural barriers to fire propagation because solid coal seams do not burn. However, the surface of the pillar and any fractured or faulted areas can be combustion zones, and in practice, many boundary pillars are breached and therefore, do not constitute a fire barrier. Boundary pillars at the outcrop, because of weathering and the availability of oxygen, are not considered fire barriers. In fact, many AML fires propagate along the outcrop. The water table serves as a barrier by limiting the amount of oxygen and by absorbing energy released by the fire. In the absence of these natural barriers, a fire in an abandoned mine can, in an extended period, burn from outcrop to outcrop.

HAZARDS OF ABANDONED MINED LAND FIRES

The primary hazards of AML fires are the emission of toxic fumes and subsidence. However, these fires also can affect the conservation of coal resources, ignite surface fires, and affect the value of adjacent property. The type and degree of hazard can influence the selection of an extinguishment technique and the extent of the extinguishment project.

The potentially most serious problem associated with AML fires is the migration of toxic fumes from the fire through overlying strata into homes or other enclosed surface structures. A fire produces carbon monoxide, carbon dioxide and water, and consumes oxygen. Carbon monoxide is the most serious hazard. This colorless, odorless gas readily combines with the hemoglobin of the blood, which normally transports oxygen; it replaces oxygen and forms carboxyhemoglobin. At blood concentrations of 10% to 40% carboxyhemoglobin, headaches, dizziness, faintness, impaired motor coordination, nausea, and vomiting are symptoms of carbon monoxide poisoning. At levels of 40% to 70%, symptoms include increased respiration and pulse rate, collapse, coma, and convulsions. Respiratory failure and death occur when 70% to 80% of the hemoglobin has been converted to carboxyhemoglobin (*30-32*).

The threshold limit value (TLV)[4] for carbon monoxide is considered 50 ppm, a level that will produce 8% to 10% carboxyhemoglobin. The recommended occupational exposure is 35 ppm for an 8-h workday (*33*). The effect of carbon monoxide exposure increases with duration of

[4]The threshold limit value (TLV) is a time-weighted average concentration of a substance in air to which workers may be exposed during a normal 8-h day or 40-h week for an indefinite period without adverse effect.

exposure, higher humidity, and lower barometric pressure. The rate of effect also increases with increased physical exertion. Other factors in individual response to carbon monoxide exposure are age (very old and very young), pregnancy, heart disease, poor circulation, anemia, asthma, lung impairment, or the presence of drugs-alcohol in the blood.

Carbon dioxide, which is also produced by fires, is normally present in air at a concentration of 0.03%. The TLV for an 8-h daily exposure to carbon dioxide is 0.5%, provided the percentage of oxygen is normal (*34*). The recommended occupational exposure as determined by National Institute of Occupational Safety and Health (NIOSH) is 1% carbon dioxide by volume for a 10-h shift in a 40-h week. During prolonged exposure to elevated carbon dioxide concentrations (1% to 3%), excess hydrogen and bicarbonate ions are produced. The body removes this excess acid through an increased breathing rate or through excretion. Prolonged exposure to elevated concentrations of carbon dioxide may cause a loss of efficiency in performing physical exercise, but has had no observed effect on problem-solving or eye-hand coordination.

Prolonged exposure to slightly decreased levels of oxygen has much the same effect as exposure to increased carbon dioxide. If the concentration of oxygen decreases from the normal 20.95% to less than 16%, breathing and pulse rates increase. At less than 10% O_2, nausea, vomiting, and loss of consciousness will occur. At less than 6% O_2, convulsions and respiratory failure occur. Persons with cardiac, pulmonary, or hyperthyroid problems experience severe effects of oxygen deficiency at lesser reductions in oxygen concentration.

In most cases, the possibility of toxic fumes from an AML fire affecting people on the surface is very small. However, these fumes can migrate for considerable distance through cracks and fractures in the overlying strata. They can enter houses through sewers or foundation cracks and can accumulate in closed, unventilated areas like basements and closets. Usually, ventilation can be used to dissipate fumes in surface structures.

Fumes and smoke from AML fires create a serious atmospheric pollution problem. The plume (fig. 11) seen at many AML fires is frequently a steam condensate. Smoke indicates the presence of particulates with the vapor emitted from the fire zone. In addition to toxic gases, fumes from a fire zone frequently contain coal distillates, mercaptans, or hydrogen sulfide, which create noxious and unpleasant odors. Fumes may be responsible for killing some species of surface vegetation in vent areas, although mosses appear to tolerate the fumes and thrive in the higher temperature areas. Small animals, seeking the warmth near vent areas, may be victims of the lethal fumes.

Subsidence occurs when a fire consumes a portion of the coal, removing support from the overlying strata. The strata over the mine then fall into the mine void. The surface expression of subsidence depends upon several factors, such as the depth to the mine and the competence of intervening rock units. The surface expression of the subsurface fire may be a small vent (fig. 12), a fracture line (fig. 13), a slight depression, or a relatively large sinkhole (fig. 14). The width of a subsidence feature can vary from a few inches to several feet. The depth is also variable. If the coalbed is relatively shallow and the overburden is primarily unconsolidated material, it is possible for the subsidence feature to extend from the surface to the mine void.

The hazards associated with subsidence due to mine fires depend upon several factors. The first is location with respect to population density. A subsidence feature in a populated area is inherently more hazardous than one in an inaccessible or remote area. However, a subsidence event in an urban or suburban area is more likely to be abated quickly. In remote areas, subsidence may constitute a long-term threat to hikers and hunters. Subsidence, whether due to mine fires or simply to mining, affects the stability of surface structures, causing minor to major damage. In addition to the normal subsidence problems, if subsidence is related to a mine fire, cracks created in foundations can act as conduits for toxic fumes. Roads, surface streams, sewers, and waterlines also can be affected by any subsidence event. If the subsidence is related to a mine fire, cracks in sewerlines may provide pathways for fume migration into buildings. Fracture zones in the overburden serve as chimneys for combustion products and can supply fresh air to the underground combustion zone.

Another hazard related to subsidence features is the possibility that people or livestock will fall into the larger sinkholes. Fumes from a fire compound this danger. A corollary hazard is related to the tendency of people to use such sinkholes as trash dumps. Hot fumes from the mine fire can accelerate the tendency of trash or garbage to spontaneously ignite, producing a fire that can spread to surface vegetation and structures. Western outcrop fires have been credited with starting brush, grass, and forest fires.

The hazards of mine fires are insidious. They are not like hurricanes, tornados, earthquakes, or floods, in which a single catastrophic event affects many people. Fires in abandoned mines and waste banks are protracted events; they can have a moderate effect on people for 20 years or more. The most widespread effect is the environmental degradation caused by noxious odors and fumes. A more serious, but less prevalent, effect is subsidence and/or fume migration into surface structures. The most extensive disruption, social and economic, caused by an abandoned mine fire is the Centralia mine fire in the anthracite region of Pennsylvania (*35*). At Centralia, the inability to control the mine fire forced the relocation of approximately 1,000 people at a cost of $42 million. Although the effects of most mine fires are less extensive, they are no less severe to the people involved.

Figure 11.—Smoke plume from AML fire.

Figure 12.—Small vent at AML fire.

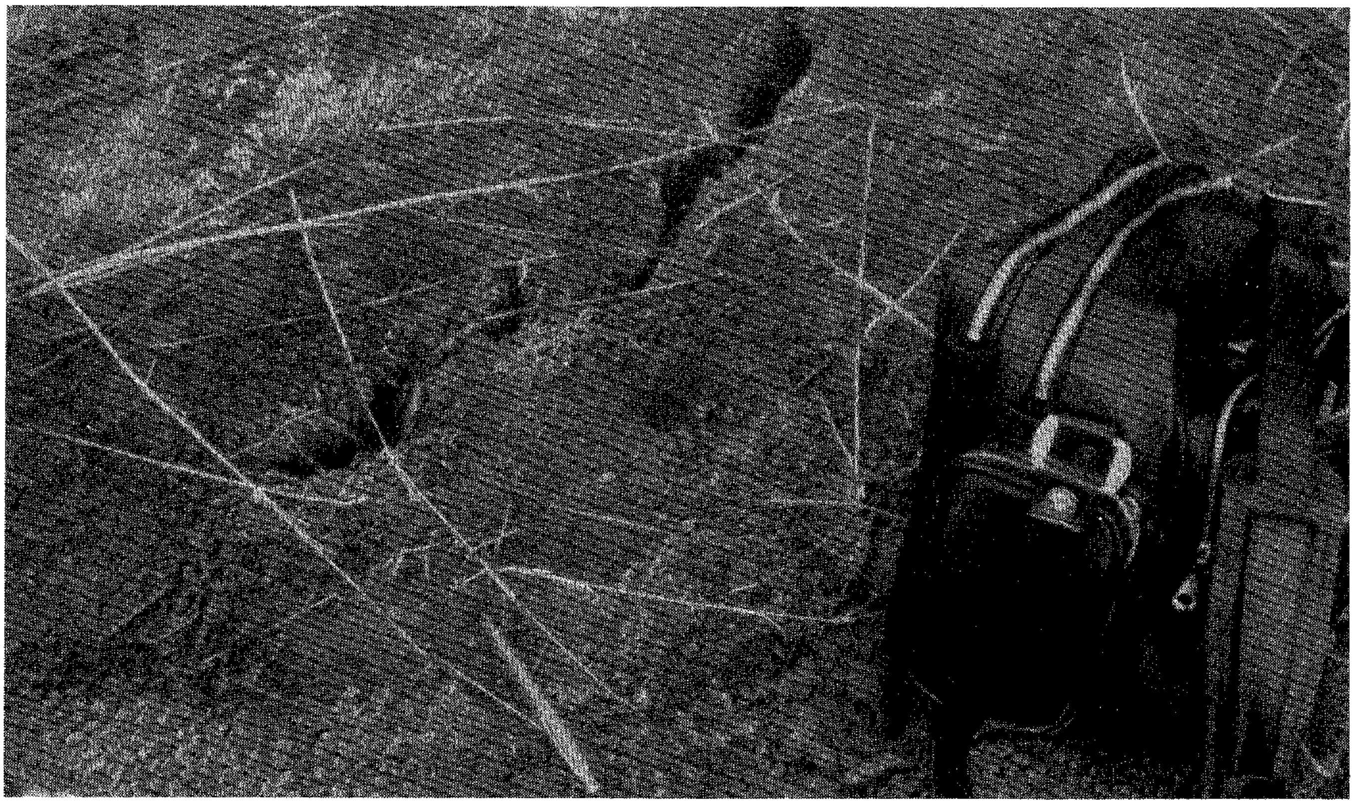


Figure 13.—Fracture line above AML fire.

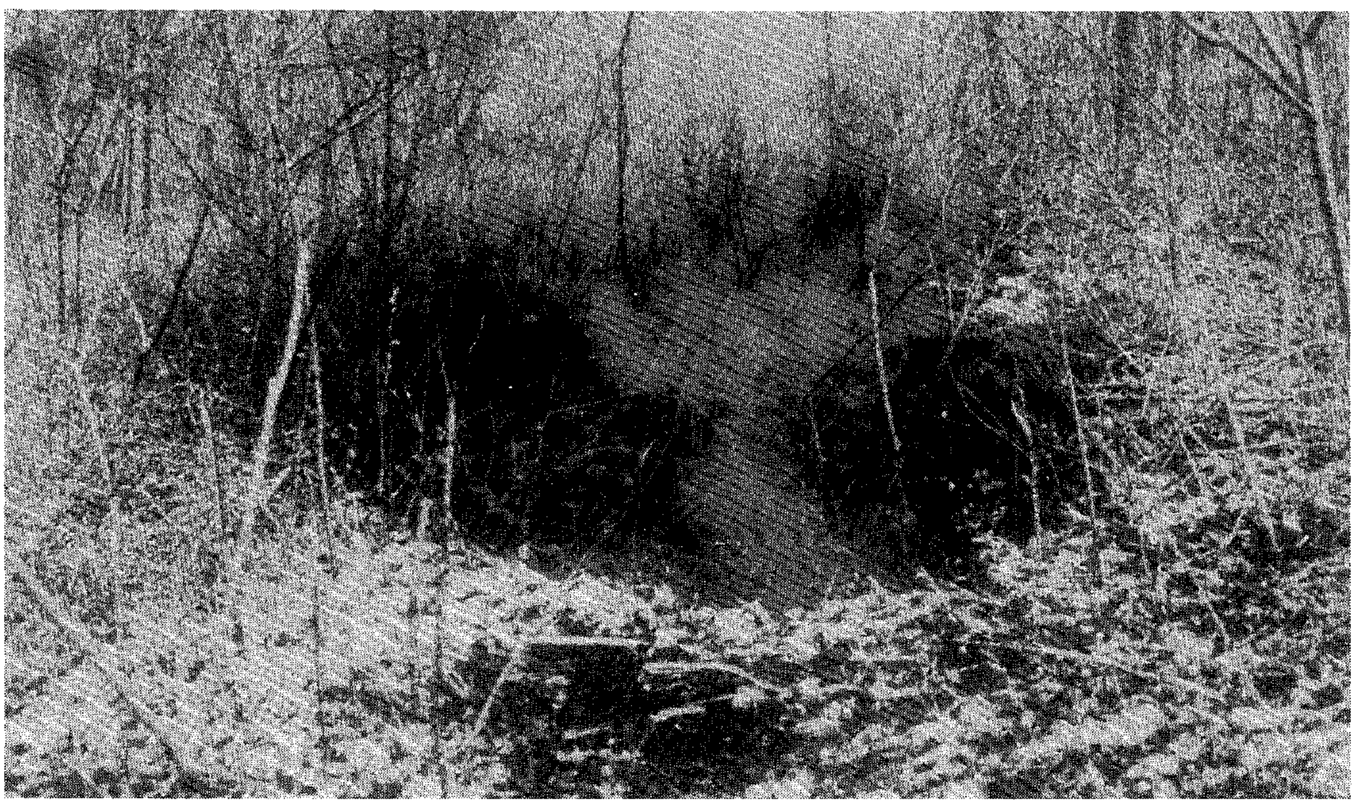


Figure 14.—Sinkhole at AML fire.

EXTENT OF ABANDONED MINED LAND FIRE PROBLEMS

An evaluation of the extent of the AML fire problem is based on estimates of the current number of fires, the area and population they affect, and probability of successful extinguishment. The responsibility for AML fire control efforts and the available funds have been and are factors in the extent of the AML fire problem.

INCIDENCE OF ABANDONED MINED LAND FIRES

Although fires in outcrops and abandoned mines have been occurring for more than 200 years, prior to 1949 no Federal or State agency collected information on the prevalence of AML fires. After 1949, the Bureau had the authority to control fires in abandoned underground mines and in outcrops. In conjunction with this work, reports listing fire control projects, extinguishment methods, and costs were published *(7, 36-37)*. Efforts were also made to estimate the extent of the AML fires and the total cost of controlling such fires *(38-39)*. With the passage of the Surface Mining Control and Reclamation Act (SMCRA) in 1977, AML fire control came under the authority of the Office of Surface Mining, Reclamation and Enforcement (OSMRE) or the States that had an approved AML program. Under this program, a national inventory of AML problems, including fires, was compiled from data submitted by the States and Indian tribes. Based on these sources, information on past fires is reviewed and an estimate made of the current extent of the problem.

For the work done by the Bureau, the country was divided into three regions: the Eastern bituminous region, the anthracite region, and the Western region including Alaska. Between 1949 and 1972, 70 fire control projects were executed in the Eastern bituminous region *(7)*. Three of these projects were located in West Virginia, one in Kentucky, one in Maryland, and the remaining 65 were in western Pennsylvania (table 1). Surface sealing, alone or in combination with other methods was used on 45 of the fire control projects. Ten of the fires were excavated, and fire barriers were used at 27. At 15 fire control projects, either dry fly ash or a fly ash slurry was injected to control the fire.

In the anthracite region, between 1949 and 1980, the Bureau attempted to control 18 fires *(27, 40)*. These involved 29 fire control projects; 18 included some form of excavation, 14 involved flushing, 3 surface seal projects, and 1 control by natural inundation (table 2). In seven of the projects, the planned fire control included more than one method. During the period between 1930 and 1970, an additional 13 fires were controlled by mining companies. Between 1980 and 1986, the OSMRE excavated six anthracite mine fires.

In the Western region, 590 coal fires were reported to the Bureau between 1949 and 1979. Of 158 fire control projects during this period (table 3),[5] 11% used excavation, 2% were isolation projects, and 87% utilized some form of surface sealing *(9, 36-37)*.

In 1977, the Bureau listed 261 fires in abandoned mines and inactive outcrops *(38)*. Twelve of these fires were in the anthracite region, and 197 were in the western States (table 4). Ten coal-producing states reported no fires in abandoned mines or outcrops.

A survey by the Bureau in 1968 located 292 burning coal refuse banks containing 270 million st of coal refuse *(39)*. Of these, 132 were in West Virginia, 184 were in other eastern and midwestern States, and the remaining 24 were in the western States (table 5). Forty-five percent of the banks were located within 1 mile of a community and six of the burning banks affected communities of more than 100,000 people. Sixty deaths were attributed to accidents at burning coal refuse piles.

Under the SMCRA, the OSMRE authorized the National Inventory of Abandoned Mined Land Problems to locate and identify AML problems and to estimate the cost of reclamation *(41)*. The inventory has also been used as a basis for allocating funds from the discretionary portion of the AML fund. The original inventory was updated in 1986 and 1987 *(42)* and has been under review and reevaluation since 1989 *(43)*.

Under the inventory, AML problems were classified under six major categories and 16 keywords. Fire problems were described as "surface burning" or "gases from underground burning." Problems were further classified as: priority 1 - presenting extreme danger to the health, safety, and general welfare; priority 2 - protection of the health, safety, and general welfare; and priority 3 - restoration of land and water resources degraded by past mining practices. Evaluation of the seriousness of a problem is also based on the evidence of impact, the potential for propagation to populated areas and expression of concern by affected people, as well as by the cost of reclamation as calculated according to OSMRE guidelines *(44)*.[6]

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[5]There are more than 158 entries in table 3 since phases of a project completed in different years are listed separately.

[6]The content, interpretation, and use of the AML inventory has been the subject of extended debate *(49)*. In this report, it is used only to indicate the probable extent and distributions of the AML fire problems.

Table 1.—Fire control projects in eastern bituminous region, 1949-1972

Project name	Location County, State	Control method	Date
Agnew Rd.	Allegheny, PA	Surface seal	1954
Ardmore Blvd.	..do.	Plug-seal	1962
Arlington Hts.	..do.	Trench-seal	1962
Baldwin Borough	..do.	Excavation	1953
Becks Run Rd.	..do.	..do.	1972
Bedford Dwellings	..do.	..do.	1953
Blairsville	Indiana, PA	Trench-plug-seal	1965
Boyds Hollow Rd.	Allegheny, PA	Plug-seal	1967
Bradenville	Westmoreland, PA	..do.	1966
Brinkerton	..do.	Trench-seal	1964
Brisbin Borough	Clearfield, PA	Trench-seal-flush	1958
Bullskin-U. Tyrone	Fayette, PA	..do.	1965
Calamity Hollow	Allegheny, PA	Trench	1963
Carpentertown	Westmoreland, PA	Surface seal	1969
Carroll Township	Washington, PA	..do.	1954
Do.	..do.	Seal-flush	1970
Catfish Run	Allegheny, PA	..do.	1958
Churchview Ave.	..do.	Surface seal	1956
Clairton	..do.	Trench-seal	1962
Coal Hollow Rd.	..do.	Surface-seal	1964
Collier	..do.	..do.	1967
Commonwealth Ave.	..do.	Plug-seal	1964
Connemaugh	Indiana, PA	..do.	1964
Cook Plan	Westmoreland, PA	Trench barrier	1950
Division St.	..do.	Seal-flush	1958
Division & 3rd	..do.	..do.	1959
Fairmont	Marion, WV	Excavation	1950
Fallowfield	Washington, PA	Trench	1961
Garden City	Allegheny, PA	Seal-flush	1965
Grant St.	Westmoreland, PA	Flush	1967
Green Valley	Allegheny, PA	Surface seal	1957
Harrison County	Harrison, WV	Excavation	1959
Hempfield Township	Westmoreland, PA	Trench barrier	1954
Highland Terrace	..do.	Trench	1961
Jefferson Borough	Allegheny, PA	Surface seal	1955
Johnsons Hollow	Fayette, PA	..do.	1967
Ken Ridge Dr.	Allegheny, PA	Flush	1969
Kennedy	..do.	Surface seal	1967
Klondike	Allegany, MD	Trench	1959
Larimer	Westmoreland, PA	Plug-seal	1971
Liberty	Allegheny, PA	Excavation	1960
Lick Run	..do.	Surface seal	1949
Lloydsville	Westmoreland, PA	..do.	1949
Do.	..do.	Flush	1968
Longview Land	Allegheny, PA	Surface seal	1963
Lookout Ave.	Westmoreland, PA	..do.	1958
Masontown	Preston, WV	Excavation	1961
Meyersdale	Somerset, PA	Trench	1960
Monongahela City	Washington, PA	Seal-flush	1969
Monroeville (I)	Allegheny, PA	Excavation	1960
Monroeville (II)	..do.	Trench-seal	1960
Moon Township	..do.	Surface seal	1971
Newell	Fayette, PA	Trench	1960
Petermans Corners	Allegheny, PA	Flush	1970
Peters Creek	..do.	Plug-seal	1968
Pikeville	Pike, KY	Surface seal	1959
Plum	Allegheny, PA	..do.	1961
Pricedale	Westmoreland, PA	Barrier-seal	1952
Robinson	Washington, PA	Plug-seal	1968
Ross Farm	Westmoreland, PA	Excavation	1952
Rostraver	..do.	Seal-flush	1956

Table 1.—Fire control projects in eastern bituminous region, 1949-1972—Continued

Project name	Location County, State	Control method	Date
Rostraver #2	Westmoreland, PA	Plug-seal	1966
Santiago	Allegheny, PA	Trench	1957
Smith Township (I)	Washington, PA	Excavation	1961
Smith Township (II)	..do.	Surface seal	1962
Turnpike	Allegheny, PA	Flush	1969
SW Monessen	Westmoreland, PA	Surface seal	1953
U. Tyrone	Fayette, PA	Seal-flush	1969
U. Wheyl	Westmoreland, PA	Plug-seal-flush	1971
Young Township	Indiana, PA	..do.	1972

Table 2.—Fire control projects in Pennsylvania Anthracite region, 1950-1987

Project name	Anthracite field	Control method	Date
Archbald	Northern	Excavate	1985
Carbondale	..do.	Flush	1950
	..do.	Excavation	1974
Cedar Ave.	..do.	Excavation-flush	1953
	..do.	Flush	1965
	..do.	Excavation	1973
Centralia	W. Middle	Excavation-flush	1966
	..do.	Barrier	1974
	..do.	..do.	1978
Coal Run	..do.	Trench-flush	1963
Eddy Creek	Northern	Flush	1974
Enyon Street	..do.	..do.	1965
Forestville	NA[1]	Excavation	1986
Hazelton	E. Middle	..do.	1969
Hughestown	Northern	..do.	1984
Kehley Run	W. Middle	..do.	1969
Kulpmomt	..do.	Trench	1950
	..do.	Excavation	1958
	..do.	Excavation-trench	1960
Larksville	Northern	Trench-excavation	1985
Laurel Run	..do.	Flush-excavation	1971
Maffett	..do.	Excavation	1987
Mt. Carmel	W. Middle	Seal	1950
	..do.	Seal-flush	1952
	..do.	Excavation	1967
North Scranton	Northern	Flush	1960
Peach Mountain	Southern	Excavation	1949
Shamokin	W. Middle	Seal	1951
Shenandoah	..do.	Innundation	1960
Sugar Notch	Northern	Excavation	1984
Swoyersville	..do.	..do.	1973
Throop	..do.	..do.	1968
Tower City	Southern	Flush-excavation	1954
Warrior Run	Northern	..do.	1971

[1]NA Not available.

Table 3.—Fire control projects in Western United States, 1949-1977

Project name[1]	Location County, State	Control method	Date completed
Alkali Butte	Fremont, WY	Surface seal	1956
Area "D" (I)	Kane, UT	..do.	1969
Area "D" (II)	..do.	..do.	1969
Area "D" (III)	..do.	..do.	1970
Area "D" (IV)	..do.	..do.	1971
Area "D" (V)	..do.	..do.	1973
Area "D" (VI)	..do.	..do.	1974
Arizona Black Mesa	Navajo, AZ	..do.	1955
Axial (I)	Moffat, CO	Excavation-seal	1964
Axial (II)	..do.	Surface-seal	1972
Baker's Garden	Richland, MT	..do.	1966
Barker Dome (I)	San Juan, NM	..do.	1966
Barker Dome (II)	..do.	..do.	1966
Belfield	Billings, ND	Excavation-seal	1962
Birch Creek (I)	Emery, UT	Surface seal	1964
Birch Creek (II)	..do.	..do.	1970
Birch Creek (III)	..do.	..do.	1979
Big Buck	Navajo, AZ	..do.	1964
Big Smokey (I)	Kane, UT	..do.	1967
Big Smokey (II)	..do.	..do.	1968
Black Mesa No. 2 (I)	Navajo, AZ	Excavation-seal	1962
Black Mesa No. 2 (II)	..do.	..do.	1963
Black Mesa No. 2 (III)	..do.	Surface seal	1964
Black Raven	Garfield, CO	..do.	1972
Boyd No. 1	Navajo, AZ	..do.	1964
Burnham No. 2	San Juan, NM	..do.	1961
Burnham No. 3	..do.	..do.	1961
Burning Coal Mine	Converse, WY	..do.	1950
Burning Hills No. 2 (I)	Kane, UT	..do.	1976
Burning Hills No. 2 (II)	..do.	..do.	1977
Canaan Creek	Garfield, UT	..do.	1971
Canfield	Campbell, WY	..do.	1950
Canfield No. 2	..do.	..do.	1964
Castle Garden	Freemont, WY	..do.	1954
Coal Bank	Sheridan, WY	..do.	1967
Coal Draw	Campbell, WY	..do.	1969
Coal Gulch	Mesa, CO	..do.	1953
Coalmont	Jackson, CO	..do.	1966
Coalmont Mine No. 1	..do.	..do.	1974
Cottontail Butte	Golden, ND	Excavation	1966
Coyote Creek	Powder, MT	Surface seal	1964
Crosby	Hot Springs, WY	..do.	1967
Crownpoint	McKinley, NM	..do.	1972
Curry	Johnson, WY	..do.	1959
Davis	Slope, ND	Excavation	1977
D & H (I)	Garfield, CO	Surface seal	1973
D & H (II)	..do.	..do.	1975
Debebekid Lake No. 1	Navajo, AZ	..do.	1964
Debebekid Lake No. 2	..do.	..do.	1964
Dead Horse No. 1	Campbell, WY	..do.	1969
Dead Horse No. 2	..do.	..do.	1969
De Mores	Golden, ND	..do.	1967
Deer Creek	Dawson, MT	..do.	1956
Dinnebito No. 1	Navajo, AZ	..do.	1964
Dry Creek	Campbell, WY	..do.	1976
Duck Creek	Converse, WY	..do.	1964
Dugger Rollins	Delta, CO	..do.	1952
Dutch Creek	Sheridan, WY	..do.	1961
Do.	..do.	..do.	1961
East Canoncito	Bernalello, NM	..do.	1963

[1]Roman numerals in parentheses refer to separate phases of one project.

Table 3.—Fire control projects in Western United States, 1949-1977—Continued

Project name[1]	Location County, State	Control method	Date completed
East Dot Klish No. 1	Navajo, AZ	Surface seal	1964
East Dot Klish No. 2	..do.	Excavation-seal	1962
East Dot Klish No. 3	..do.	Surface seal	1964
East Quitchupah	Emery, UT	..do.	1966
Elk Creek	Campbell, WY	..do.	1952
Farmer's Mutual	Mesa, CO	..do.	1969
Fish Canyon	Routt, CO	..do.	1972
Ford Butte	San Juan, NM	Excavation	1966
Fuller	Dawson, MT	Surface seal	1955
Garden	Navajo, AZ	..do.	1964
Gebo	Hot Springs, WY	Excavation	1971
George Harvey	San Juan, NM	Surface seal	1960
Glendive Creek	Dawson, MT	..do.	1956
Haas	Garfield, CO	Excavation	1961
Haileyville	Pittsburgh, OK	Surface seal	1968
Hart	Richland, MT	..do.	1966
Hoffman Creek	Carbon, UT	..do.	1958
Hoffman Creek (II)	..do.	..do.	1959
Hoffman Creek (III)	..do.	..do.	1976
Hogback (I)	San Juan, NM	..do.	1968
Hogback (II)	..do.	..do.	1972
Homer	3rd Judicial, AK	Barrier	1954
Horse Camp	Campbell, WY	Surface seal	1972
Hot Point	Garfield, CO	..do.	1965
Hunt	Custer, MT	..do.	1961
I.H.I. Mine	Garfield, CO	Barrier	1949
I.H.I. #2 Mine	..do.	Surface seal	1953
Indian Coulee	Rosebud, MT	Excavation-seal	1962
Iron Springs	Big Horn, MT	Surface seal	1968
Jennison	Richland, MT	..do.	1961
Killsnight Creek	Big Horn, MT	..do.	1964
Lame Deer	..do.	Excavation-seal	1962
La Plata	San Juan, NM	Surface seal	1954
Laur	Campbell, WY	..do.	1950
Linwood (Utah)	Sweetwater, WY	..do.	1954
Little Missouri 1	McKenzie, ND	Excavation	1960
Little Missouri 2	..do.	..do.	1960
Little Missouri 3	..do.	Surface seal	1961
Little Thunder	Campbell, WY	..do.	1950
Logging Creek	Rosebud, MT	..do.	1964
M.A.	Sweetwater, WY	..do.	1973
McKenzie County	McKenzie, ND	Excavation	1959
Mesa Verde (I)	San Juan, NM	Surface seal	1967
Mesa Verde (II)	..do.	..do.	1968
Mesa Verde (III)	..do.	..do.	1971
Mesa Verde (IV)	..do.	..do.	1978
Mexican Springs	McKinley, NM	Excavation	1967
Middle Prong Wild Horse	Campbell, WY	Surface seal	1970
Minnesota Creek	Delta, CO	..do.	1961
Moose Creek	3rd Judicial, AK	..do.	1954
Moyer Gulch	Campbell, WY	Barrier-seal	1950
Mt. Garfield	Mesa, CO	Surface seal	1969
Navajo 1	San Juan, UT	..do.	1967
Nenamo	AK	..do.	1972
Newcomb	San Juan, NM	..do.	1956
Newton Murphy 1	Dawson, MT	..do.	1959
Newton Murphy 2	..do.	..do.	1959
Nine Mile 1	Sweetwater, WY	..do.	1971
Nine Mile 2	..do.	..do.	1971
Nine Mile 3	..do.	..do.	1971
Ninilchik	AK	Excavation	1971

[1]Roman numerals in parentheses refer to separate phases of one project.

Table 3.—Fire control projects in Western United States, 1949-1977—Continued

Project name[1]	Location County, State	Control method	Date completed
North Park	Jackson, CO	Barrier	1949
Nuxoll.	Custer, MT	Surface seal	1964
Onion Lake	Montrose, CO	..do.	1955
Owens (I)	Rosebud, MT	..do.	1974
Owens (II)	..do.	..do.	1975
Owens (III)	..do.	..do.	1976
Owl Creek	Hot Springs, WY	..do.	1967
Padlock	Campbell, WY	..do.	1951
Park	Richland, MT	..do.	1961
Poposia	Fremont, WY	..do.	1957
Powder River	Sheridan, WY	..do.	1972
Pyle Dam	San Juan, NM	..do.	1950
Recci	Sevire, UT	..do.	1957
Reservation Creek	Rosebud, MT	..do.	1958
Rio Puerco	Sandoval, NM	..do.	1960
Robertson	Converse, WY	..do.	1964
Rosebud No. 1	Jackson, CO	..do.	1963
Rosebud No. 3	..do.	..do.	1969
San Juan	Sandoval, NM	..do.	1951
Skull Creek	Rio Blanco, CO	Barrier	1951
Slagle	Ouray, CO	Surface seal	1954
Soda Lake	Carbon, WY	..do.	1954
Soldier Gulch	Rosebud, MT	Excavation	1967
Smokey Mountain (I)	Mesa, CO	Surface seal	1961
Smokey Mountain (II)	..do.	Excavation-seal	1962
Smokey Mountain (III)	..do.	Surface seal	1963
Smokey Mountain (IV)	..do.	..do.	1964
Smouse	San Juan, NM	..do.	1960
Snake River	Carbon, WY	..do.	1953
Southeast Dot Klish	Navajo, AZ	..do.	1964
Spotted Horse	Campbell, WY	..do.	1970
Standing Rock	McKinley, NM	..do.	1963
Steamboat Springs	Navajo, AZ	Excavation	1967
Stony Butte	San Juan, NM	Surface seal	1960
Stove Canyon	Garfield, CO	..do.	1966
Ten Mile Draw	Sweetwater, WY	..do.	1972
Terrett	Custer, MT	..do.	1959
Terry	Prairie, MT	..do.	1956
Three Forks	Powder River, MT	..do.	1958
Toadlena	San Juan, NM	..do.	1960
Traub	Powder River, MT	Excavation-seal	1966
Tsaya	San Juan, NM	Excavation	1966
Tsaya No. 2	..do.	Excavation-seal	1969
Two Trees	Powder River, MT	Surface seal	1957
Undem 2	Prairie, MT	..do.	1965
Ute Mountain 1 (I)	San Juan, NM	..do.	1965
Ute Mountain 1 (II)	..do.	..do.	1966
Ute Mountain 2 (I)	..do.	..do.	1965
Ute Pasture (I)	Montezuma, CO	..do.	1968
Ute Pasture (II)	..do.	..do.	1971
Ute Pasture (III)	..do.	..do.	1977
Virgil Widner	Dawson, MT	..do.	1958
Watson	Navajo, AZ	..do.	1964
West Canoncito	Bernalello, NM	..do.	1963
West Quitchupah	Emery, UT	..do.	1965
White River No. 1	Rio Blanco, CO	..do.	1959
White River No. 2	..do.	..do.	1959
White Rock	San Juan, NM	Excavation	1967
Wild Horse Creek	Campbell, WY	..do.	1970
Wilson	Navajo, AZ	Surface seal	1964
Windmill	..do.	..do.	1964
Wise Hill No. 3	Moffat, CO	..do.	1976
Yellow Jacket Pass	Rio Blanco, CO	..do.	1954
Zion (I)	Kane, UT	..do.	1965
Zion (II)	..do.	..do.	1974

[1]Roman numerals in parentheses refer to separate phases of one project.

Table 4.—Abandoned mined land fires, 1977

State	No. uncontrolled fires	Estimated reclamation cost, $K
Alaska	3	40
Arizona	10	309
Colorado	47	1,641
Kentucky	5	463
Maryland	2	263
Montana	65	853
New Mexico	9	233
North Dakota	15	185
Ohio	7	920
Pennsylvania:		
Anthracite	12	58,653
Bituminous	30	8,165
South Dakota	2	22
Texas	1	14
Utah	17	636
Washington	2	59
West Virginia	8	1,036
Wyoming	26	2,060
Total	261	75,552

Table 5.—Abandoned coal waste bank fires

State	No. uncontrolled fires	Estimated area, acres	Estimated reclamation cost, $K
Alabama	6	100	25,300
Colorado	15	130	27,500
Illinois	4	140	12,500
Kentucky	27	160	37,000
Maryland	2	3	100
Montana	3	6	500
Ohio	6	20	3,200
Oklahoma	1	1	100
Pennsylvania:			
Anthracite	26	680	96,100
Bituminous	48	580	96,100
Utah	4	30	4,900
Virginia	17	80	6,300
Washington	1	100	5,300
West Virginia	132	1,190	153,100
Total	292	3,200	467,900

The AML inventory is not comprehensive. It is a list of priority one, priority two, and some priority three abandoned minesites requiring reclamation according to guidelines and restrictions established by OSMRE. The affected area is usually an estimate of surface area that would be included in the reclamation project. The estimated cost is based on the volume of the fire area (length and width of the inferred combustion zone times the average overburden depth) and an average unit value for excavation.

Because of the way in which the data are collected, (i.e., fires requiring immediate abatement or those posing a potentially serious threat are included), the prevalence of fires in the Eastern United States (table 6) may be related to the extent of past mining, the proximity to populated areas, and to geological conditions, especially in the anthracite fields. However, priority one and two AML fires are essentially those that have a serious impact on local populations. Fires that are located in remote or inaccessible areas are not included in the AML inventory. This may account for some of the difference between the data previously reported and that in the AML inventory.

From the data in the inventory (table 6), fires in Pennsylvania account for approximately 25% of the estimated cost of controlling surface (wastebank and outcrop) fires and 97% of the cost of controlling subsurface (abandoned mine) fires. The subsurface fires in Pennsylvania are divided evenly between bituminous and anthracite regions. In Pennsylvania, bituminous mine fires account for only 5% of the estimated cost, with the cost per project ranging from $150 thousand to $14 million with the average cost at $2.8 million. Fires in the anthracite region that account for 95% of the estimated cost, range from $280 thousand to $183 million with the average at $42.6 million. If the data for Pennsylvania are excluded, the average estimated cost of controlling a surface fire is $158 thousand, and the average estimated cost of controlling a subsurface fire is $306 thousand. On an historical basis, less than 10% of AML fires have been in the anthracite coalfields (fig. 15), but anthracite fire control projects have been at least 10 times as expensive as projects to control fires in lower rank coals (fig. 16).

As of 1989, OSMRE had obligated over $45 million to an additional 278 priority 1 (emergency) fire control projects in 19 States (table 7). Nine completed fire control projects were listed in the Abandoned Mined Land Inventory System (AMLIS) reports in 1989. Based on the data available, there currently are over 600 fires associated with past mining that require some form of remediation.

Although there is some degree of uncertainty in this data, particularly regarding size and cost of abatement, it can be used to indicate the magnitude of the AML fire problem. Twenty-five percent of the priority two surface fires and 38% of the underground fires are located in the western coalfields. Sixty-eight percent of the surface fires and 60% of the underground fires are located in the Appalachian coalfields. Of these, Pennsylvania and West Virginia account for over 50% of the underground fires. One hundred thirty-four of the 154 surface fires in the Appalachian region are in Kentucky, Pennsylvania, and West Virginia. Less than 5% of all fires are found in the interior coalfields. Almost 75% of the emergency fire control projects are located in Kentucky, Pennsylvania, and West Virginia.

Table 6.—Abandoned mine fires, AML inventory, October 1988

State-Tribe	Surface fires	Est. area, acres	Cost, $K	Underground fires	Est. area, acres	Cost, $K
Alabama	14	57	601	1	NA	107
Colorado	9	20	173	11	12	885
Hopi	0	0	0	1	NA	NA
Iowa	1	10	97	0	0	0
Illinois	2	606	260	0	0	0
Indiana	3	68	833	0	0	0
Kansas	2	40	400	0	0	0
Kentucky	43	176	5,698	20	188	9,953
Missouri	6	9	474	1	1	NA
Montana	23	148	2,589	6	94	1,353
Navajo	3	31	320	0	0	0
New Mexico	4	31	686	1	30	414
North Dakota	1	NA	NA	0	0	0
Ohio	4	5	280	0	0	0
Pennsylvania	33	143	11,963	35	4,933	721,552
Tennessee	2	1	5	0	0	0
Utah	9	20	731	6	32	5,187
Virginia	10	23	838	1	1	240
Washington	1	2	10	0	0	0
West Virginia	48	243	16,351	3	27	588
Wyoming	7	17	138	13	40	887
Total	225	1,650	42,447	99	5,358	741,116

NA Not available.

Table 7.—Federal AML fire control projects by State, 1989

State	Number of fires	Obligated funds, $K
Alabama	1	145
Arkansas	1	11
Arizona	2	852
Colorado	10	785
District of Columbia	1	32
Iowa	1	1
Illinois	4	25
Indiana	2	32
Kansas	2	5
Kentucky	78	6,359
Missouri	1	1,043
Montana	11	409
North Dakota	4	5
New Mexico	9	255
Ohio	6	43
Pennsylvania	88	6,358
Utah	3	31
Virginia	5	927
West Virginia	42	7,295
Wyoming	7	593
Total	278	45,312

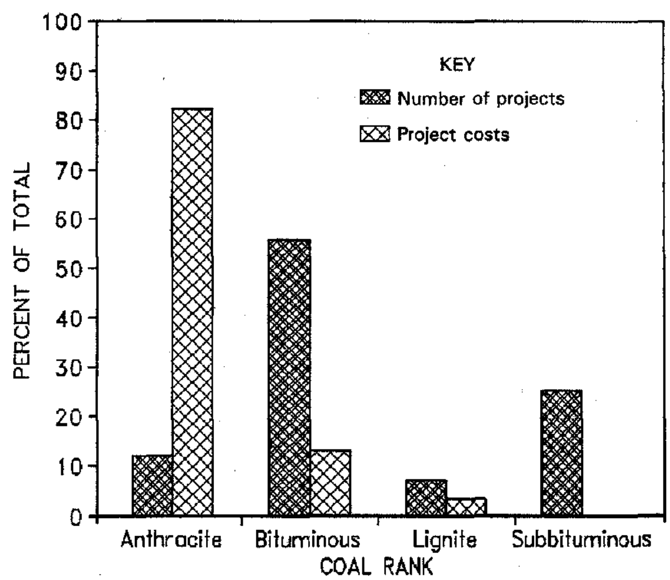

Figure 15.—Percentage distribution of occurrence and cost of AML fire control projects by coal rank.

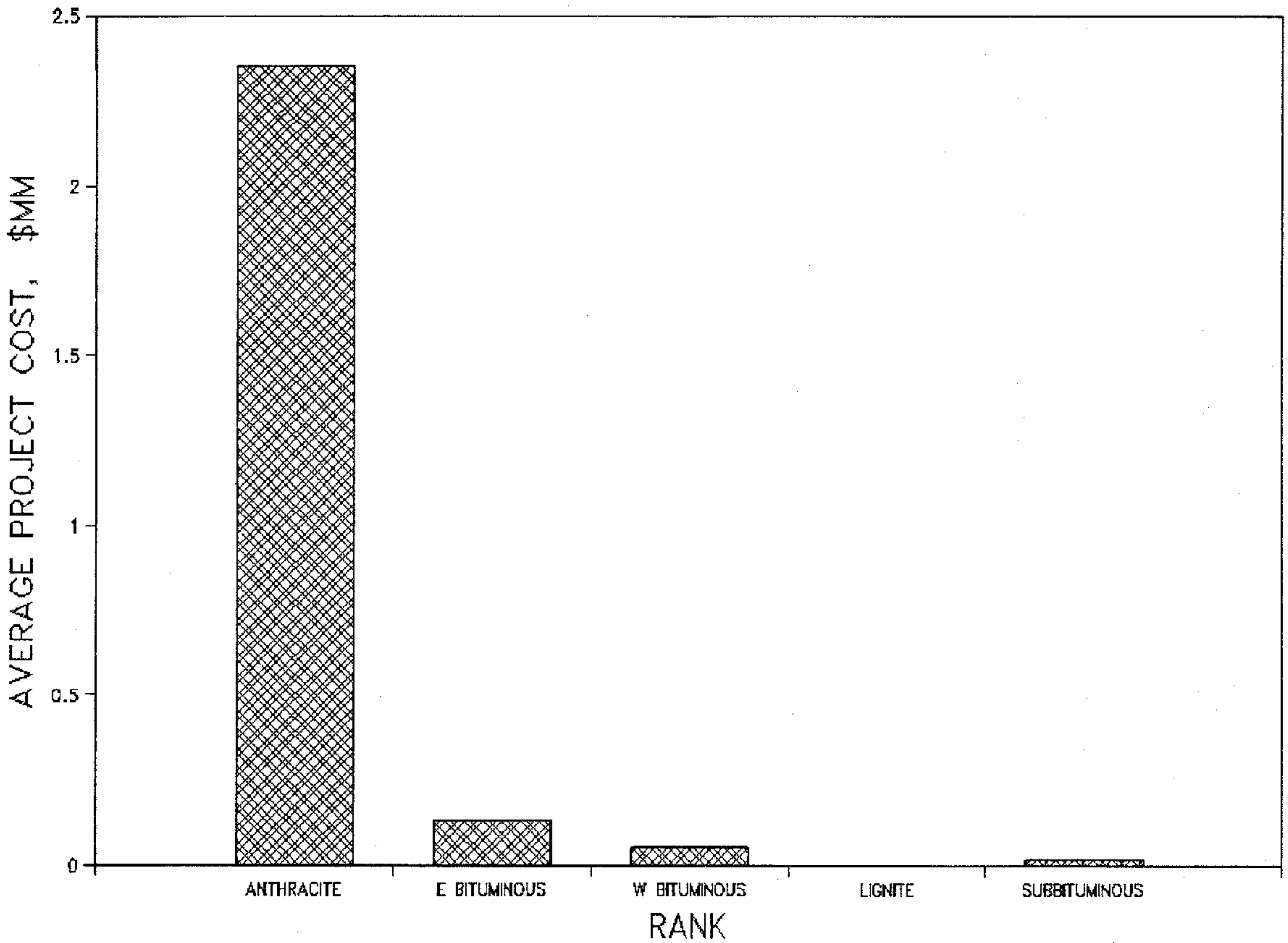

Figure 16.—Average cost of AML fire control project versus coal rank. (E Bituminous - eastern bituminous; W Bituminous - western bituminous.)

CONTROL OF ABANDONED MINED LAND FIRES

In 1948, the Appropriations Bill of the Department of Interior, Public Law 841, 80th Congress, 2nd session, authorized the Secretary of the Interior to expend appropriated funds to control or extinguish fires in inactive coal deposits, paying not less than one half of the expenditure. The States, their subdivisions or the owners of private property were responsible for the remaining cost. Prior to this act, the Federal Government, through the Bureau, had been limited to investigating reported fires and providing consultation and advice. In 1954, Public Law 738, 83rd Congress, provided funds for surveys, investigations, and research into the causes and extent of outcrop and underground fires in coal formations and into methods for control or extinguishment of such fires. It also allowed the Bureau to plan and execute projects for the control and extinguishment of such fires under certain conditions: (1) in coal owned or controlled by the Federal Government, (2) in coal formations owned by the Federal Government under privately owned land, (3) in privately owned coal formations that endangered Federally owned coal, and (4) in abandoned mines on privately owned land, providing that the State, local government, corporation, or individual paid half of the total cost of the work.

In 1965, the role of the Federal Government in controlling abandoned mine fires was expanded by Public Law 89-4 of the 89th Congress, the Appalachian Regional Development Act. This act authorized the Secretary of the Interior to plan and execute projects to extinguish underground and outcrop mine fires in the Appalachian Region in accordance with the provisions of the 1954 law, without regard to appropriations ceiling. It also authorized the Federal Government to expend up to 75% of the cost of fire control projects on non-Federal land.

In 1977, the SMRCA established an abandoned mine reclamation program, including a fund to reclaim and restore areas affected by past mining *(45)*. Money for the fund is collected from coal operators based on short tons of coal produced. Collection of these fees was originally mandated from the 1977 passage of the act until 1992, and then extended until 1995. Monies from the fund finance Federal, State, Indian, and rural reclamation programs. Fifty percent of the money collected annually in any State or Tribe is reserved for that State or Tribe. As much as 20% of the funds collected annually can be allocated to the Department of Agriculture's Rural Abandoned Mine Program (RAMP). Ten percent, to a maximum of $10 million, can be reserved for the Small Operators' Assistance Program (SOAP). The remaining amount, at least 20%, may be expended in any State or Tribe at the discretion of the Secretary of Interior to meet the purposes of SMCRA. Money from the fund is available only when appropriated by Congress and is generally considered inadequate to solve all AML problems.

The 1977 act established priorities for expending funds collected under the act. The first priority was to protect the public health, safety, general welfare, and property from extreme danger of adverse effects of coal mining practices. The second priority was to protect the public health, safety, and general welfare from the adverse effects of coal mining practices. The fund was then to be used to restore land, water, and the environment previously degraded by mining practices, provide for research and demonstration projects relating to reclamation and water quality control, to protect, repair, replace, construct, or enhance public facilities, and to develop publicly owned land adversely affected by coal mining practices.

States or Tribes identify projects according to the priorities and request annual grants to fund administration of the program and the projects, i.e., those listed in table 6 *(44)*. To be eligible for grants from the fund, the States must have an approved regulatory program for active coal mining and an approved AML program. The requirement for an approved regulatory program does not apply to the Indian tribes. Fire control projects in nonprogram States, those that do not have active mining operations, but do have eligible abandoned minesites, are reclaimed with funds from the Secretary's discretionary fund. RAMP funds are used to reclaim rural sites by the department of Agriculture's Soil Conservation Service *(46)*.

Based on published data *(8-9, 27, 40)* and from private communications on past fire projects, estimates were made on the cost and effectiveness of AML fire control. The cost of controlling abandoned mine fires has been highly variable. It depends upon the depth, location, and extent of the fire, on the extinguishment method, and the availability of equipment and materials. Between 1950 and 1988, the cost of fire control projects ranged from $3,000 to $11.6 million.

The estimates of effectiveness are even less exact than the cost data. They were based on published evaluations or inferred from repeated projects at a single site over an extended time frame. Because of the way in which the data were collected and evaluated, the estimates in tables 8 and 9 are considered only order of magnitude indicators.

Table 8.—Mine fire control costs and effectiveness by rank

Rank	Number of fires	Average cost, $K	Estimated effectiveness, %[1]
Anthracite	22	2,350	40
Bituminous	102	111	60
East	62	132	NA
West	40	53	NA
Lignite	13	4	NA
Subbituminous	46	18	44

NA Not available.

Table 9.—Mine fire control costs and effectiveness by method

Method	Number of projects	Average cost, $K	Estimated effectiveness, %
Excavation	57	685	70
Flushing	16	533	27
Seal	86	28	42
Trench	4	119	<10

For the evaluations, projects listed in tables 2 and 3 at the same location were considered related to a single fire. Projects listed separately for one location were considered separate projects; projects listed as phases were considered one project. For example, there are six fire control projects for Centralia, PA over a period of 20 years. This was counted as one fire and six projects. The "Area D" fire, actually an outcrop fire affecting 20 to 25 coalbeds near Glen Canyon City, UT was controlled in six phases between 1969 and 1975. This was counted as one fire and one fire control project. Since complete information was not available on all projects, the number of projects given in tables 8 and 9 does not agree with the number of projects listed in other tables.

The effectiveness of past fire control efforts is a very rough estimate. It was a common practice to consider a fire controlled or extinguished at the end of a project. Generally, there was neither time, money, or personnel available to check on actual effectiveness. For this report, a fire control project was considered ineffective if the same project name and location reappeared after a few years in the project lists. In this type of analysis, the degree of uncertainty is relatively high. The tables are intended only to indicate costs and the relative probability of effective control.

In comparing fire control efforts versus the rank of the coal, fires in anthracite are the most expensive to control and have the lowest probability of success (table 8). Bituminous fires are two to three times more expensive to control if they are in the Eastern United States than if in the west. When comparing fire control methods, excavation and surface seals are most frequently used (fig. 17). Excavation is the most expensive, and surface seals are the

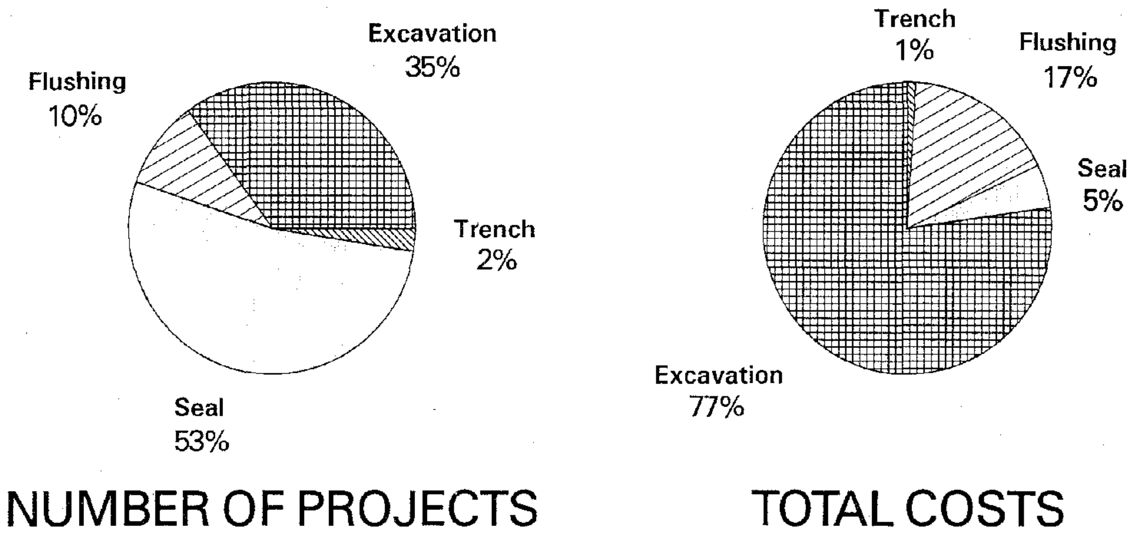

Figure 17.—Distribution of AML fire control projects by method.

least expensive control technique (table 9). Based on historical data, excavation has the highest probability of success. If because of location, cost, or other factors, excavation is not a control option, other currently available fire control options have a lower probability of success.

There is actually no relationship between effectiveness and expense; over all fire control efforts, effectiveness could be considered a random parameter. In most projects to control fires in abandoned mines, the extent of the fire was unknown. The selection of a method to control the fire was often based on funds available, site constraints, and experience. There was often no flexibility to alter the plan and no postproject evaluation. The conventional approach to fire control is not oriented toward a systematic evaluation of available options or their cost versus probable effectiveness.

ABANDONED MINED LAND FIRE EXTINGUISHMENT-CONTROL

A fire requires three elements, fuel, oxygen, and energy. To extinguish a fire at least one of these elements must be removed (fig. 18). Fuel is removed when it is consumed or when it is physically separated from the burning mass. Excavation and most barriers are fuel removal methods of fire control.

Oxygen removal depends on either the introduction of an inert atmosphere or on the isolation of the fire zone from sources of fresh air. The injection of inert gases is intended to suppress combustion by decreasing the available oxygen supply. Flushed barriers are intended to isolate the combustion area and also to interrupt the continuity of the fuel supply. Surface sealing is the most frequently used oxygen exclusion method. It is based on the premise that if atmospheric air can be excluded, the fire will eventually be extinguished.

Heat removal, the cooling of all fuel below the reignition point, can be a method in itself or it can be used in conjunction with fuel removal or oxygen exclusion. Without some form of heat removal, the chance of successfully extinguishing an AML fire becomes smaller.

Heat removal can be accomplished by moving a heat absorbing agent (usually an inert gas or water) through the mine. It is more common, however, to allow heat to dissipate naturally while suppressing combustion. Convection and conduction through the overburden account for most of the heat loss in a mine fire. The normal lack of air movement in a mine makes convection an extremely slow process. The time to cool a fire zone under 100 ft (3,000 cm) of cover by thermal conduction through the overburden can be estimated by:

$$t = x^2/k = [3{,}000 \text{ cm}]^2/0.01 \text{ cm}^2/\text{s} = 9 \times 10^8 \text{ s} = 28.5 \text{ years},$$

where t is the time, x is the overburden thickness, and k is the thermal diffusivity of the overburden (sandstone in this example) *(47)*.

To dissipate heat by natural convection would require that the combustion zone(s) be completely isolated while a rapid influx of cooler air from the outcrop and the exhaustion of heated fumes through fractures in the overburden removes stored heat. However, a typical fire

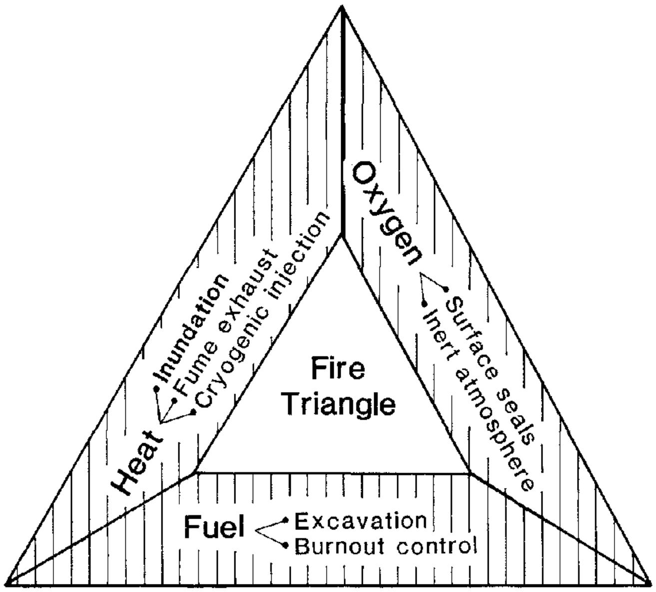

Figure 18.—Fire triangle and control methods: fuel removal, oxygen exclusion, and heat removal.

generates a higher pressure area that forces heated fumes deeper into the mine while drawing cooler air from the outcrop or from other areas of the mine. This type of internal convection cell may account for the discontinuous propagation of mine fires. Even when the supply of oxygen is relatively low, continuous heating at low temperatures may drive off inherent water from the coal and allow for increased adsorption of oxygen. Experimental data *(14)* has shown that accelerated oxidation begins at temperatures between 80° and 120° C for anthracites, depending to some extent upon the amount of prior oxidation. Accelerated reactions begin for bituminous coals at temperatures as low as 50° to 70° C. Convective heat transfer in a mine occurs when heated vapors from the combustion zone migrate to other parts of the mine. If the coal has been preheated or conditioned, spontaneous ignition may occur, even though these areas are remote from the original source of heat. In contrast, a flame spread mechanism requires that coal adjacent to a burning area be heated by conduction and radiation to its ignition temperature of 400° to 500° C.

Low temperature conditioning and spontaneous ignition may be factors in the discontinuous propagation of mine fires. In a hypothetical situation, a fire occurs near a portal or outcrop (fig. 19). The fire induces circulating air currents, which carry fumes and heat into the interior of the mine. The effective ambient temperature of a large area of the mine is slowly increased. Drying and accelerated oxidation continue to raise the temperature of the coal. If in these localized regions, the heat is not readily dissipated and sufficient oxygen is present, spontaneous heating will eventually cause active combustion to occur. After a period, several fires may occur in the interior of the mine without a continuous combustion pathway from the original firesite. Noncontinuous propagation of a mine fire imposes two constraints on an extinguishment method. First, it must affect all the burning material and second, it must be effective until all the material within the combustible zone is cooled below 100° C. This applies to adjacent noncombustible rock that has been heated by the fire.

Normal heat transfer to the overburden occurs by conduction or radiation, which because of its low heat conductivity generally acts as an insulator. Roof coals and carbonaceous shales even with carbonaceous contents as low as 25% may exhibit spontaneous heating behavior. Heat conduction through the roof coals and shales may serve as a pathway for the spread of the fire. Even if no combustion occurs in the roof, heat transferred to the overburden creates a very large heat reservoir. For example, the combustion of 1 st of medium volatile bituminous coal releases 30 million Btu. If this energy is simply adsorbed by the roof rock, it would raise the temperature of 75 st of rock, approximately 900 ft^3, to 500° C. Depending on the rock, the extent of combustion, and the length of time the fire has been burning, the amount of heat stored in the coal and adjacent strata can be more than 1 billion Btu's. If all combustion ceases, it would take 10 to 30 years for this amount of heat to dissipate by conduction through the overburden.

To prevent reignition of the fire, all coal and heated rock must be cooled below the reignition temperature. Even very small, isolated fires or areas where the coal is oxidizing at a high rate can serve as reignition points if the control measure fails and oxygen becomes available. It is generally assumed that if the temperature is below 100° C, the chance of reignition is small.

In many cases, if extinguishment is technically improbable or economically impractical, controlling the fire is a desirable alternative. By limiting the propagation of the fire, by isolating it, or by slowing the combustion rate, safety considerations can be met until natural processes consume all the fuel and/or dissipate the heat. Control methods require a commitment to maintain the appropriate conditions for an extended time and should include a method to monitor the condition of the fire.

TEMPERATURE AND GAS MONITORING

Most fires in abandoned mines and wastebanks are not visible on the surface. Occasionally, glowing coal can be seen in an abandoned portal, but this is the exception. Abnormal snow melt, changes in vegetation, and odors are the usual indicators of a subsurface fire. Abnormal snow melt (fig. 20), most pronounced in light to moderate snowfalls, indicates areas where the heat transmission

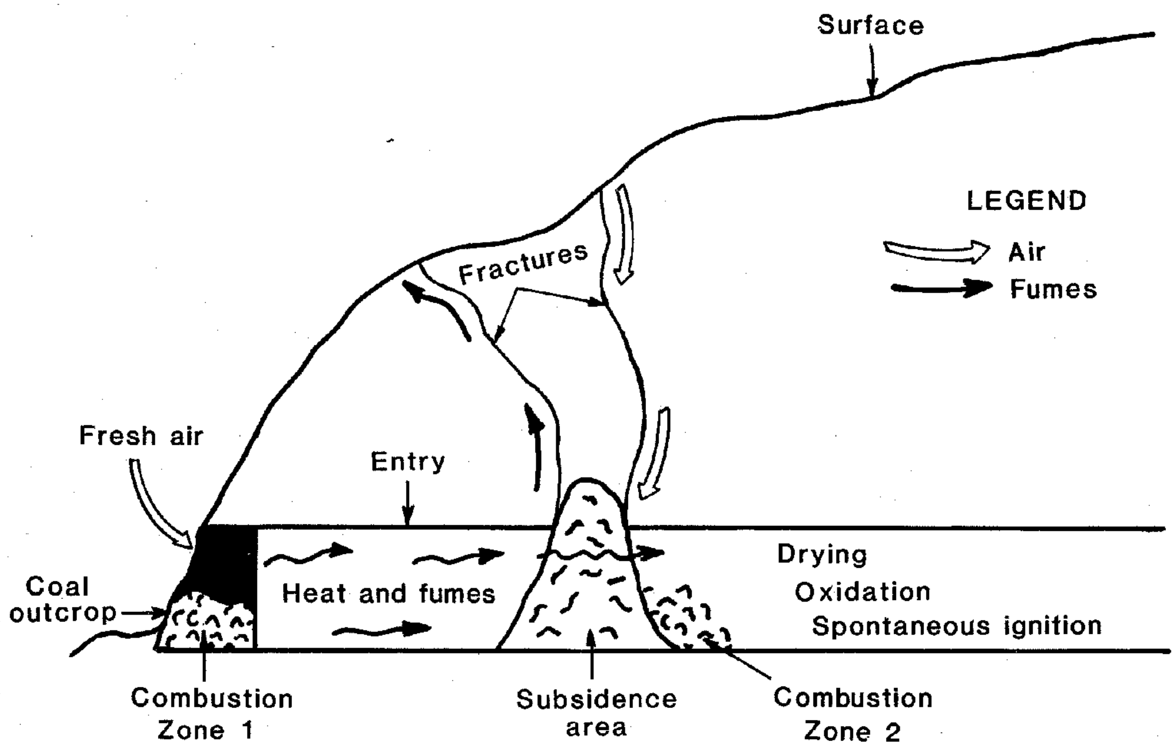

Figure 19.—Discontinuous fire propagation in abandoned mines.

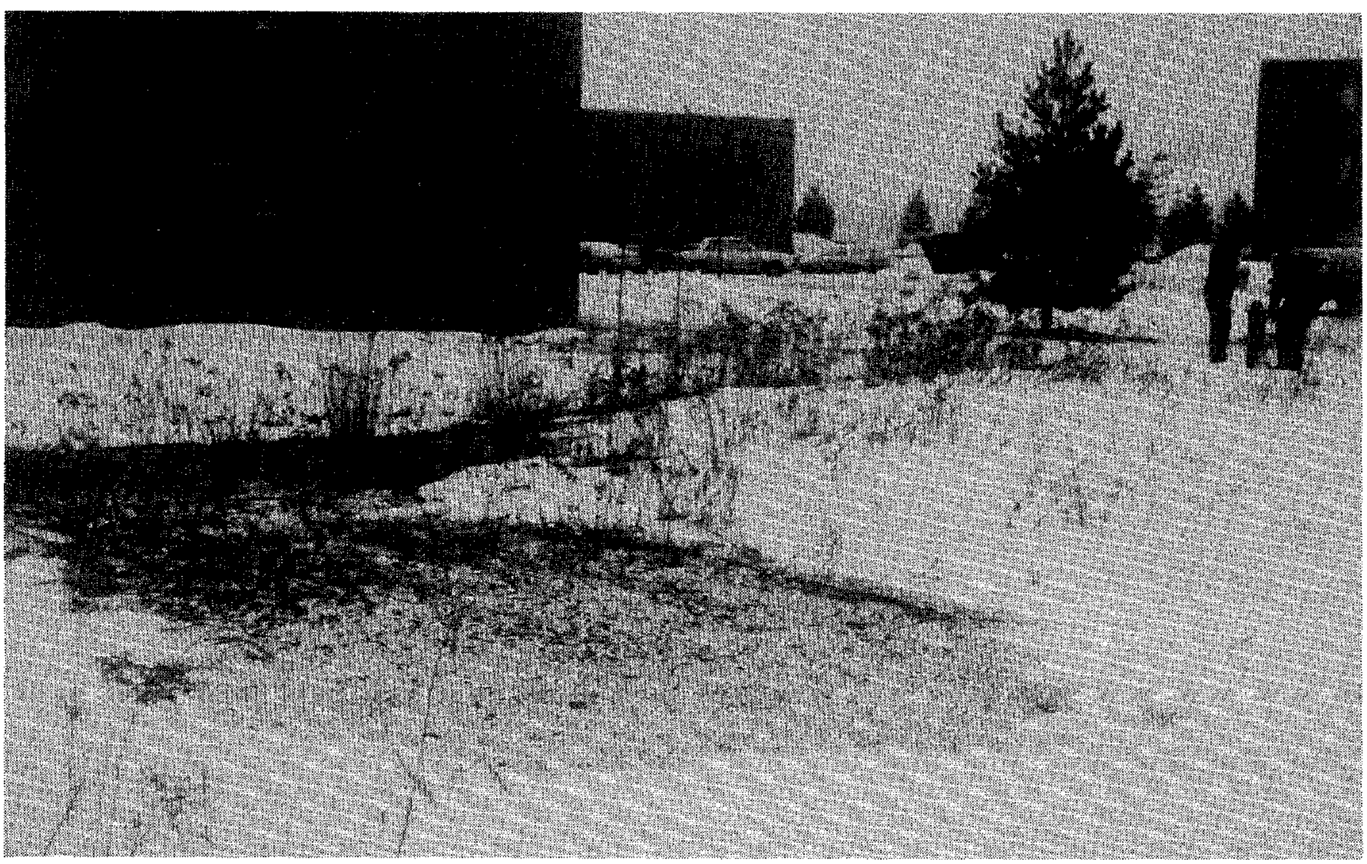

Figure 20.—Abnormal snow melt indicating subsurface heating.

through the underlying strata has raised the ground temperature to above 0° C. The effect is usually transient and may be related to causes other than a fire, such as the distribution of heat absorbing minerals in a waste pile. Dead or dying vegetation (grass, shrubs, trees) may be found near some vents where the heat is sufficient to scorch roots (*8*). Conversely, some mosses seem to thrive in the high temperature area around vents. Odors are associated with fumes from the fire that also may contain hydrogen sulfide. Strong and persistent noxious odors, due to the presence of coal distillates characteristic of burning coal, are among the most serious AML fire problems, but are not a reliable indicator of a fire's location.

Smoke and vapor at vents, fractures, and sinkholes are the usual indications of an AML fire. Smoky plumes contain particulates, indicative of relatively low temperature and inefficient burning (*8*). Steam condensate plumes indicate relatively high temperature, efficient fires. They may be visible only as heat refraction patterns or as vapor condensing in cooler air. The emission of smoke and vapor is controlled by the location of vents and fracture zones formed by normal geologic processes. Therefore, smoke is not necessarily observed immediately above the combustion zone in which it originates.

Temperature and gases have been the conventional indicators of unseen fires. Temperature measurements have been used to delineate fires and to indicate long-term changes in combustion activity. Temperature measurements alone are considered a poor indicator of fire location. Abandoned coal fires usually involve small volumes of smoldering coal; very hot spots are localized with a rapid drop-off to cooler temperatures. These fires tend to be discontinuous, and surrounding rock can provide additional insulation. Borehole temperatures may be near normal underground temperatures within several feet of a combustion zone. Under appropriate conditions, borehole temperatures are a relatively quick and inexpensive method to monitor changes in combustion activity.

Subsurface temperatures are measured by thermocouples suspended in boreholes to the mine void. Temperatures measured by probes placed within the casing are affected by the thermal conductivity of the surrounding rock and the casing. Updrafts and downdrafts also may affect the temperature measured in the casing as opposed to that in the mine void.

A 5-ft length of stainless steel sheath, type K (Chromel-Alumel) thermocouple temperature probe is recommended. This configuration normally places plastic connectors and insulation above the casing bottom where temperatures above 100° C could melt the plastic. A portable digital thermometer is used to read the downhole temperature. Permanent installation of the thermocouple yields more accurate results, since lowering the thermocouple for each reading is time-consuming, labor-intensive, and introduces sources of error. Generally, a thermocouple measures the highest temperature within a volume of 1 to 2 ft^3 immediately surrounding the thermocouple tip, i.e., a maximum radial distance of approximately 10 in. To compare temperatures over a period requires that each measurement be made at the same point within the mine void. Even careful insertion of the thermocouple is unlikely to meet this requirement. For example, a discrepancy of 1 in. in the placement of the thermocouple is a 10% error in the radial distance. In a 50-ft borehole, this requires a placement accuracy of ±0.2%. Also, opening a borehole allows the mixing of subsurface and ambient air, depending on the relative pressures. This introduction of cooler or warmer air may distort the measured subsurface temperature. If temperatures are high, these errors may be inconsequential. However, small changes to infer long-term heating or cooling trends cannot be determined unless the thermocouple installation is permanent.

Even under stable conditions, subsurface temperatures yield limited information about fire conditions. Borehole temperatures were taken at a fire project in the Pittsburgh coalbed over a period of 2 years (*48*). Of 38 boreholes, three had temperatures greater than 100° C, 25 boreholes had average temperatures between 30° and 100° C (table 10). Ten boreholes had average temperatures below 30° C. The normal subsurface temperature in the mine would be expected to be in the 11° to 15° C range, and only one borehole had a temperature in this range. The relative standard deviation was between 1% and 29%; the relative variation in temperature for most of the holes was less than 5% over the 2-year period. Based on temperatures alone, active combustion was occurring along the buried outcrop, and large areas of the mine were at higher than normal temperatures. Heat capacity considerations and gas composition data indicate that the active combustion zones extend to the interior of the mine.

At another mine fire project in the anthracite region, borehole temperatures were taken over a period of 3 months (*24*). Of 34 boreholes, two had temperatures over 100° C, 15 boreholes had average temperatures between 30° and 100° C (table 11). Seventeen boreholes had average temperatures below 30° C, but only one was in the 11° to 15° C range. The relative variation in temperature during the monitoring period was between 1% and 150%, with most boreholes in the 5% to 10% range. Elevated temperatures were not well correlated with other combustion indicators.

Table 10.—Mean borehole temperatures, Large mine fire

Borehole number	n	T, °C	Standard deviation	
			± °C	%
1	91	23	1	4.29
2	96	36	1.86	5.11
6	93	47	4.21	8.99
7	98	32	4.94	15.39
8	98	59	4.25	7.23
10	98	26	.59	2.26
11	98	44	1.1	2.50
12	63	18	.87	4.87
13	67	54	3.78	7.00
15	66	73	1.01	1.38
16	64	62	1.6	2.58
20	67	50	14.57	28.97
22	66	31	.49	1.58
23	65	28	4.08	14.68
28	20	30	.49	1.61
29	20	21	.4	1.89
30	19	27	.44	1.62
31	20	36	.34	.93
32	19	47	.04	.08
33	19	47	1.76	3.74
34	18	119	5.04	4.24
35	18	54	.89	1.64
36	20	37	.34	.93
42	19	60	.96	1.61
43	15	47	.42	.89
44	18	107	4.94	4.62
45	17	353	19.18	5.44
46	19	38	.36	.95
47	19	29	.23	.80
48	19	15	.7	4.62
49	16	19	3.65	19.72
50	19	38	.4	1.06
54	7	20	.91	4.45
55	7	35	.12	.34
56	7	34	.76	2.23
57	7	49	.43	.87
58	6	34	.05	.15
59	8	42	3.24	7.69

Long-term temperature monitoring can indicate heating or cooling trends. However, heating or cooling rates are very low and one annual temperature measurement may fall within the normal variation. For example, for a measured temperature of 30° C, the normal variation, assumed to be ±5%, is 1.5° C. Based on the data in a Montana study (*49*), the average cooling-heating rate may be as low as 0.1° C per year (table 12). The rate of temperature change showed no correlation with the initial temperature (fig. 21). Evaluations of control effectiveness based on temperature monitoring should consider that the magnitude of the temperature change should be greater than the expected normal variation and should show consistent trends over a minimum of 5 to 10 years (fig. 22).

Table 11.—Mean borehole temperatures, Carbondale mine fire

Borehole number	n	T, °C	Standard deviation	
			± °C	%
1	11	73	2.45	3.37
2	6	38	1.50	3.96
3	11	157	66.29	42.11
4	11	34	1.82	5.41
5	11	25	1.47	5.83
6	11	121	12.88	10.61
7	10	40	6.47	16.21
8	10	51	.99	1.92
9	8	69	3.10	4.48
10	11	33	2.00	6.15
11	9	60	1.66	2.75
12	10	16	1.50	9.49
13	11	18	1.43	7.93
14	8	85	1.61	1.90
15	10	60	8.64	14.35
16	11	19	1.61	8.30
17	11	17	1.90	10.93
18	10	18	6.49	36.18
19	9	19	1.38	7.12
20	8	16	.97	6.05
21	8	14	1.66	11.70
22	8	32	47.45	150.35
23	11	31	1.42	4.64
24	10	22	1.34	6.03
25	11	19	1.84	9.48
26	11	23	2.46	10.74
27	11	17	1.269	7.36
28	7	18	1.49	8.16
29	11	16	.82	5.28
30	11	16	.99	6.08
31	11	21	1.60	7.57
32	7	37	2.20	5.98
33	8	55	.80	1.44
34	8	47	.97	2.08

Table 12.—Variation in cooling rate at western mine fires[1]

Borehole number	Temperature decrease, °C	Time, months	Cooling rate °C/year
Frank Mine Fire:			
1	2	67	0.31
3	23	67	4.06
4	9	67	1.60
5	17	67	3.00
6	12	67	2.19
11	9	67	1.65
12	17	67	3.12
13	7	67	1.33
15	24	67	4.34
16	31	67	5.53
18	10	32	3.73
19	10	32	3.67
20	10	32	3.69
21	8	32	2.88
22	10	32	3.88
23	7	32	2.79
24	8	32	3.08
25	9	32	3.33
Shadwell Creek A:			
2	14	33	5.19
4	9	34	3.29
5	5	22	2.76
6	4	34	1.45
9	32	34	11.39
10	5	34	1.90
11	40	34	13.94
12	16	34	5.71
13	9	34	3.02
14	10	34	3.39
15	20	4	59.17
16	9	34	3.31
17	8	34	2.98
18	9	34	3.06
19	10	34	3.65
Shadwell Creek C:			
8	33	34	11.65
9	26	34	9.12
10	7	34	2.39
11	34	34	11.90
12	15	34	5.12
13	10	34	3.57
14	10	34	3.49
15	33	34	11.53
16	18	34	6.37
17	14	34	4.80
18	5	34	1.61
19	6	34	2.06
26	12	34	4.29
Muster Creek A:			
2	1	33	.24
3	2	33	.85
4	6	33	2.24
5	26	33	.89
6	4	33	1.56
Muster Creek A—Continued			
7	6	33	2.18
10	8	33	2.97
13	1	33	.53
15	9	33	3.09
16	7	33	2.63
17	1	33	.44
18	2	33	.55
19	2	33	.55
22	10	33	3.47
23	9	33	3.35
25	9	33	3.17
26	20	33	7.11
27	6	33	2.02
Muster Creek B:			
2	1	33	.34
3	4	33	1.29
4	9	33	3.15
5	6	33	2.06
6	11	33	4.08
7	11	33	3.82
10	18	33	6.71
13	1	33	.44
15	10	33	3.80
16	9	33	3.27
17	2	33	.65
18	2	33	.65
19	2	30	.62
22	24	30	9.44
23	14	30	5.76
24	35	30	14.11
25	14	30	5.58
26	22	30	8.62
27	7	30	2.69
Muster Creek C:			
2	2	33	.67
3	6	33	2.00
4	11	33	4.04
5	9	33	3.15
6	23	33	8.48
7	12	33	4.28
10	18	33	6.63
13	8	33	2.89
15	16	33	5.68
16	15	33	5.62
17	6	33	2.28
18	2	33	.69
19	1	33	.36
20	7	33	2.57
22	39	30	15.49
23	20	30	8.09
24	26	30	10.24
25	13	30	5.00
26	20	30	8.00
27	5	30	1.93

[1]Data from Hanson (*49*).

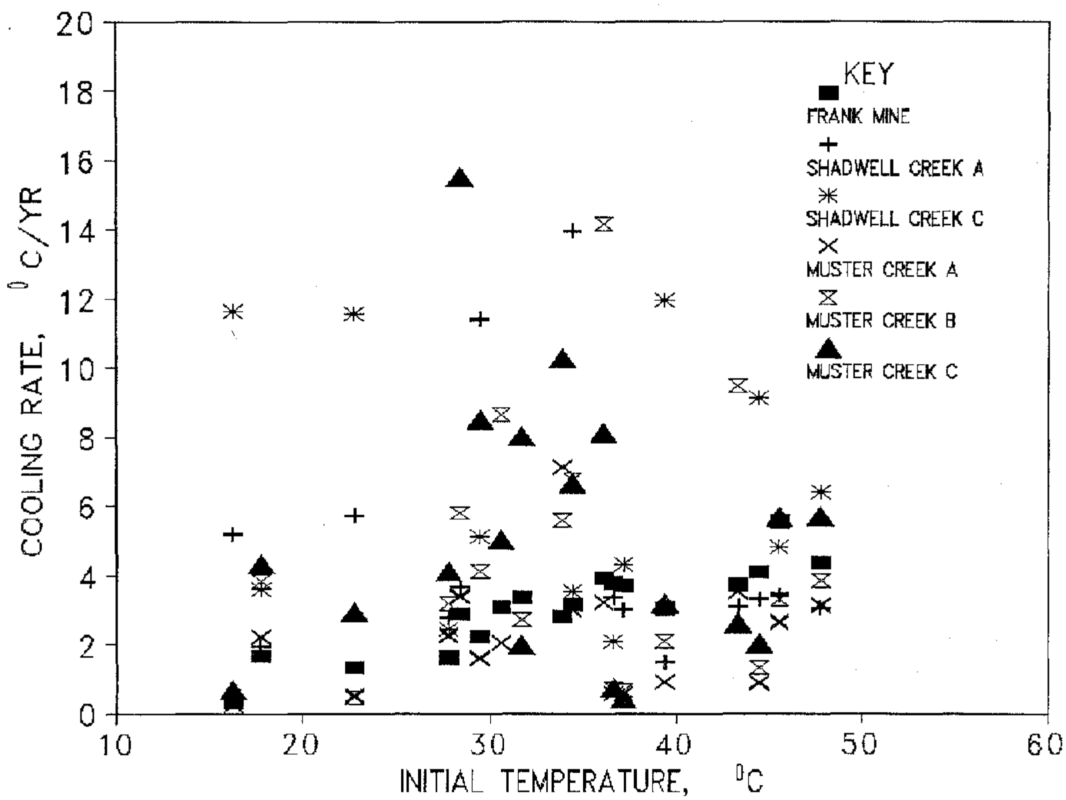

Figure 21.—Rate of subsurface cooling versus initial temperature. Based on data in reference 49.

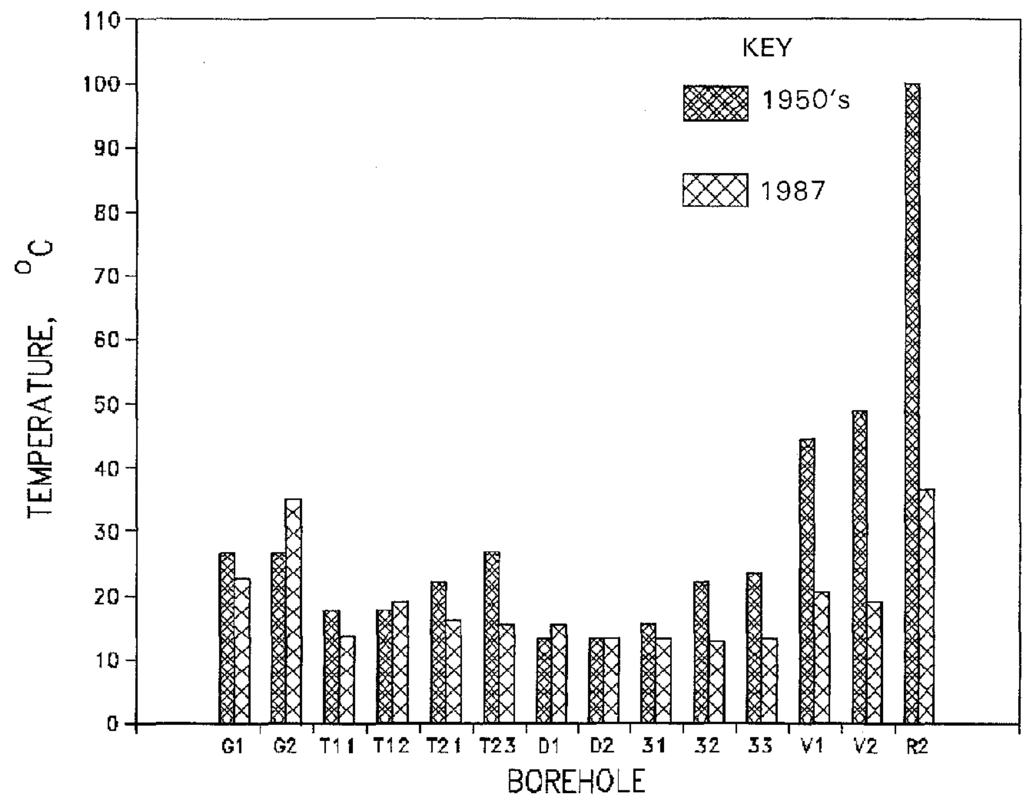

Figure 22.—Change in subsurface combustion zone temperature over 30-year period. Based on data in reference 49.

Gas composition as a combustion indicator has been used occasionally to monitor abandoned mine fires. Gas samples must be obtained from the mine void or from an area near the combustion horizon. The composition of samples taken from near the top of a borehole is dependent on the pressure differential between the atmosphere and the mine, the temperature gradient, and diffusion. Under any sampling conditions, subsurface fire indicators based on the gaseous products of combustion, carbon dioxide, carbon monoxide, and a decrease in oxygen are not sensitive or accurate. Ratios such as the Jones-Trickett ratio[7], the airfree CO concentration and the ratio of CO to CO_2[8] *(51)*, and the CO/dO_2 *(52)* index[9] *(53)* are frequently used in active mines, particularly to monitor gob areas. Combustion product ratios often yield ambiguous results when applied to abandoned mine fires. The dilution factor, gases from noncombustion processes, the ventilation pathway, high humidity, the adsorptive surface of coked coal and the accumulation of combustion products over extended periods may be factors in the low accuracy of these indicators when used at abandoned mines.

In field and laboratory studies *(17, 27, 48)*, variations in the concentrations of carbon dioxide, carbon monoxide, and oxygen were not consistent indicators of elevated temperature. It was found that the average carbon dioxide concentration varied inversely with the oxygen concentration irrespective of temperature (fig. 23). In controlled experiments, it was found that carbon monoxide is not produced from coal below a temperature of 120° C (fig. 24). In the field study, only 9 of 38 boreholes had average carbon monoxide concentrations greater than 0. The absence of carbon monoxide can indicate that the coal is cold and no carbon monoxide is produced or it may mean that complete combustion is occurring in an oxygen rich environment and no carbon monoxide is produced. Of the boreholes in which carbon monoxide was detected, more than half had oxygen concentrations below 8%, supporting the theory that carbon monoxide is produced by combustion reactions in a low oxygen environment. The ratio of carbon dioxide to carbon monoxide is variable, but asymptotically approaches a limiting value of three (fig. 25). Gas composition and the JTR can indicate whether combustion is occurring in a relatively oxygen-rich environment. Over an extended period, an oxygen concentration that remains constant or increases indicates a source of fresh air.

[7]Jones-Trickett Ratio (JTR) = $([CO_2] + 0.75[CO] - 0.25[H_2])/(0.286[N_2] - [O_2])$.

[8]$(CO)_{Airfree} = ([CO]/(100\text{-}4.76\,[O_2]))*100$.

[9]Graham index $= CO/dO_2 = [CO]/(.268[N_2] - [O_2])$
where [CO] = concentration of CO in ppm
dO_2 = oxygen deficiency in pct.

The static differential pressure (the difference between the ambient surface barometric pressure and the measured pressure in the mine) can be determined. A differential pressure of zero indicates that the mine is at the same pressure as the atmosphere. The differential pressure in the mine may be influenced by changes in barometric pressure. However, if differences are due only to the rate at which the mine breathes, the differential pressure should be uniform throughout the mine. Variations in differential pressure indicate that the mine fire is causing the formation of a convection cell within the mine. Elevated pressures may also be due to mass addition of combustion products to the airstream and to thermal expansion of the hot gases. Areas that exhibit negative differential pressures may indicate areas in which air is being drawn into the mine. The static differential pressure is highly variable (relative standard deviations greater than 100%), and has not been correlated to changes in other fire related variables.

Temperature and product of combustion gas concentration measurements are relatively easy to obtain. However, they are best suited to long-term monitoring of fire status. They are not effective indicators of a fire's areal extent or of short-term changes in combustion intensity.

CONVENTIONAL METHODS

Conventional methods of controlling and/or extinguishing AML fires include excavation i.e., dig out and quench, daylighting, and excavated barriers; flushing, either pneumatic or hydraulic, and surface seals. Excavation and surface seals have been used most frequently (fig. 26). These comprise a limited arsenal of dealing with the AML fire problem. None of the methods are routinely successful. Most of the methods involve some degree of hazard, have varying costs, and may disrupt more surface area than the fire threatens.

Excavation

Excavation (loading out, daylighting, dig and quench, stripping) is a fuel removal method that is the most successful of the AML fire control techniques *(54)*. It involves physically removing the burning material and cooling it to extinguish the fire. The hot material is cooled either by spraying it with water or by spreading it out on the ground and allowing it to cool in air. Water, because of its relatively low cost and its general availability, is preferred as the heat removal medium. It is also used to protect equipment from high temperatures and to suppress dust. However, in some areas, particularly in the Western States, sufficient water is not available, and the hot material is cooled by contact with the cooler air.

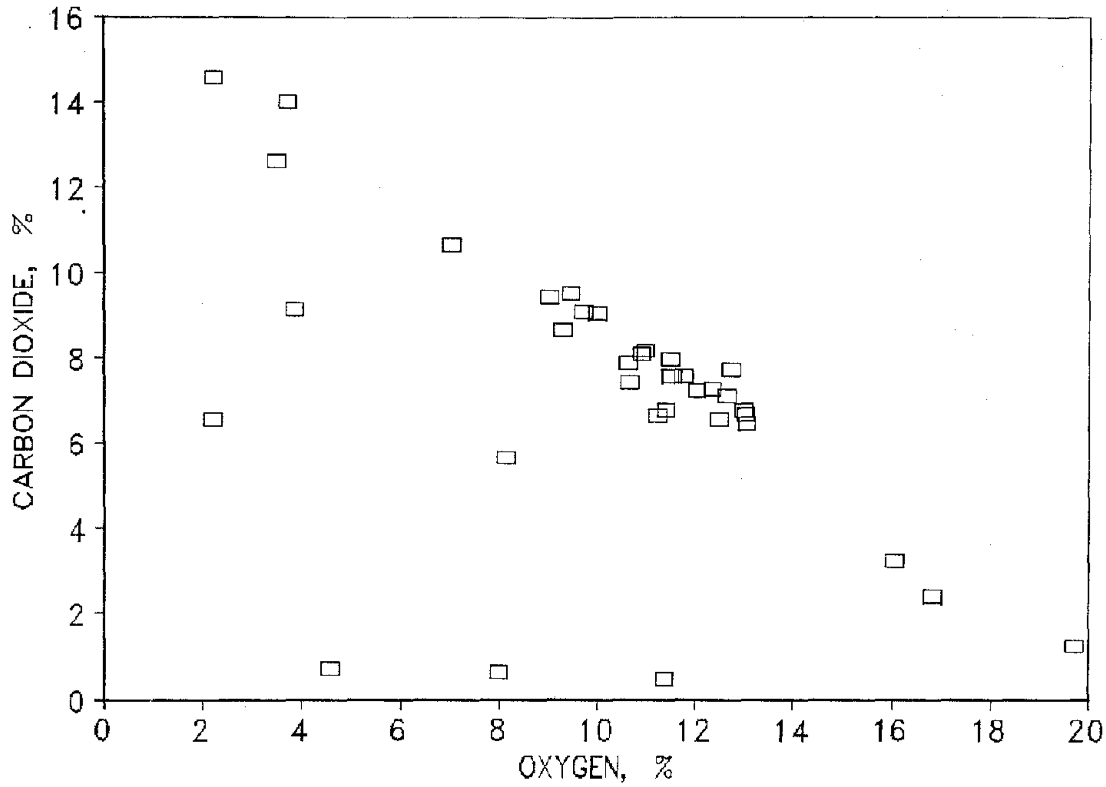

Figure 23.—Variation in carbon dioxide and oxygen concentrations at Large mine fire.

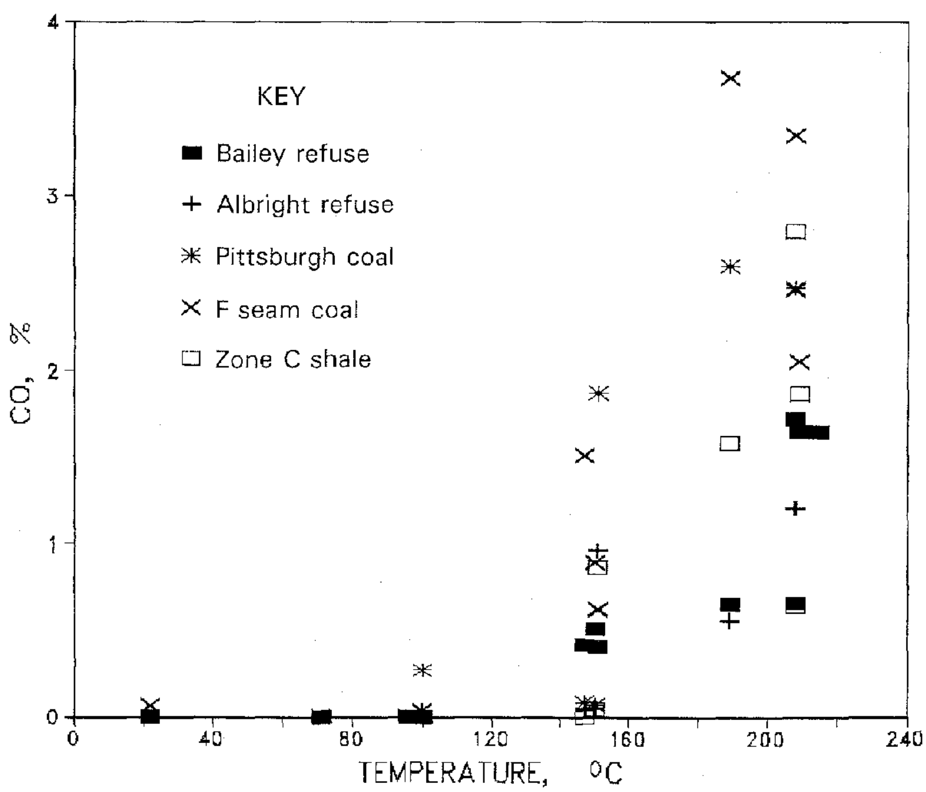

Figure 24.—Carbon monoxide concentration versus temperature.

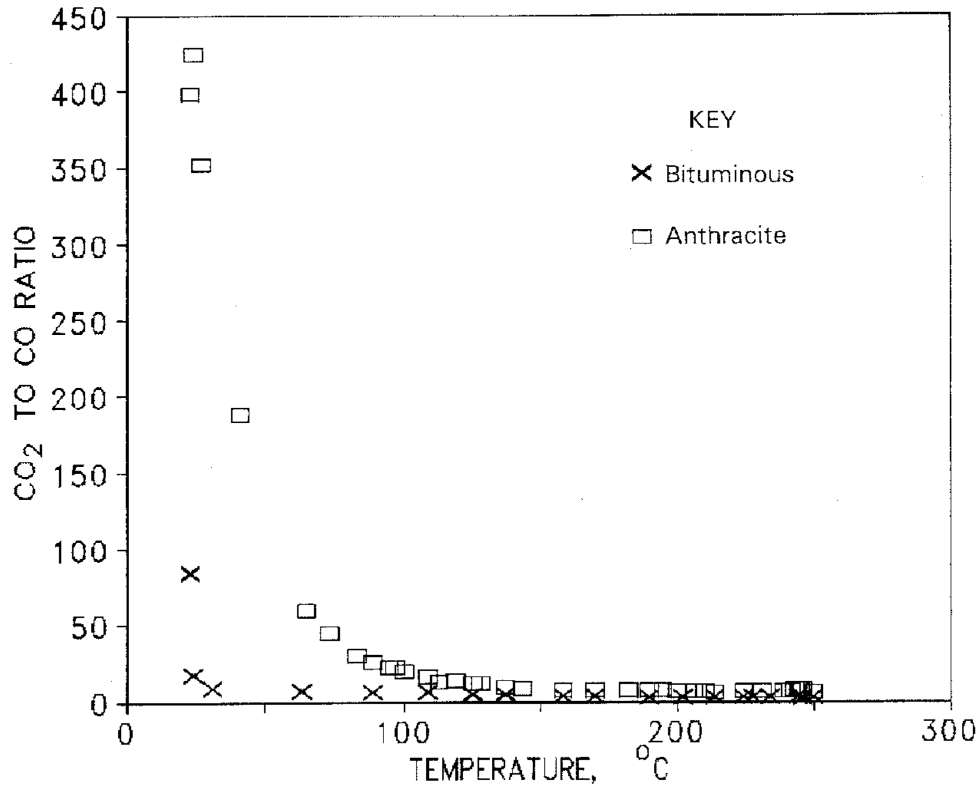

Figure 25.—Ratio of CO_2 to CO versus temperature.

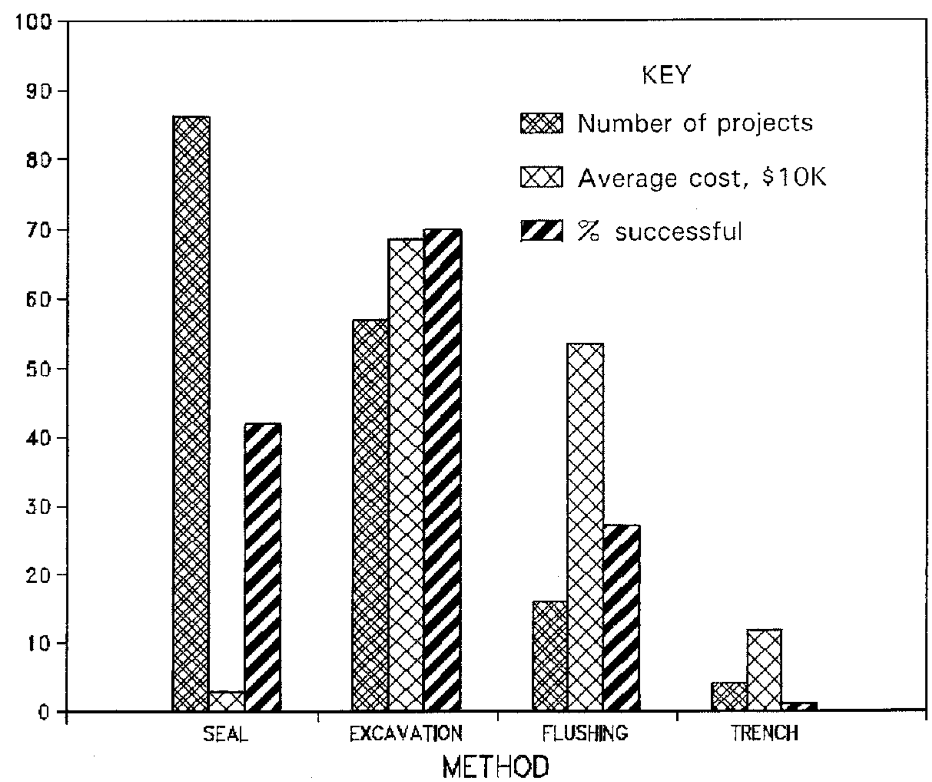

Figure 26.—Cost and effectiveness of AML fire control projects by method.

The cooled material is disposed of as landfill; layering with incombustible material, such as clay, reduces the probability of reignition. If another disposal site is not available, the cooled material is used to backfill the excavated fire zone.

To inhibit the propagation of the fire to the interior of the mine (fig. 27), excavation should begin at the inby side of the fire and proceed toward the outcrop (fig. 28). The excavation of a waste bank fire involves the problem of moving personnel and equipment on possibly unstable slopes. Also, the increased supply of oxygen may propagate the fire to the interior of the bank or to contiguous, buried outcrops. In waste bank fires, as in mine fires, excavation should proceed from the interior limit of the fire toward the surface if possible (fig. 29).

Excavation is inherently dangerous. It requires handling hot material that emits toxic fumes. Moving combustible material or even a shift in the wind can produce a locally high concentration of carbon monoxide. Hot coal exposed to air can very quickly turn a large mass of coal into a raging fire (fig. 30). Hot fines and dust, when disturbed, can generate an explosive cloud. In some cases, putting water in the wrong place in a fire zone can produce explosive water-gas reactions. Although there have been few reports of injuries related to excavating AML fires,

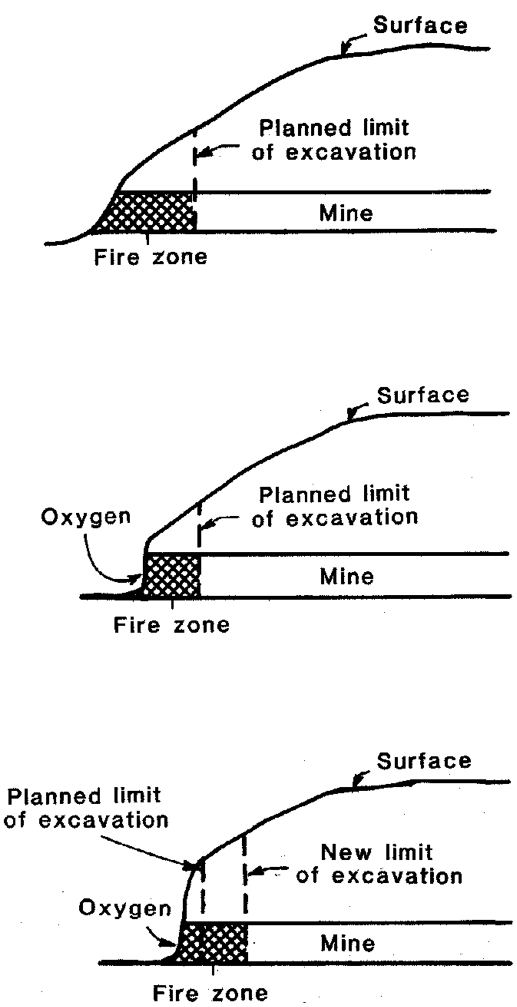

Figure 27.—Schematic of excavation of fire zone allowing propagation of fire into interior of mine. Top, Preexcavation; middle, first cut; bottom, final excavation.

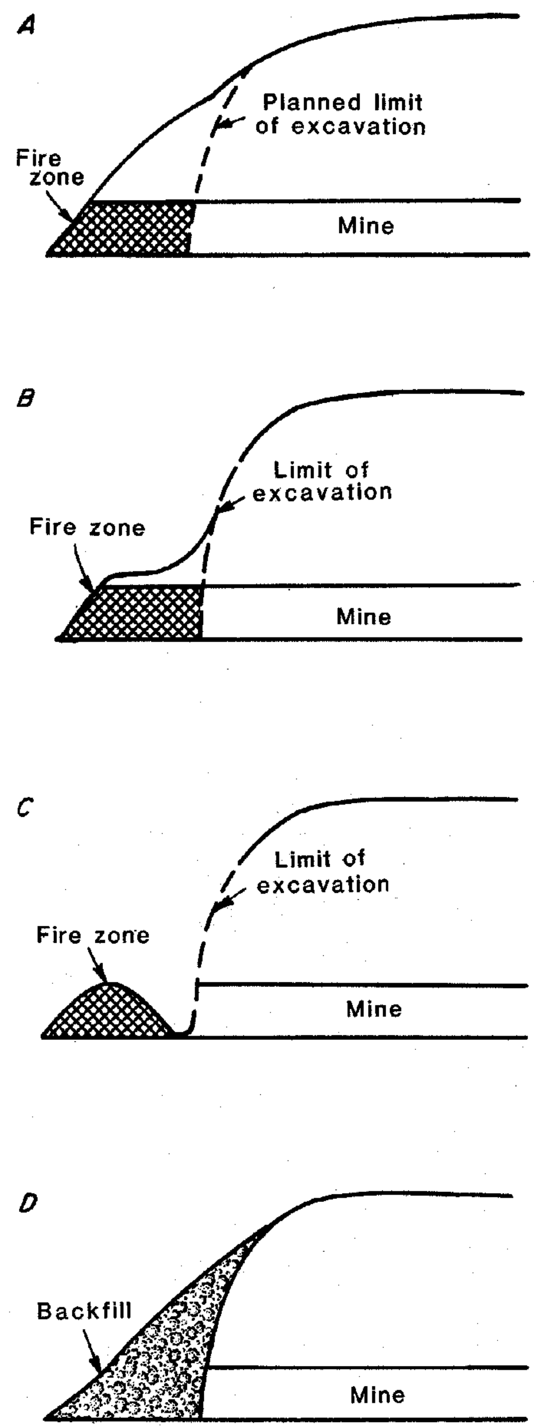

Figure 28.—Schematic of excavation to mine fire to inhibit propagation. *A*, Preexcavation; *B*, first cut; *C*, isolated fire zone; *D*, excavation completed and backfilled.

such projects are usually considered to involve hazardous working conditions (fig. 31).

If properly applied, excavation is the surest method of extinguishing AML fires. The recurrence of excavated fires is usually due to one of two causes: the failure to completely excavate the fire or the failure to lower the temperature of all the excavated material beyond the reignition point. In the first case, the extent of excavation is usually based on surface expression of the fire (vents and fractures) or on subsurface temperatures with a periphal margin added for safety. The excavation may be insufficient if either the fire exists beyond the original boundaries or if it propagates during excavation to previously cool zones. Since fires can be discontinuous, it is possible for the excavator to be unaware that fire zones exist beyond the excavated area. Such fires become apparent on the surface usually within 2 to 10 years after completion of the original project. Excavation also fails when incompletely quenched material is used as backfill in the original excavation. This material can continue to smolder until suitable conditions allow the fire to propagate.

The published cost of excavation for completed projects has ranged from $5,000 to over $11 million. Generally, the area of the excavation, the depth of overburden, the availability of equipment, the proximity to a disposal site,

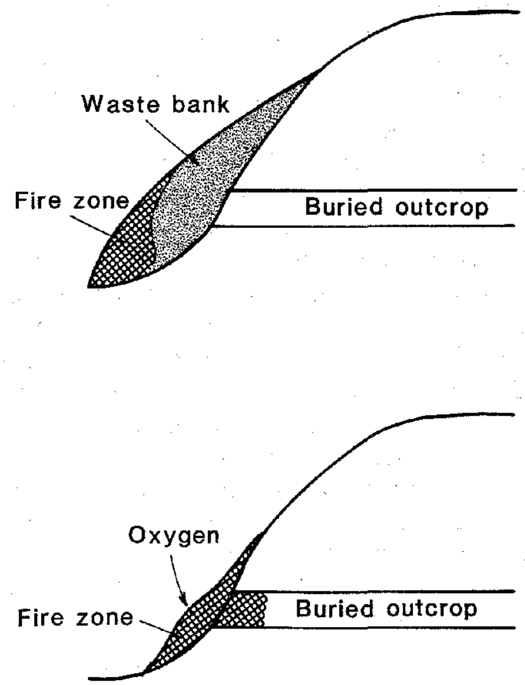

Figure 29.—Schematic of propagation of waste bank fire during excavation. Top, Burning waste bank adjacent to buried outcrop; bottom, fire zone propagated to buried outcrop during excavation.

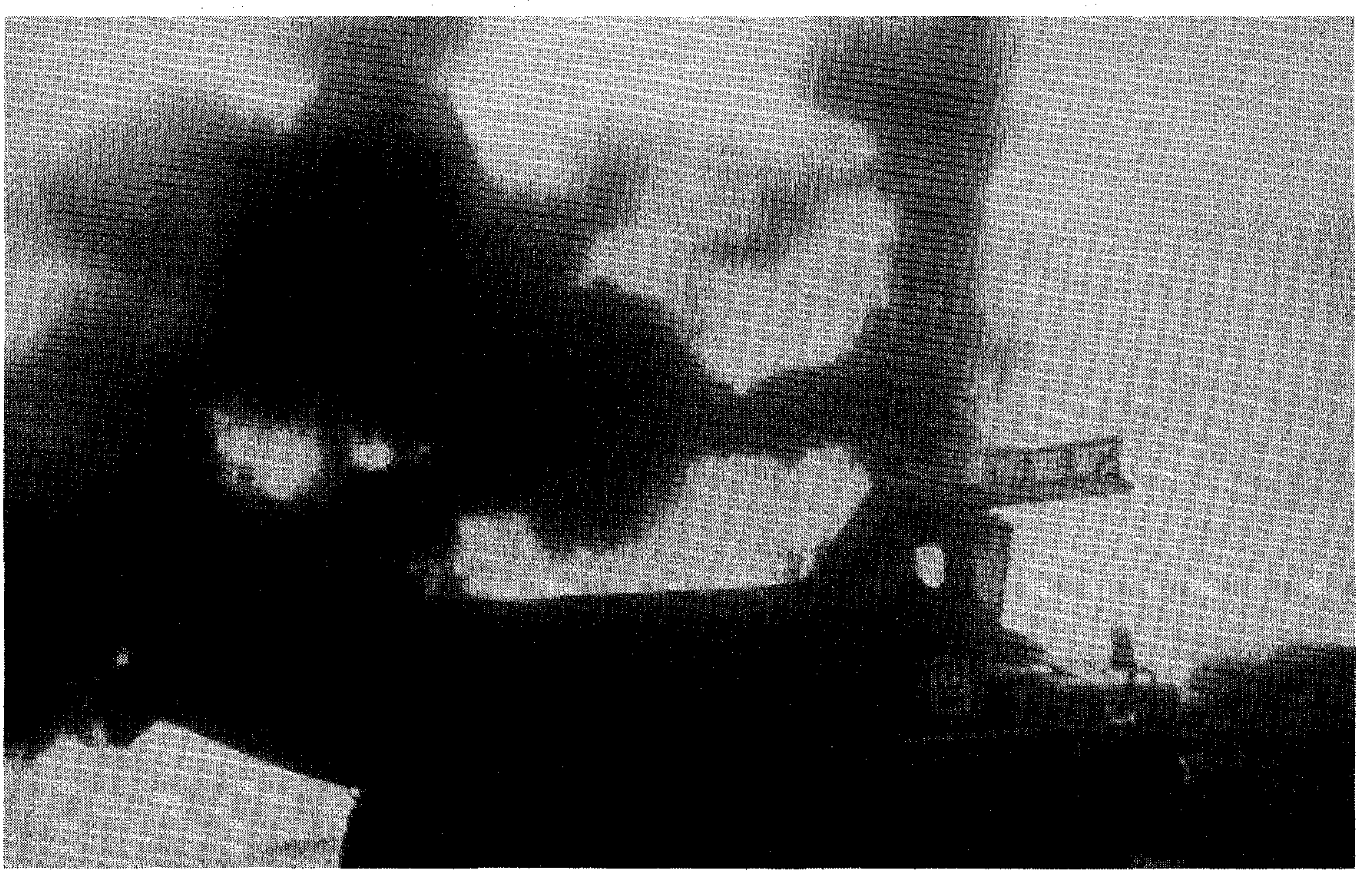

Figure 30.—Increased fire intensity during excavation (photo - courtesy of WVDNR).

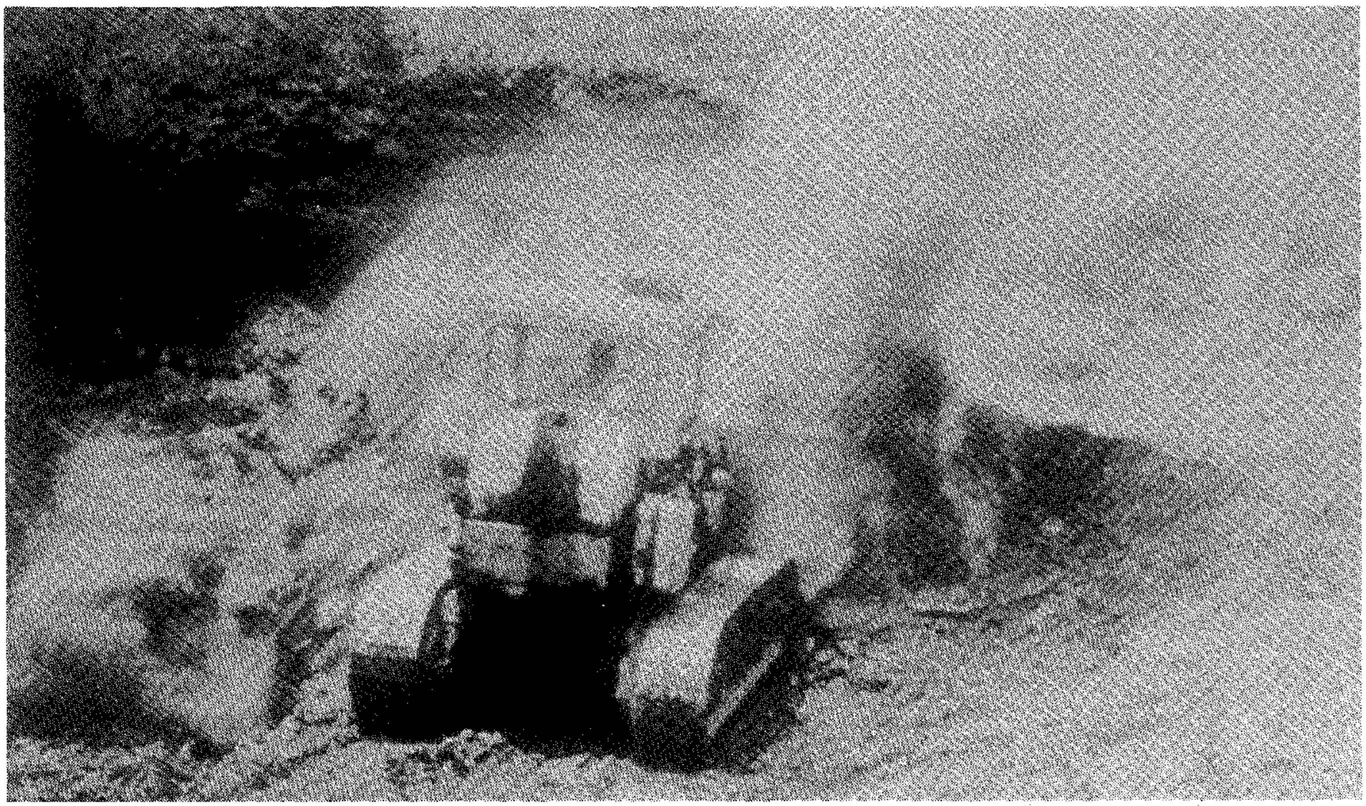

Figure 31.—Hazard of AML fire excavation.

the access to large volumes of water, and the presence of surface improvements will determine the cost of an excavation project. These same factors are considered in determining the suitability of a project for excavation. Particularly, the depth of overburden, the volume of excavated material, the lack of a disposal site, or the cost of transporting hot material to an area where it can cool, and the presence of utilities, homes, or roads may make excavation inappropriate as a fire extinguishment technique.

Inundation-Flooding

Inundation methods involve the underground use of water to lower the temperature of the burning material (heat removal). Covering the burning material with water also stops the combustion reaction by oxygen exclusion. To raise the water level, dams are constructed underground. The water level must cover not only the burning coal, but also must reach the overlying heated rock. This method is limited to use on fires that are small, are at or near the water table and have been burning for a relatively short time to minimize the amount of stored heat. It is expensive and often dangerous to construct dams in inaccessible areas or where strata are not competent to withstand the additional hydrostatic head. Confining water underground may be impossible near an outcrop or where fractures extend below the coalbed. In flooding, the consequences of the catastrophic failure of remote dams or other confining elements must be considered. Generally, flooding is not suitable for controlling underground AML fires. For surface fires, the construction of an impoundment more than 1 or 2 ft high is generally not practical. The use of flooding presupposes that sufficient water is available. It also assumes that water lost by leakage or evaporation will be replaced until all the burning material has cooled below the reignition point. Water that has been in contact with coal or coal waste for an extended period may be acidic and will have to be disposed of in accordance with regulations for acid mine drainage.

Another inundation method provides for the continuous flow of water through the hot material. This can be accomplished by continuous pumping or by gravity flow from a surface impoundment (fig. 32). The volume of water required, the cost of high capacity pumps and time considerations have limited the utility of continuous pumping. The gravity flow method has apparently been tried on waste banks by excavating a reservoir on the top of the bank and allowing water to flow naturally downward *(55)*. The constraint on either of these methods is that the water is not uniformly distributed. It may flow through channels and may bypass the fire zone. If the water fails to cool a small amount of material, the probability of reignition is high.

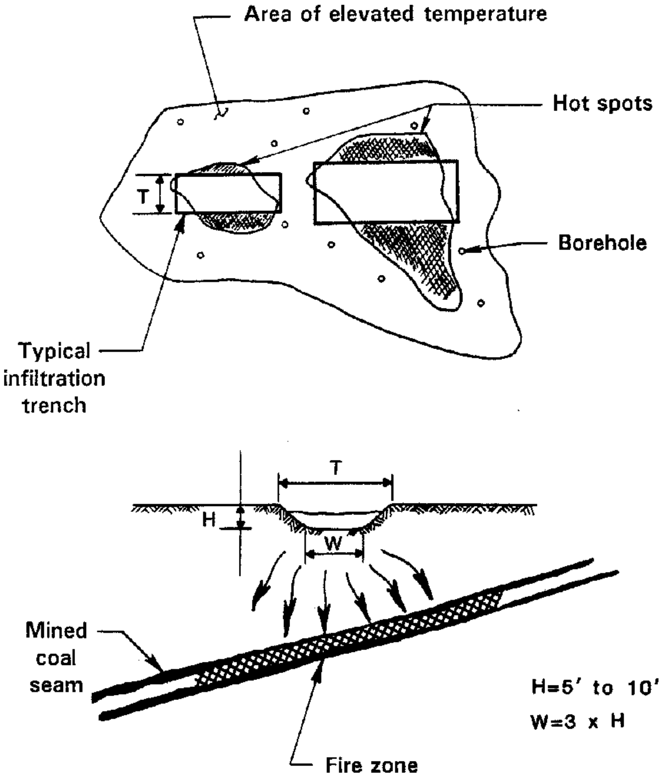

Figure 32.—Inundation by water infiltration from surface impoundment (after (*48*)).

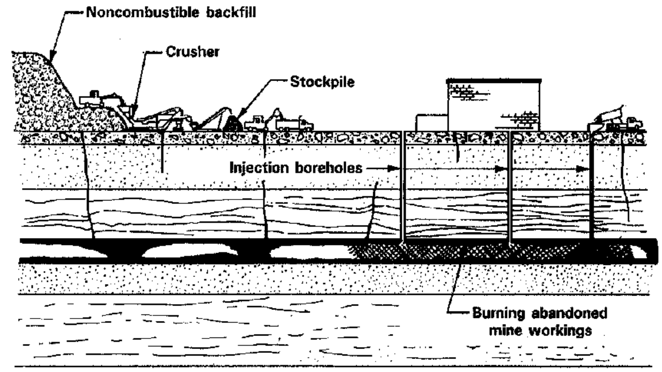

Figure 33.—Noncombustible barrier injected from surface (after (*48*)).

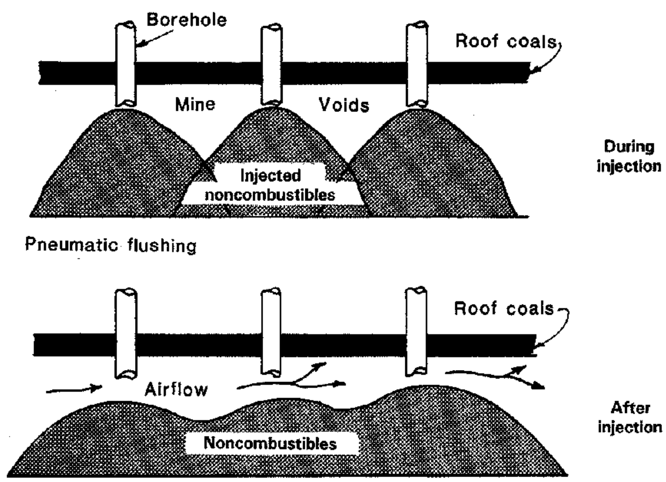

Figure 34.—Flushed boreholes during and after injection.

Flushed Barriers

Flushing is designed to fill the voids in an underground fire zone with fine, noncombustible solids (fig. 33). The noncombustible material is intended to cover the burning material and fill the interstices in adjacent rock, limiting the amount of oxygen in the system and absorbing heat (fig. 34). The high percentage of incombustible material, if properly emplaced, is expected to form a barrier to further propagation of the fire. Flushing can be effective where deposition of the noncombustible material can be controlled, where the voids have a relatively simple geometry, and where the injected material will remain in place.

Sand, silt, red dog, crushed limestone, and fly ash are the most commonly injected materials. Air or water are usually used to carry the material through a borehole into the mine. With pneumatic (air) flushing, the noncombustible material is deposited at the bottom of the borehole. It forms a conical pile that theoretically reaches to the roof of the mine. Material is pumped into the hole to rejection, when it is assumed that the void is filled. Pneumatic injection has two constraints: the material does not penetrate fractured strata and the material tends to slump, which reduces the contact with overlying strata and allows air to flow near the roof.

In hydraulic flushing, water is used to produce a slurry of the incombustible material. When the material is emplaced in the mine, the solids settle as the water drains down dip. This method is believed to carry material further than dry flushing and to have some penetration through porous material. To create an effective seal, injection boreholes are located on 10-ft centers *(7)*. Three lines of boreholes, 10 ft apart, are generally used around the perimeter of the fire area (fig. 35). The amount of drilling, availability of flushing material, transportation costs, and the availability of water affect the cost of flushing projects. An average flushing project can consume 10 to 40 st of material per hole. Water consumption may range from 10,000 to 40,000 gal/d.

Grout slurries have been pumped underground to form fire control barriers. Cement in the grout slurry solidifies to form a competent seal, which also add support to collapsed strata. The addition of foaming agents and incombustible materials, like sand or soil, has been used to

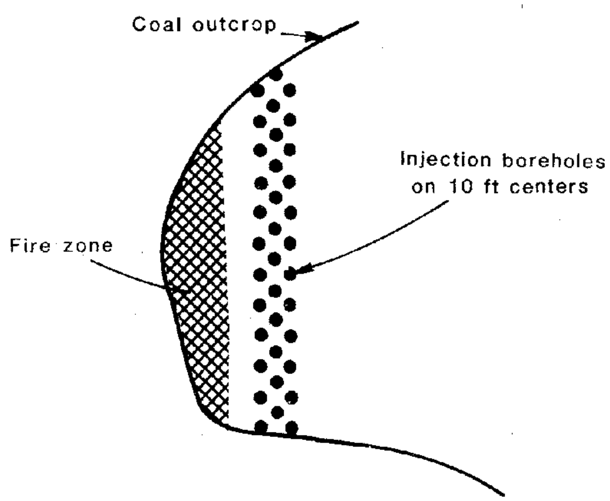

Figure 35.—Plan view of injection boreholes for hydraulic flushed barrier.

produce a lower density foam grout that hardens to a cellular concrete (fig. 36). By mixing various proportions of foam and port-land cement, grouts with dry densities between 85 and 120 lb/ft^3 and compressive strengths between 500 and 4,000 psi can be produced. The grout encapsulates the burning coal and limits combustion by limiting exposure to oxygen. The foamed grout has a low thermal conductivity, between 3 and 7 Btu•hr•ft^{-2}•°F^{-1}•in^{-1} (80 to 228 cal•min•m^{-2}•°C^{-1}•cm^{-1}), and acts as an insulator, retaining heat within the coal. To remove heat, a thermal aggregate, small metal particles, can be added to the grout *(56)*. To be effective, the remotely emplaced grout seal must be complete, encapsulating all burning material and isolating it from other combustible materials, and the grout barrier must be stable for extended periods while the material cools.

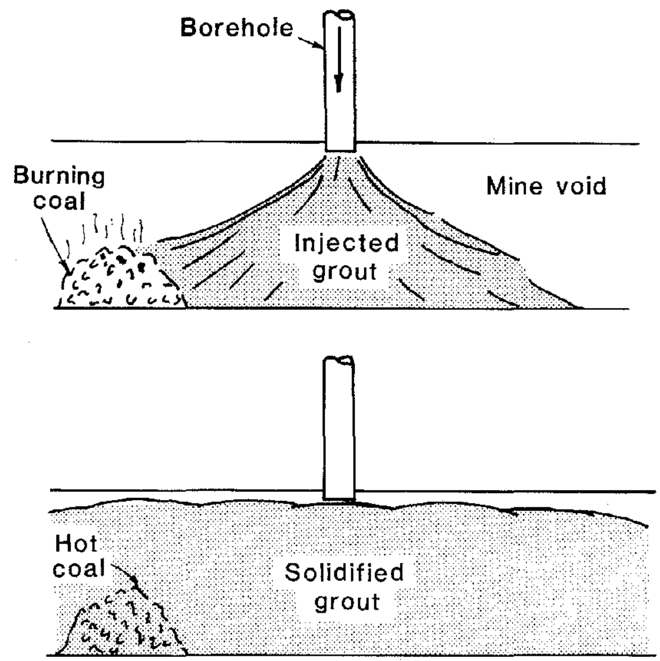

Figure 36.—Injection of foaming grout or cellular concrete to encapsulate burning coal.

Excavated Barriers

An excavated barrier is intended to limit the spread of a subsurface fire by removing the combustible material around the fire zone. When backfilled with noncombustible material, the fire barrier is a dam between the fire and the contiguous coal. The barrier breaks the continuity of the coal and carbonaceous shales and must be wide enough to prevent heat transfer from the fire side to the cold side.

A trench barrier is constructed by excavating an open trench between the fire and the threatened area and then backfilling it with incombustible material. Horizontally, the trench extends from outcrop to outcrop or to the water level to isolate the combustion zone from the unburned coal. A trench extends vertically from the surface to the bottom of the coalbed (fig. 37). A minimum width of 12 ft at the bottom of the trench has been considered

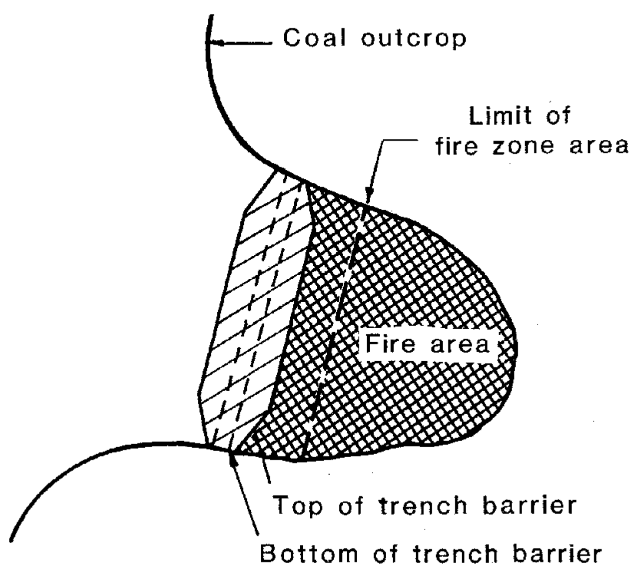

Figure 37.—Plan view of trench barrier for AML fire control.

essential to prevent the spread of fire across the trench. The walls of the trench must be sloped at least 15° (fig. 38) to prevent their collapse during excavation *(7)*. A trench that is 12 ft wide at the bottom and 10 ft deep must be at least 16 ft wide at the top. If the trench is 100 ft deep, it must be at least 66 ft wide at the top. Although a trench may be benched to minimize the required width, the extent of surface disruption is a constraint on the use of a trench barrier as a fire control method. The limit of the fire area must be known prior to excavation of the trench barrier and a margin of safety provided. Usually in planning the excavation, the tendency is to restrict the size of the trench as much as possible to control costs. However, if the trench is too close to the fire zone, the disruption of the overburden can supply sufficient oxygen to accelerate the fire, which can rapidly move beyond the partially excavated trench. The trench must be backfilled as quickly as possible to prevent its collapse and to decrease the amount of fresh air reaching the fire. For economy, the excavated material is often used as backfill; noncarbonaceous material being separated from the coal and carbonaceous shale. The material is selectively pushed back into the trench so that all noncarbonaceous material is at the bottom of the trench and so that the carbonaceous material is isolated and buried. Eventual settlement in the fill material must be controlled.

Plug barriers and tunnel barriers (fig. 39) are variations on the excavated barrier. The plug barrier was used where a complete outcrop to outcrop barrier could not be used because of excessive overburden. It begins at the outcrop and terminates under more than 60 ft of cover, in flooded workings or in solid coal. The 60 ft of cover criterion was based on the belief that a fire would not propagate into *unmined* coal under more than 60 ft of cover if the surface is sealed (*36*). There is no factual basis for the 60 ft rule and it was applied to any 60 ft of cover. Depending on the overlying strata, it is possible for a fracture zone to extend more than 60 ft vertically. If the coal is extensively mined, it is also possible for the fire to produce a convection cell bringing in air from other parts of the mine. Heat transfer considerations and the failure to isolate the fire zone decrease the probability that plug barriers are effective fire control methods.

A tunnel barrier is an underground tunnel backfilled with noncombustible material. It is proposed as a means of extending a trench barrier when the overburden depth is too great to excavate from the surface. Finely divided material is injected through boreholes to fill the tunnel void. In addition to the technical problems of excavating a tunnel in an abandoned mine, unstable roof and toxic fumes make this inherently hazardous. Attempting to perform such an operation in a safe manner escalates the costs even further. No reference to the actual use of a tunnel barrier to control an AML fire has been found.

Surface Seals

Surface sealing is a relatively inexpensive method of controlling abandoned mine fires. It is intended to inhibit ventilation of the fire zone (fig. 40). The exclusion of air and the accumulation of combustion products suppresses the rate of fire propagation. If the seal can be maintained

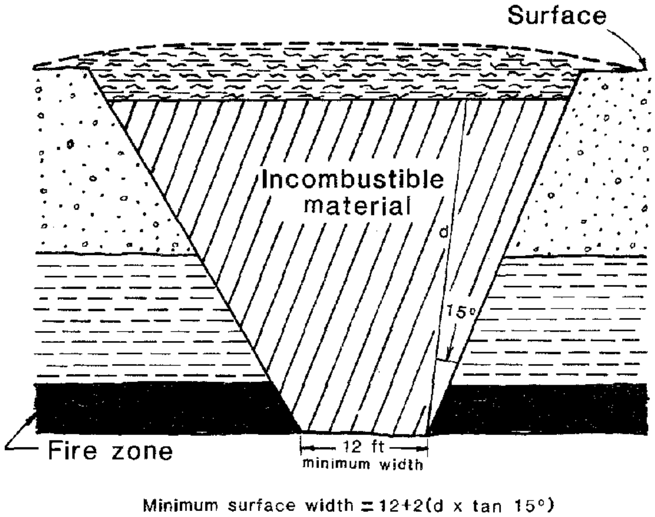

Figure 38.—Schematic of trench barrier for AML fire control.

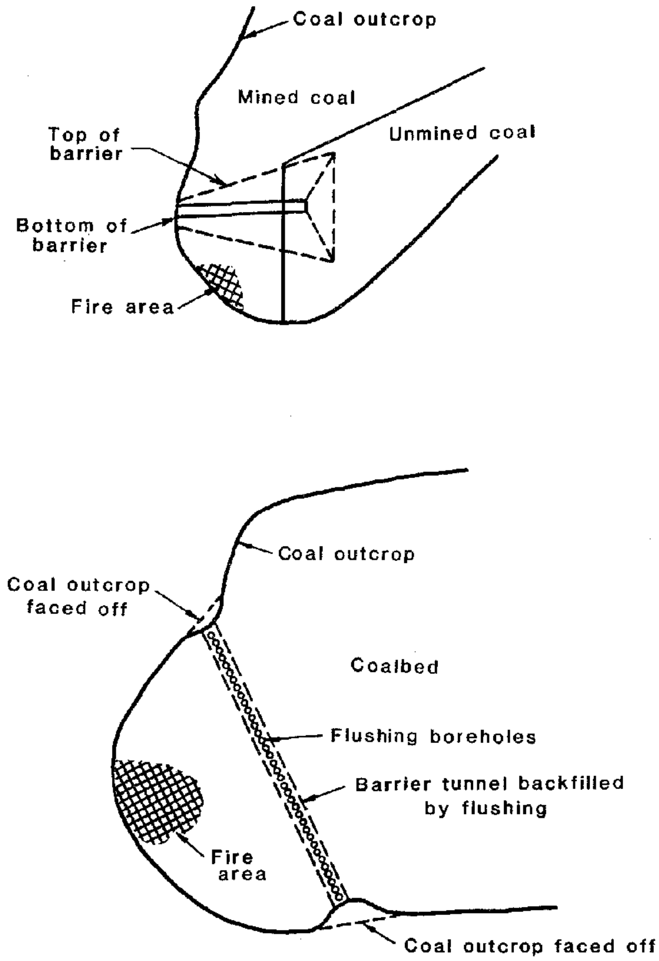

Figure 39.—Plan view of plug and tunnel barriers for AML fire control.

while all the stored heat dissipates, the fire may eventually be extinguished. During this period, the seal must be maintained. Surface seals frequently fail between 1 and 3 years after construction. Failure may be related to settling, shrinkage, slope failure, drying, or increased fire activity. Because surface seals can prevent the egress of hot combustion products, the changed distribution of heat underground can cause propagation of the fire to other areas of the mine.

In eastern fires, a surface seal is generally constructed by pulverizing the surface to a depth of 4 to 8 ft *(7)*. The surface seal begins at or near the outcrop (fig. 41), depending on whether the outcrop has been exposed, whether there are drift openings, and whether the area has been stripped (fig. 42). The seal must extend beyond all surface indications of the fire. All vegetation, including brush and trees should be removed from the area of the seal. The seal is constructed by plowing the surface along the contour and then twice crossplowing at 45° angles to the original contours. Drainage traps are constructed to

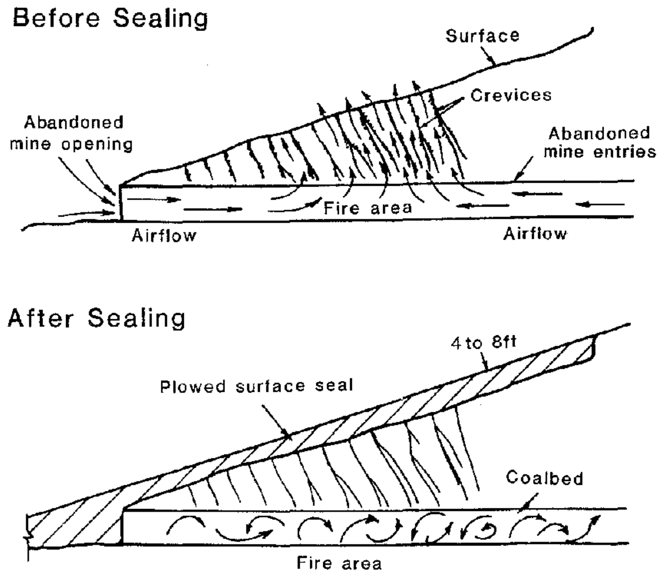

Figure 40.—Surface seal to control AML fires in Eastern United States (after *(7)*).

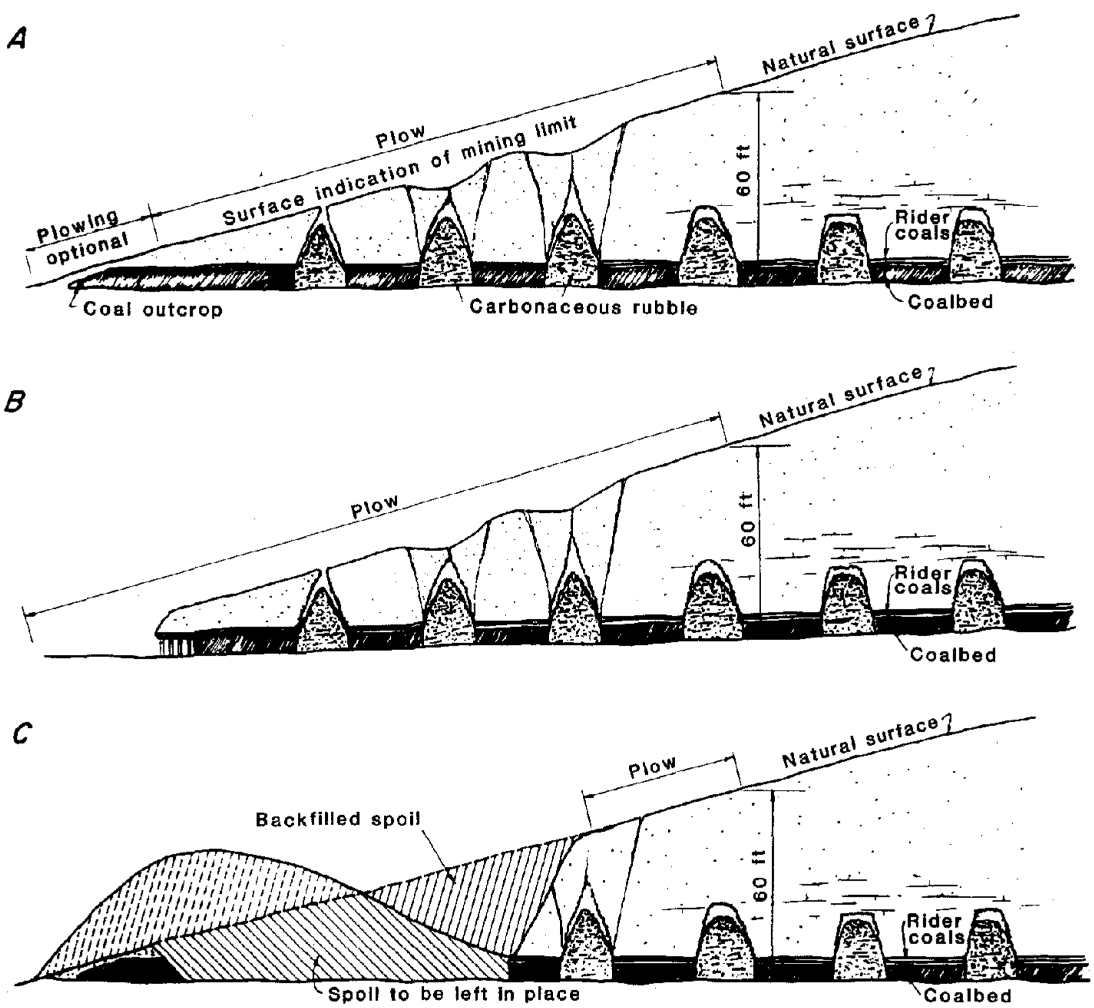

Figure 41.—Extent of surface seal, depending on condition of mine. *A*, Outcrop not exposed; *B*, drift opening into outcrop; *C*, outcrop contour strip mined.

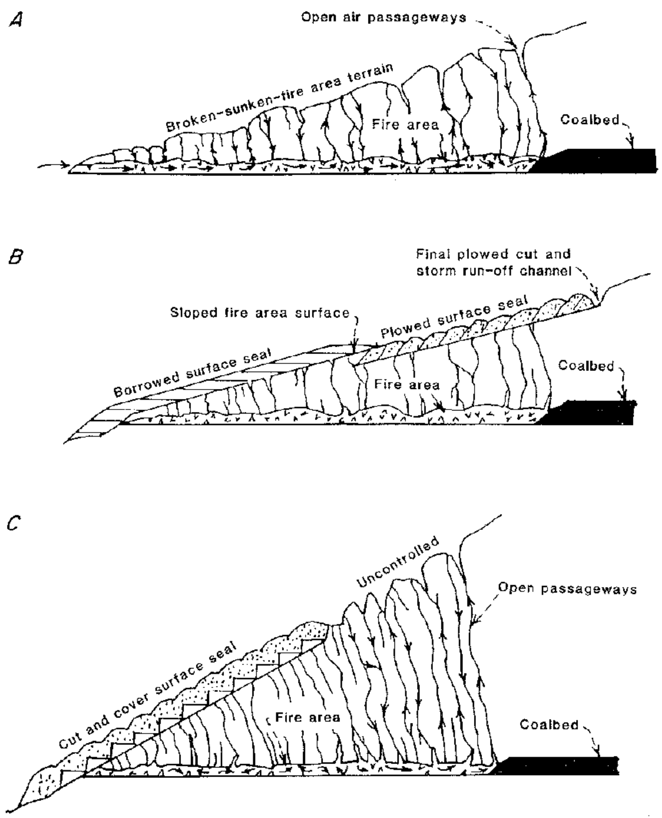

Figure 42.—Surface seal used in western AML fires. *A*, Normal surface; *B*, borrowed and plowed surface seal; *C*, cut and cover seal.

allow water to flow from the coal mine while preventing air from entering it. Drains and ditches must be installed to prevent erosion from destroying the seal. The area is reseeded to minimize erosion and control runoff of surface water through the sealed area. Provision must be made for regular inspection of the seal and for monitoring the condition of the subsurface fire zones.

In the Western United States, 85% of fire abatement projects are surface seals. This is due to the relatively low cost, the topography of the area, and the lack of water needed to implement other methods *(9)*. Most of the fires in the western coalfields occur within either the Missouri River or the Colorado River drainage systems. The surface-sealing method as used in these regions differs slightly.

In the Missouri River drainage region, the fire sites are generally located on accessible, flat to rolling terrain with a maximum slope of 25°. Generally, the surface strata over the fire area contains 2 to 10 ft of relatively thin, friable sandstones, shales, siltstones, and mudstones that can be easily worked by bulldozer. If necessary, the covering materials are excavated from borrow pits, then transported to the fire area and deposited in 6- to 8-in layers. With in situ surface sealing, the area's residual mantle and/or underlying strata are the source of the incombustible material. With both sources of covering materials, the area is sloped with a bulldozer to fill in large cracks and to grade uneven terrain. The bulldozer is used to cover the area with incombustible materials and plow the affected area. The plowing, performed on the contour to minimize erosion, emplaces a competent 3- to 4-1/2-ft-thick seal. In the cut-and-cover technique, a bulldozer starts at the lower perimeter of the fire area, and makes a cut along the contour. In succeeding upslope cuts, the material is cast onto the previous downslope cut, producing a seal between 4 and 8 ft thick. A diversion ditch around the seal area controls erosion due to surface runoff.

In the Colorado River basin, slopes are steep and surface strata are massive sandstones, shales, siltstones, and mudstones. In addition to bulldozer cut-and-cover methods, blasting was often used to produce material suitable for sealing the fire area. It's use is now limited because of costs associated with bonding and insurance. Surface sealing under these conditions is more labor intensive, more time consuming, and more costly. However, it is still the most practical and cost-effective method of controlling fires in this area.

Surface sealing suppresses surface evidence of a fire. If the seal is maintained for a sufficient length of time (10 to 20 years), the fire may be extinguished. A breach in the seal before the coal and associated rock has cooled below 100° C will probably reactivate the fire. Surface seals tend to contain the hot combustion products within the mine. Under appropriate conditions the hot products may spread the fire to other portions of the mine. However, in sparsely populated areas where there are no surface structures threatened by the fire, surface seals adequately control subsidence, inhibit unsightly venting, and limit the emission of noxious fumes. If extinguishment is not critical, surface seals, with regular and periodic maintenance, can provide an adequate control mechanism.

RECENT DEVELOPMENTS

The focus of the recent research on AML fires has been to improve currently available techniques and to develop remotely emplaced techniques that minimize surface disruption, to improve cost effectiveness, and to dependably protect people and property near AML fires.

The SMCRA authorized the use of the AML fund for research and development (priority four) (*45*). A research program, established by OSMRE in 1985, was transferred to the Bureau in 1987. Of the 54 research projects funded, 8 have dealt with various aspects of the AML fire problem (table 13). Funding for fire projects totaled $1.3 million; the average cost per project was $167 thousand. Prior to the establishment of the AML research fund, studies on novel or more effective, more efficient methods of controlling AML fires were conducted primarily by the Bureau. The results of many of these projects, both under AML and previous funding, are discussed below. Current or continuing work on topics such as diagnostics, extinguishment, and control-containment methods are discussed in the "Research Areas" section.

MINE FIRE DIAGNOSTICS

One factor in the failure of some abandoned mine fire control projects was that the extent of the fire was unknown when the project was planned. A corollary factor was that there was no adequate provision for monitoring the propagation of the fire during and/or after the fire control project. To locate a remote fire zone, it is necessary that: (1) the fire have a measurable characteristic, (2) the characteristic be detectable through appropriate sampling methods, and (3) the data be interpreted correctly.

Temperature Monitoring

Borehole temperature monitoring provides point source data that are of very limited utility. The area for which thermocouple data is accurate is approximately 12 ft^2 around the borehole. To use subsurface temperatures as an indicator of subsurface combustion zones would require the use of boreholes on 10-ft centers. Even with this constraint, elevated borehole temperatures may be related to the movement of hot combustion products, rather than to the proximity to burning material. Elevated temperatures indicate that combustion is occurring, but give limited information about the areal extent of the combustion zone.

Aerial Infrared

Attempts to use aerial infrared to locate subsurface fires have not been particularly successful. The primary constraint on this method is that it measures temperatures within a few inches of the ground surface. This detects surface fracture zones and vents, but cannot detect deeper heated areas. Triangulation methods to extrapolate surface temperature data to depth require that heated combustion products move along straight line paths from the source to the surface, a condition that is not usually met. Also, heat absorbing features on the surface, like bodies of water, tend to appear on infrared as localized hot spots. In general, infrared methods have not been shown to locate subsurface combustion.

Soil Hydrocarbons

Soil sampling for thermally produced hydrocarbon gases, high-molecular weight alkanes, or the lower molecular weight aromatics (benzene and toluene) has been proposed for locating subsurface fires. The simpler, less expensive sampling procedure would reduce the cost. However, the analytical equipment is the more complex gas chromatograph-mass spectrometer (GC-MS). Sampling at the surface assumes that the gases sampled have moved by a relatively linear path from the source. Since the compounds of interest are gases, their migration through a nonhomogeneous medium may be influenced by changes in pressure, the location of natural fracture zones, areas of natural drainage, and differences in normal diffusion rates. At present, there is no data to support the use of soil sampling of gases as an indicator of underground combustion.

Table 13.—AML research projects, 1987-1990

Project	Contractor	Amount
Determining effectiveness of past mine fire surface seal abatement methods.	L. C. Hanson Co., Helena, MT	$99,604
Self-heating characteristics of coal and related carbonaceous materials.	Bureau of Mines, Pittsburgh Research Center	160,000
Use of foaming mud cement to terminate underground coal fires and to control subsidence of burn cavities.	Colorado School of Mines Research Inst. and Wyoming Dept., Environmental Quality.	251,456
Location, extinguishing, and reignition inhibition of refuse and underground fires through high pressure water-jet utilization.	University Missouri-Rolla and Montana Department of State Lands.	201,478
Characterization of remote combustion	Bureau of Mines, Pittsburgh Research Center	237,100
Cryogenic extinguishment of waste bank fires	..do.	243,000
Improved method for extinguishing coal refuse fires.	MSA Research Corp.	160,000
Development of fire diagnostic techniques for burning coal waste piles.	Bureau of Mines, Pittsburgh Research Center	237,500

Magnetic Anomalies

It has been suggested that the measurement of small subsurface magnetic anomalies can be used to delineate fire areas, particularly in coal refuse. The effect is assumed to be due to the change in remnant magnetism when magnetic minerals are exposed to high temperatures (*57*). This method has had limited use in attempts to locate buried refuse and as a diagnostic technique for subsurface fires. Depth and the presence of steel borehole casings have an effect on the measured magnetic anomaly. At present, there is insufficient data (laboratory or field) to evaluate this technique as a mine fire diagnostic method. A surface survey of electrical potential anomalies related increased conductivity to the presence of coked coal (*58*).

Desorbed Hydrocarbons-Communication Testing

The Bureau has developed a mine fire diagnostic methodology in which the measured characteristics are the temperature, pressure, and hydrocarbon concentration at the base of an array of boreholes (*51, 59-60*). The sampling method uses an exhaust fan to impose a pressure gradient to control the direction of airflow. Changes in pressure determine whether the fan has influenced the flow of gas at any borehole. The temperature is measured for comparative purposes, but is not a variable in the determination of fire signatures. Changes in a hydrocarbon concentration ratio are compared with an empirical scale based on the laboratory determination of fire signatures. Interpretation is based on ability to control and therefore know the direction of airflow, and on relative changes in the fire signature.

The combustion signature used in the Bureau's mine fire diagnostic methodology is a ratio based on hydrocarbon desorption from coal. The low molecular weight hydrocarbons, methane through pentane, are adsorbed on the internal surface of coal. At normal temperatures, methane and a small percentage of higher hydrocarbons are desorbed. As the temperature of the coal increases, the rate of desorption increases and the concentration of higher hydrocarbons increases. In a laboratory study of temperature dependent desorption (*59-61*) from coals and coal wastes, a ratio R1, relating the concentrations of methane and total hydrocarbons, was defined as:

$$R1 = \frac{1.01[THC] - [CH_4]}{[THC] + c} \times 1000$$

where [THC] = concentration of total hydrocarbons, ppm,

$[CH_4]$ = concentration of methane, ppm,

and c = constant, 0.01 ppm.

The ratio was found to increase with increasing temperature and decrease with decreasing temperature (fig. 43). The concentration of desorbed gas and the ratio were related to the rank of the coal. For bituminous samples, the value of R1 is interpreted according to the empirical scale:

R1	*Relative Coal Temperature*
0 to 50	Normal (<30° C)
50 to 100	Possible heated coal (30° to 100° C)
>100	Heated coal (>100° C).

The absolute value of R1 is not related to a particular temperature. For a given coal, R1 values during heating may not be the same as those during cooling at the same temperature (fig. 44). The value is influenced by rank, by internal surface structure, and by the amount of gas adsorbed on the coal surface. However, for bituminous

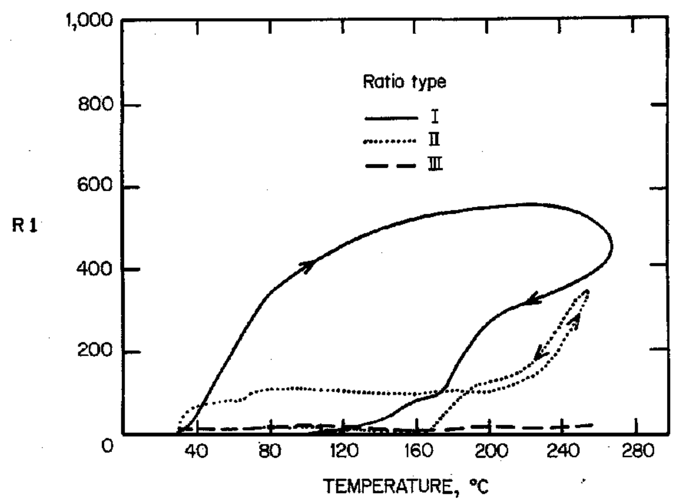

Figure 43.—Changes in mine fire diagnostic ratio with temperature.

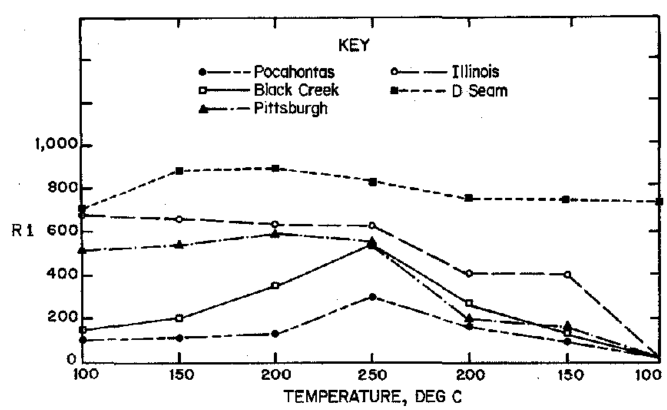

Figure 44.—Values of mine fire diagnostic ratio during heating and cooling of selected coals.

samples, the ratio increases during heating and decreases during cooling within the ranges listed on the previous page. The hydrocarbon ratio is sensitive, unaffected by dilution, and requires relatively simple analytical methods. The emission of higher molecular weight hydrocarbons from anthracite is relatively low. In a field study, changes in the absolute concentration of methane was found to correlate with hot and cold subsurface zones.

The mine fire diagnostic methodology, in addition to the hydrocarbon ratio, uses communication testing to define hot and cold subsurface zones (*24*). This assumes that a sufficiently large negative pressure (vacuum) applied to underground regions will cause the gases in the mine atmosphere to flow from some distance toward the point of suction. Repeated sampling at all points in a borehole pattern[10] provides data to determine the presence or absence of fire along pathways between sampling points (fig. 45). A measured change in pressure of at least 0.01 in H_2O defines the area in which the fan produced a pressure change and therefore a flow of gas. For each test, a quadrant indicating hot (R1 > 100), cool (R1 < 50), or insufficient hydrocarbons, is placed on a straight line drawn through the borehole and the suction point (fig. 46). Reiteration of the tests using various boreholes as suction points produces a composite map of heated and cold zones (fig. 47). The tests are repeated, sometimes with the drilling of additional boreholes, until a cold boundary can be defined. To date, three field studies have supported the use of the Bureau's mine fire diagnostic methodology to define remote combustion zones (*23-24, 51*). Sampling the mine atmosphere during extinguishment can indicate the current status of the fire. At one project, the mine fire diagnostic method defined three noncontiguous areas of combustion. During attempted extinguishment, determination of R1 indicated that one area was cooling, one area showed no change, and one area was becoming hotter (fig. 48).

The Bureau's mine fire diagnostic technology is a significant improvement in locating abandoned mine fires, in the essentially two-dimensional plane of a mine. The Bureau is using a physical model of a waste bank to verify the application of the diagnostic methodology in the three-dimensional volume of a waste bank. The test pile, 4 by 4 by 8 ft, is instrumented with pressure probes; two boreholes, 4 and 2 in, were placed to a depth of 30 in from the top and can be used alternately as suction points. Airflow through the waste bank material was determined to be within the limits of Darcy flow. Therefore, flow in a waste bank under vacuum can be characterized as laminar and a model based on conventional fluid flow equations can predict the combustion source within a waste bank *(62)*.

It cannot be emphasized more strongly that the first step in a successful fire control-extinguishment project is knowing where the fire is, and of equal importance, knowing where it is not. It is also important to determine during the course of the project that the fire is not propagating to previously cold areas. The last step in a successful fire control extinguishment project is continued monitoring to determine that the fire is out and remains out.

MINE FIRE EXTINGUISHMENT

The extinguishment of any fire requires that at least one element of the fire triangle be removed, fuel, oxygen, or heat. Recently, completely new methods of accomplishing this or adaptations of conventional methods have been tried.

FUEL REMOVAL METHODS

Burnout Control

The Bureau has developed a technique called Burnout Control that can control fires in abandoned coal mines and waste banks, and can also extract the thermal energy represented by such wasted coals (fig. 49) (*63-69*). The technique involves complete combustion of the coal in place while maintaining total control of the resulting heat and fumes. The thermal energy produced and brought to the surface as high temperature flue gas (up to 1,000° C) can be 20 times the equivalent thermal energy required to operate the Burnout Control system.

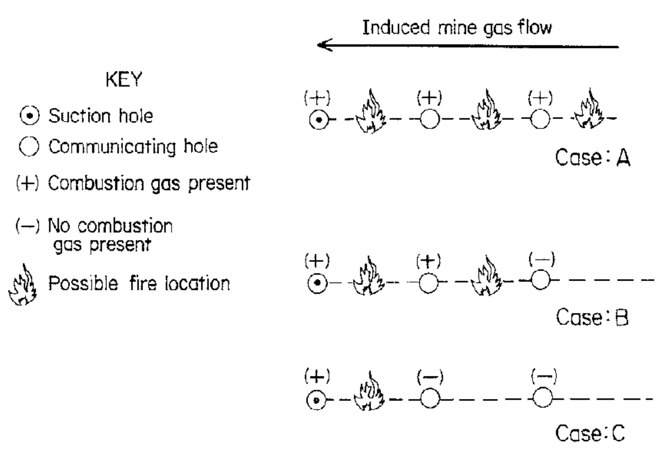

Figure 45.—Schematic of communications testing for mine fire diagnostics.

[10]Generally, the borehole pattern is dictated by the size and the topography of the site. As a first approximation, a pattern of 8-in boreholes on 100-ft centers is adequate.

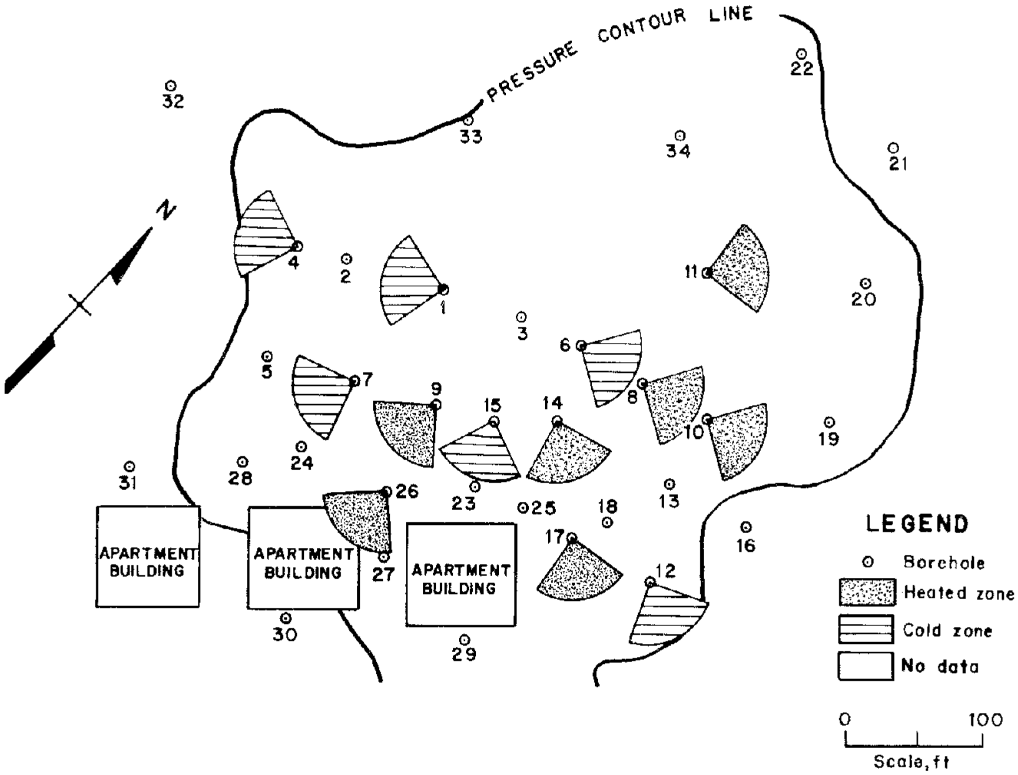

Figure 46.—Mine fire diagnostic map of results of one communication test.

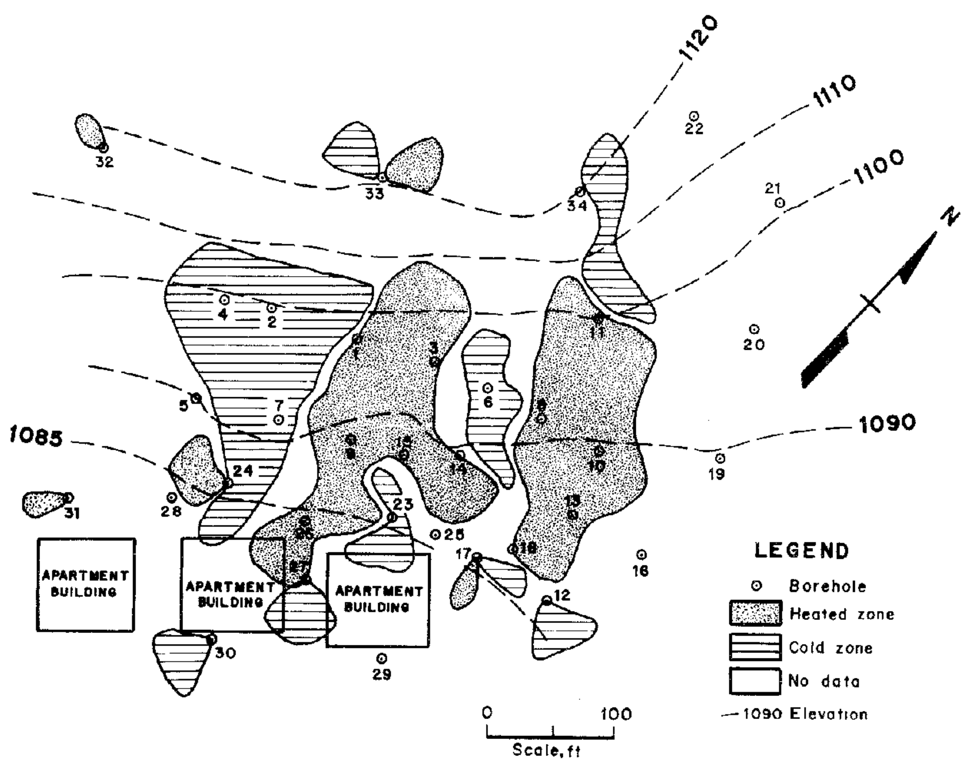

Figure 47.—Mine fire diagnostic map produced from repeated communication tests.

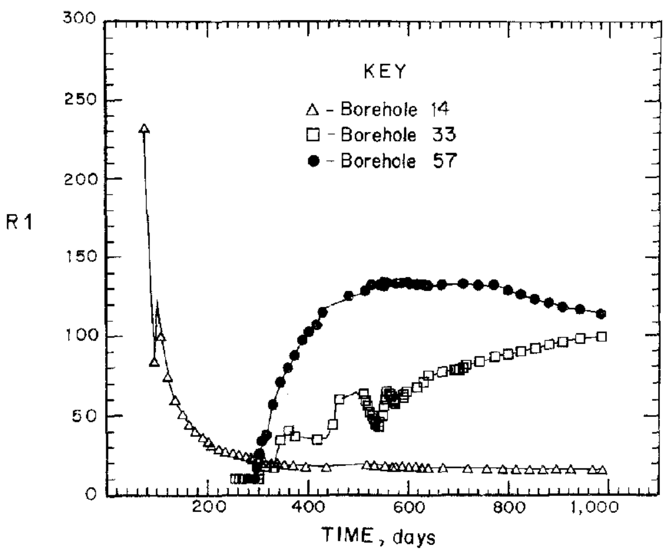

Figure 48.—Changes in mine fire diagnostic ratio at three boreholes during extinguishment project.

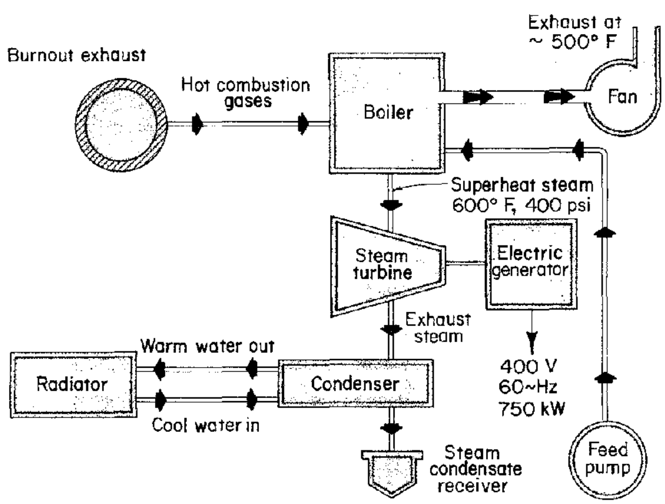

Figure 49.—Schematic diagram of Burnout Control with energy utilization.

During Burnout Control (fig. 50), the burning waste bank or coal mine is placed under negative pressure relative to the atmosphere. Air flows into the underground combustion zones through natural fractures, crevices, and pores in the ground and/or through specially drilled air inlet boreholes. An exhaust ventilation system, consisting in part of a large borehole, which acts as a combustion manifold, and a fan that draws hot gases from the fire zone, pulling them out at a single point. Burnout Control has several advantages:

1. The affected mine or refuse bank will be at negative pressure, relative to ambient; hence, few or no fumes will be emitted to the atmosphere except at the fan exhaust point.

2. Accumulation of all the fumes at the fan exhaust point will enable postburn incineration of the exhaust to insure complete combustion of products to carbon dioxide and water. If needed, flue gas scrubber treatment also can be applied to remove air pollutants such as sulfur dioxide and particulates.

3. The heat of combustion of the burning coal will appear as sensible heat in the exhaust - at temperatures as high as 1,000° C. This heat is recoverable for producing steam and/or electricity.

4. The complete burnout of carbonaceous material and pyrites in a mine or waste bank will permanently solve the environmental problems of an active fire. In contrast, fires extinguished by cooling and sealing leave wasted coal with its potential for reignition and acid water formation.

5. The product of complete burnout of a coal refuse bank is "red dog," a gravel substitute with commercial value. The "red dog" material, if injected into mine voids, also has potential for mitigating subsidence and acid mine drainage.

Burnout Control has not yet been applied to completely burn out an AML fire, but it has received two limited field trials during its development. The first trial was a 4-month controlled burn of a shallow, abandoned coal mine fire in a confined area of the Pittsburgh seam (*65-69*). The second trial was a 1-year test of the process as applied to a 0.9-acre section of a 6.5-acre abandoned coal waste pile fire (*64*).

At Calamity Hollow (fig. 51), exhaust control (i.e., vacuum >0.1 in H_2O) was maintained over an underground area of about 2 acres that encompassed the fire zones. Over 102 days of fan operation, an estimated 1,100 st of coal were burned, producing exhaust gases at an average temperature of 600° C and thermal power level of 3.2 MW (fig. 52). At the maximum design level output of 900° C and 5 MW, it would have taken 1.6 years to completely burn the 10,000 st of coal at the site. The total thermal energy, if converted to electricity through a small mobile steam turbine-generator system, could have produced 14 to 18 million kilowatt-hours of electricity, about 20 times more energy than that required to operate the Burnout Control system.

During the course of the mine fire field trial, significant slow subsidence and ground fracture did occur, but apparently not to an extent that affected the burnout process itself. Surface disturbances were handled by relatively simple techniques involving construction of additional footings for equipment support, and sealing the ground surface for fissures. In terms of air pollution, test data indicated that all the fuel-sulfur appeared as SO_x in the exhaust, but only 5% of the fuel-nitrogen appeared as NO_x. From an environmental viewpoint, it is probable that removal of SO_x from the exhaust will be required in the actual practice of

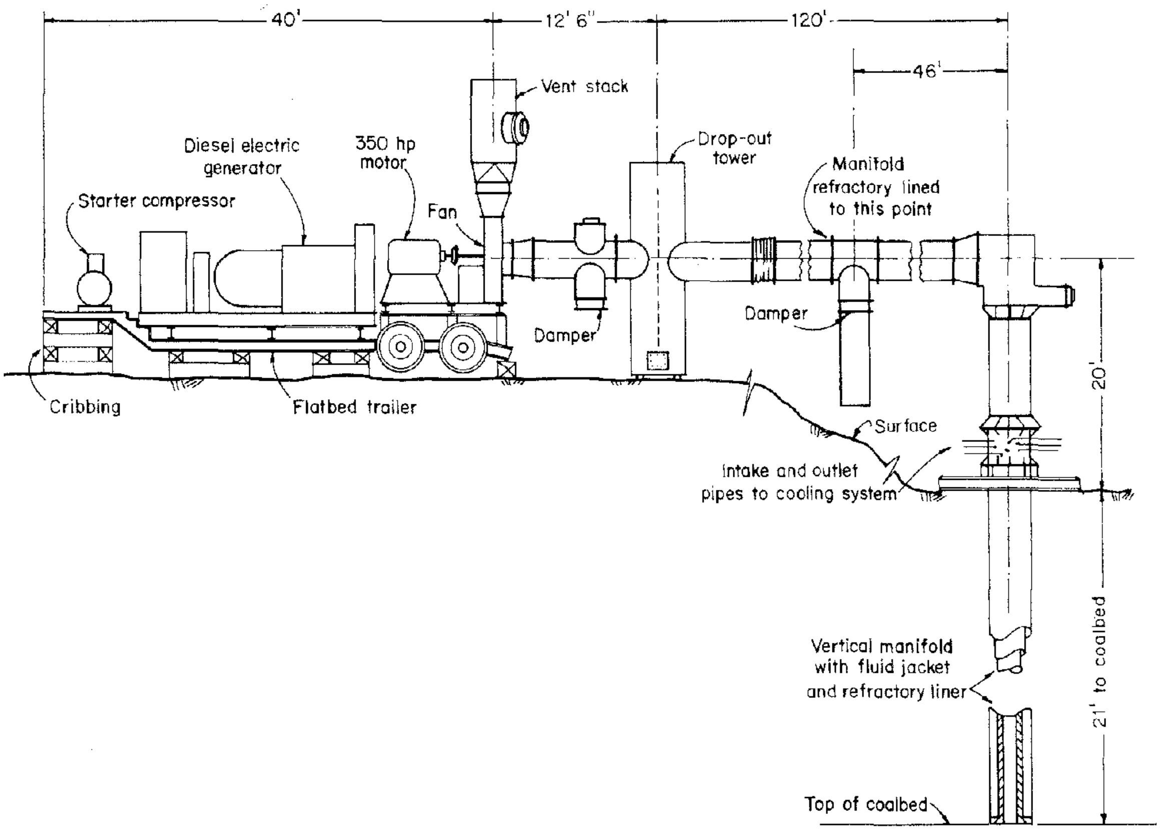

Figure 50.—Schematic of Burnout Control system - Calamity Hollow mine fire project.

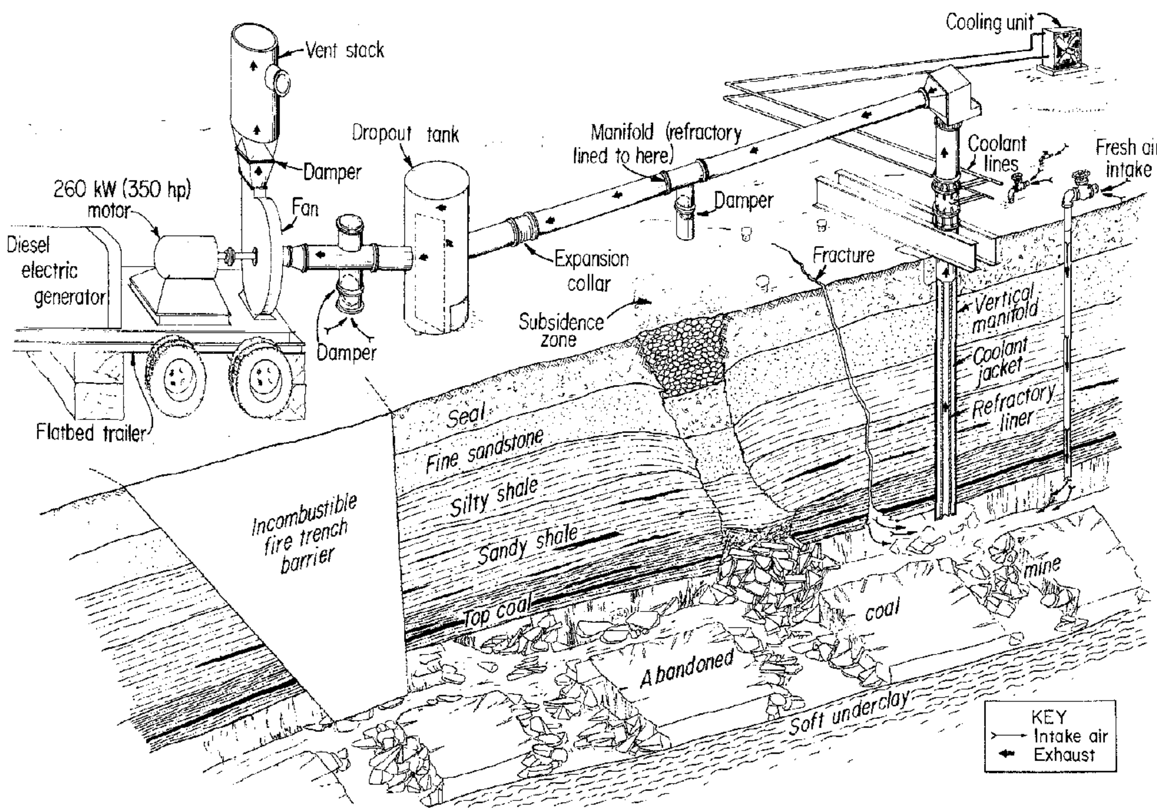

Figure 51.—Artist's version of Burnout Control system at Calamity Hollow.

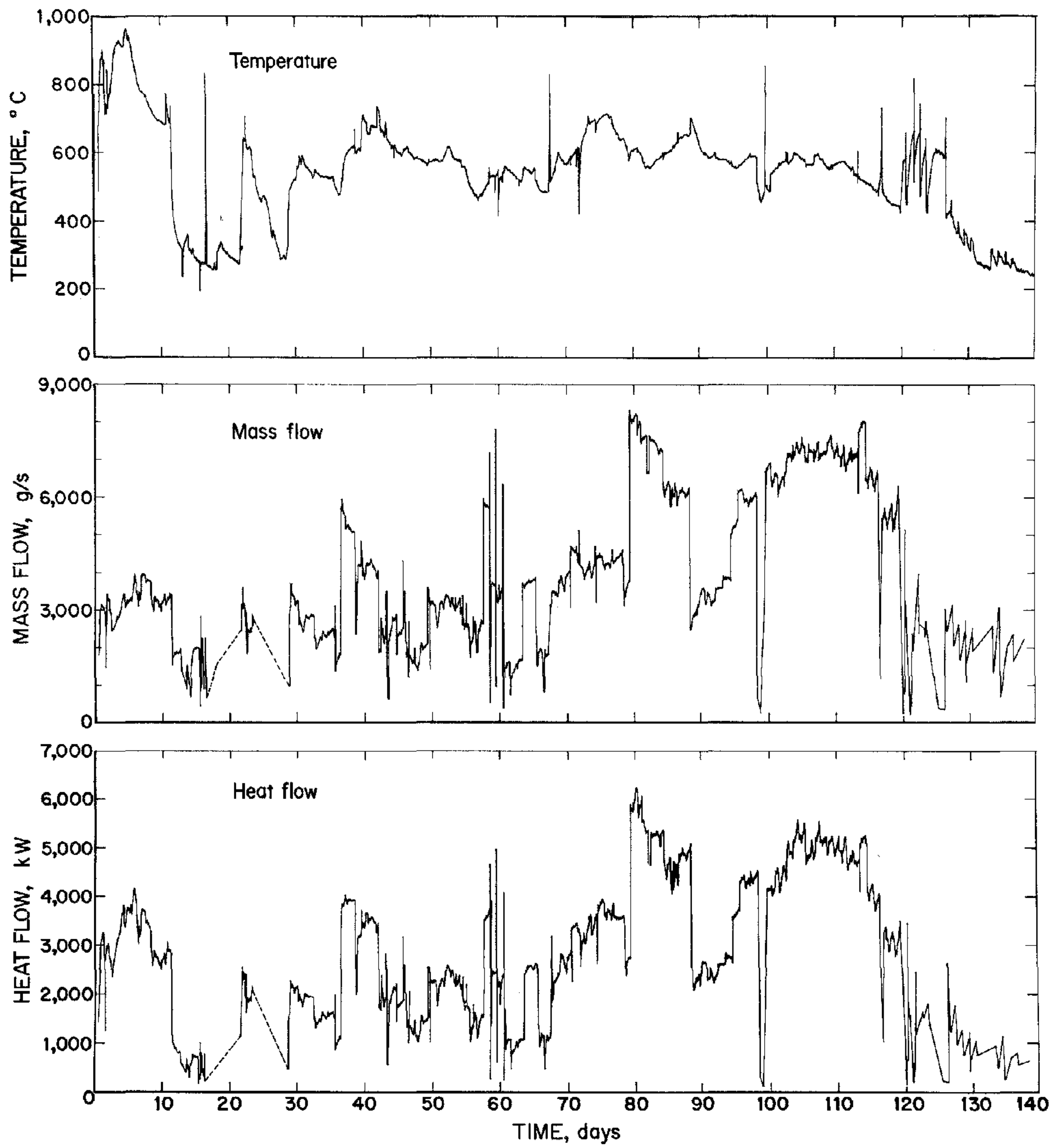

Figure 52.—Results of Burnout Control test at Calamity Hollow.

Burnout Control. A royalty-bearing license to use Burnout Control for power generation from underground mine fires is currently held by Coal Dynamics, Inc., a wholly owned subsidiary of Environmental Power Corp.

The field trial of Burnout Control at the Albright waste pile was also designed to operate at a 5-MW (thermal), 900° C exhaust output; however, the engineering of the combustion manifold was considerably different from that used at Calamity Hollow *(70)*. At Albright, a 3-ft diameter, 140-ft-long stainless steel combustion manifold was set horizontally at the bottom of the pile along its base (fig. 53). A 50-ft-long perforated section of the manifold served to draw heat and fumes from a volume of waste estimated at over 10,000 st, which at the design output would have taken 0.75 year to burn producing 113 billion British thermal units of thermal energy. Engineering design problems and the need to control air pollution during the trial prevented long-term continuous burnout operations at the site. However, during 1,600 h of fan operations, an estimated 700 st of waste were burned producing 8.12 billion British thermal units of exhaust thermal energy. The designed output was exceeded over several days

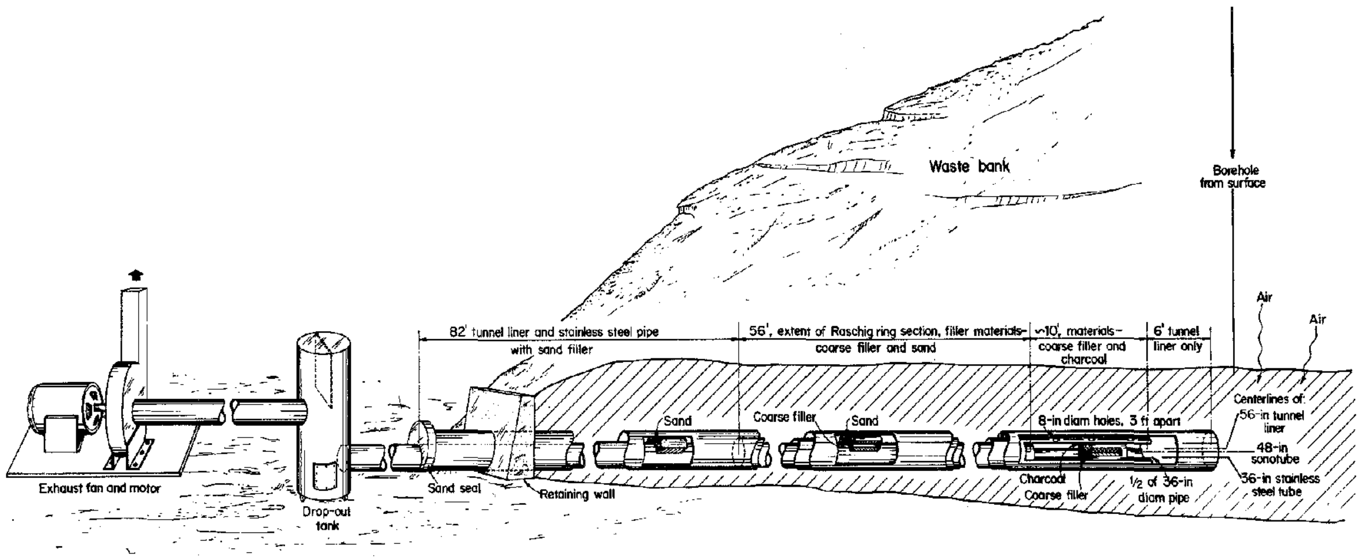

Figure 53.—Schematic of Burnout Control at Albright waste bank.

before burnout operations were terminated when excessive temperatures and vacuum combined to collapse the combustion manifold.

A key finding at the Albright field trial was that as the fire was spread under Burnout Control, the pile acted as a large gasifier; hence, there was a vital need to afterburn the exhaust gases in the combustion manifold. Only 30% of the fuel-sulfur appeared in the exhaust, but without full stoichiometric burning, sufficient amounts of reduced sulfur gases (e.g., H_2S, COS, and CS_2) were present to cause odor problems for nearby residents. Considerable subsidence occurred on top of the waste pile over the fire zones, but as in the case of the Calamity Hollow trial, the subsidence holes could be readily filled. With improved engineering designs and developments, particularly with regard to maintaining the structural integrity of the combustion manifold and improving its operation as an afterburner, it is believed that Burnout Control can be successfully applied to controlling AML coal waste pile fires.

Water Jetting

Another fuel removal method tested was the excavation of burning coal by high pressure water jet (*71*). The fire was located in an outcrop above the Yellowstone River in Montana. Holes were drilled horizontally and vertically through 25 to 30 ft of overburden. Although the drilling could be accomplished, the direction of the water could not be controlled. In most circumstances, it would form a channel out of the coal seam. When the water did reach burning coal, it produced an explosive reaction and high concentrations of carbon dioxide. The drilled holes were found to serve as sources of additional oxygen and the overlying rock tended to collapse. These conditions made it difficult to remove all the burning coal. In general, this technique was not considered a potentially useful method of excavating AML fires.

HEAT REMOVAL METHODS

Water

Removing heat, one of the three essential elements, from an underground fire requires the introduction of a heat-absorbing medium, its controlled movement through the mine and the removal of the heated substance (*72*). Theoretically, moving very large volumes of cold air through a mine will remove heat and lower the temperature. However, the air introduced usually supplies oxygen, which increases the oxidation rate and increases temperature. Water, where it is plentiful and inexpensive, is a desirable heat exchange medium because of its high heat capacity and its latent heat of vaporization.

In two projects, the Bureau has used injected water with the suction induced removal of heated gases. In theory, the water is injected into heated subterranean areas. The water is converted to steam. Under the influence of an exhaust fan, the steam is moved through the mine, adsorbing more heat from the heated coal and roof strata. A fan can be used to exhaust the heated steam to the atmosphere or to a heat exchanger where its thermal energy can be used.

The Bureau's water injection-fume exhaustion method had mixed results. During the cool down phase of the Calamity Hollow Mine fire project (*66*), water was injected by gravity flow through an array of 1-in hose and 2-in pipes. Simple pinch clamps were used to regulate the flow of water (fig. 54). Prior to quenching, the average

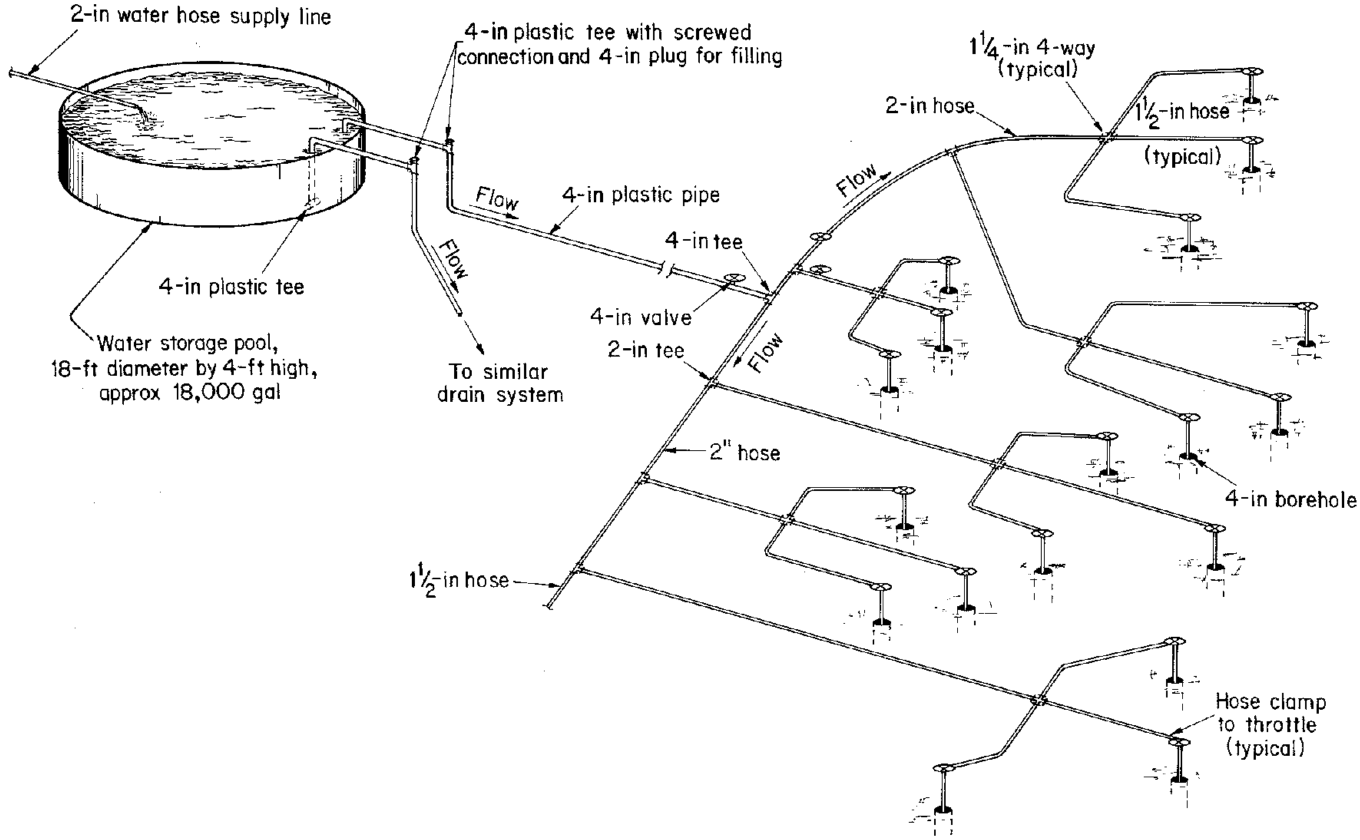

Figure 54.—Water distribution system for quenching fire zone at Calamity Hollow site.

temperature of the exhaust gas was 600° C. The system was operated at an injection rate of 2 to 3 gpm per borehole for 8 h each day for 21 days. For an additional 10 days, the water was injected continuously. Over the 30 days, 2.8 million gal of water was injected. The temperature of the exhaust was lowered to 162° C (fig. 55), and 300 million Btu of heat was removed from the mine (fig. 56). Although the method did lower the temperature of the fire zone, the estimated heat removal efficiency was not high, 7 cal/g compared with the heat of vaporization of 540 cal/g. It was known during the operation of the water injection-fume exhaustion system that much of the water was flowing out of the mine and was not reaching the burning material. When the water injection rate was increased, the seepage rate also increased (fig. 57). However, the system achieved its objective of cooling the combustion zone prior to excavation in a relatively short period.

Based on the Calamity Hollow project, an attempt was made to extinguish a fire in an abandoned mine at Renton, PA (*23, 51*). Three noncontiguous combustion sites, totaling about 10 acres, were located on the perimeter of the 60-acre site. Water was supplied by gravity to spray nozzles located at the casing bottom in each borehole. The fan was operated for approximately 6 h per day, and the water injection rate was approximately 1 gpm per

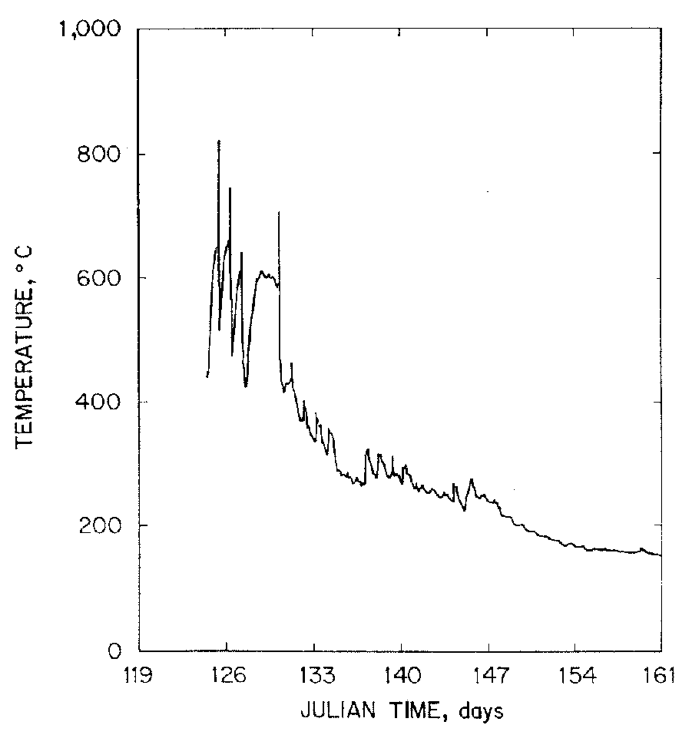

Figure 55.—Exhaust temperature during quenching at Calamity Hollow site.

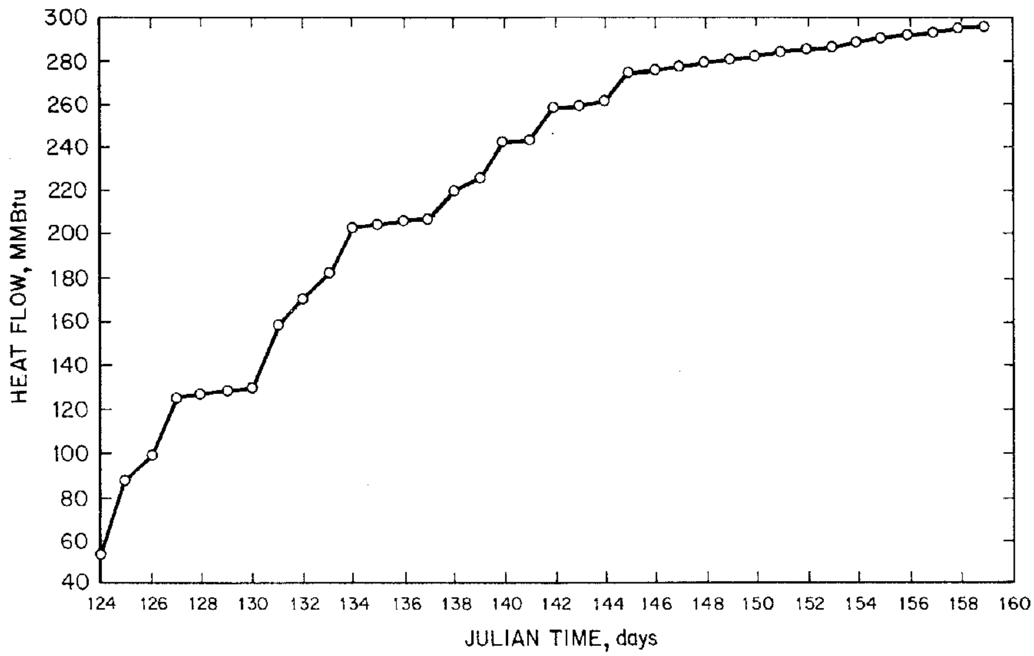

Figure 56.—Cumulative heat flow during quenching at Calamity Hollow.

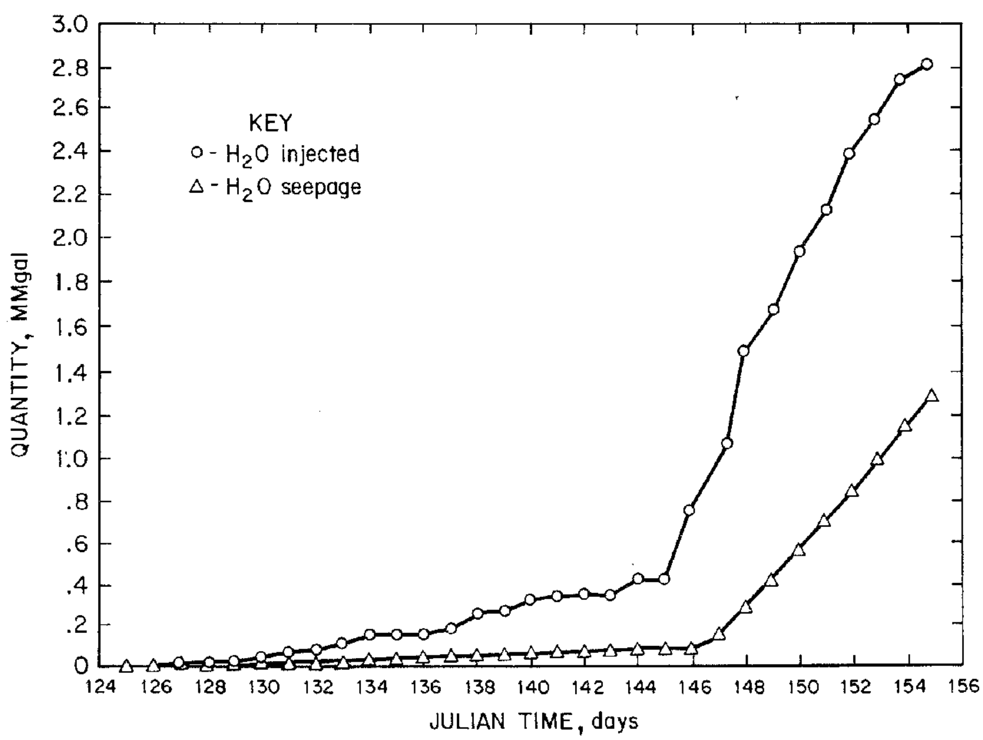

Figure 57.—Cumulative waterflow during water injection at Calamity Hollow site.

borehole. The water injection-fume exhaustion system was operated in this configuration for about 6 months. Then the injection tubes were reinstalled on the outside of the casing about 1 to 2 ft below the surface. In this manner, the water would flow down the casing and through the strata above the mine void. However, this modification produced no general improvement in cooling efficiency. Analysis of the data led to the conclusion that combustion was occurring in the roof coal and carbonaceous shales. It was unlikely that the water reached these areas and no significant conversion to steam occurred. Not enough heat was removed to slow or stop the combustion process. A better delivery system for placing the water in contact with the heated material was needed.

Foam

In the Renton fire project, it was determined that unless the injected water is rapidly converted to steam, the movement of the water through heated areas of the mine cannot be controlled. The use of foam as an extinguishing agent is common for surface fires; a variety of foams are used for well servicing in the petroleum industry. If any of these foams can be used to retain moisture in the fire area, foam injection might be used as a heat transfer method. A stable gelled foam can be pumped into the strata around the fire zone to act as a cold barrier. The foam injection-fume exhaust (FIFE) extinguishment method is considered a potentially significant improvement in remote fire control (fig. 58). The use of foam as a water transport agent has two distinct advantages: it would keep the water in place long enough for it to be entrained in the airstream; in voids, the foam could build upon itself to reach the mine roof where combustion may be seated.

Foam is a dispersion of gas in water. It is made of water, a suitable gas, either air or nitrogen, and a surfactant. Depending on its purpose, it also may contain fire inhibiting chemicals. Two sources of foams, which are potentially useful in extinguishing subsurface fires, are fire fighting foams used on surface fires and injectable foams used in oil field operations.

High expansion fire-fighting foams used on surface fires those with a high volume to water ratio, can quickly fill voids, but are relatively fragile and break down when in contact with uneven surfaces. Low-expansion foam has greater stability, but does not build upon itself, i.e., it will not fill voids. Medium-expansion foam is thought to incorporate the desirable qualities of the other foams, being stable and capable of filling voids. The standard fire-fighting foams tend to break down when pumped through porous media. Thickeners or gels added to the foam are believed to improve the lateral distribution of foams pumped through material the size of mine refuse *(73)*.

A wide variety of foams are used for well servicing in the petroleum industry. These are designed for pumping under pressure in relatively tight formations. Additives are used to adjust the stability of the foam and its viscosity. Gelling agents can be used to increase the stability of the foam. Because of the complexity of the subsurface fire problem, probably a variety of foams will be needed for this application. Gelled foam because of its stability can be used to reinforce barriers. Medium quality well-fracturing foam can be pumped through fractured strata for greater lateral dispersion *(74)*. Medium expansion fire-fighting foam can be used to fill voids. The foams are used to distribute water underground, to keep water in place until it can be entrained in an airstream, to protect nonfire areas from the migration of hot gases, and to reach areas of the mine that are not within reach of a simple gravity feed system.

Cryogenic Liquids

The use of cryogenic liquids as a heat removal medium in wasted coal fires has the potential advantages of uniform distribution of the liquid and isotropic expansion of a cold gas. If water is injected into a waste bank, gravity causes it to flow downdip. As the water flows, erosion causes the size of the drainage channel to increase. The distribution of the heat removal agent, water, affects a relatively small area, and cannot be controlled. If a cryogenic liquid is injected, moisture in the material freezes, displacing the injected liquid to another area. This increases the size of the area affected by the injected liquid. Also, as the temperature of the gas increases, the gas expands, creating a cold pressure front that moves from the point of injection to the surface of the bank.

In small-scale tests of cryogenic injection using a 1/2 in injection line to a central point in a 55-gal drum filled with coal refuse, cryogenic CO_2 was used as the heat transfer liquid. At atmospheric pressure, the injected CO_2 forms a solid, like snow. In a relatively short period, this solid forms around the injection point and blocks the flow of liquid.

In medium-scale tests conducted in a 320-ft^3 box of coal waste, liquid nitrogen was used as the heat transfer medium. These tests indicated that if the refuse was wet, the formation of ice during cryogenic injection could contain and direct the flow of the liquid nitrogen. However, at any point where the refuse was dry, the nitrogen would act like a liquid and flow to the bottom of the box.

In a test conducted in the Bureau's Surface Trench Burn Facility at the Pittsburgh Research Center, 11,000 lb of liquid nitrogen was injected into the center of a 540-ft^3 (20 st) bed of coal at the rate of 100 gal/h. Prior to injection, the maximum temperature in the coal was approximately 100° C. Within a few minutes of the start of injection, the temperature near the injection point was −68° C. In 1/2 h, the temperature of half of the trench was less than 0° C, and −100° C in an hour. The lowest temperature recorded was −170° C. Allowing the N_2 to evaporate through the open top of the bed, it took 30 days for the temperature of the coal to reach −20° C (fig. 59).

For the trench experiment, changes in temperature showed the distribution of liquid-gaseous nitrogen throughout the bed from a single injection point. When the cryogenic liquid was contained, the vaporization of the nitrogen was effective at lowering the temperature of the coal between 100° and 200° C at the rate of 1 lb of nitrogen per 4 lb of coal.

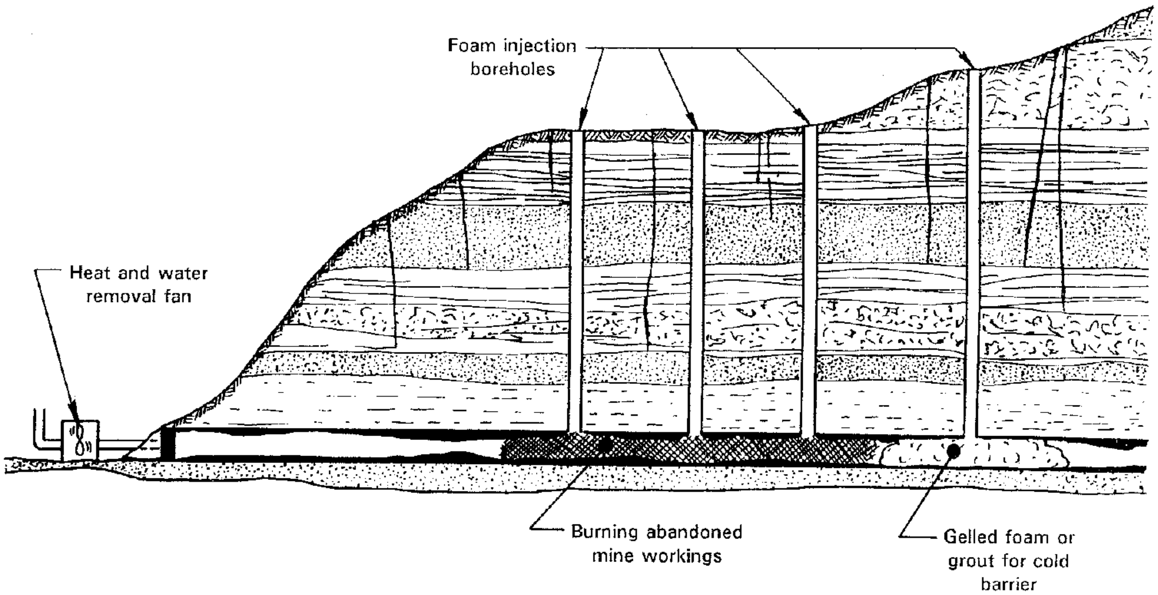

Figure 58.—Foam injection-fume exhaust (FIFE) system for extinguishing AML fires.

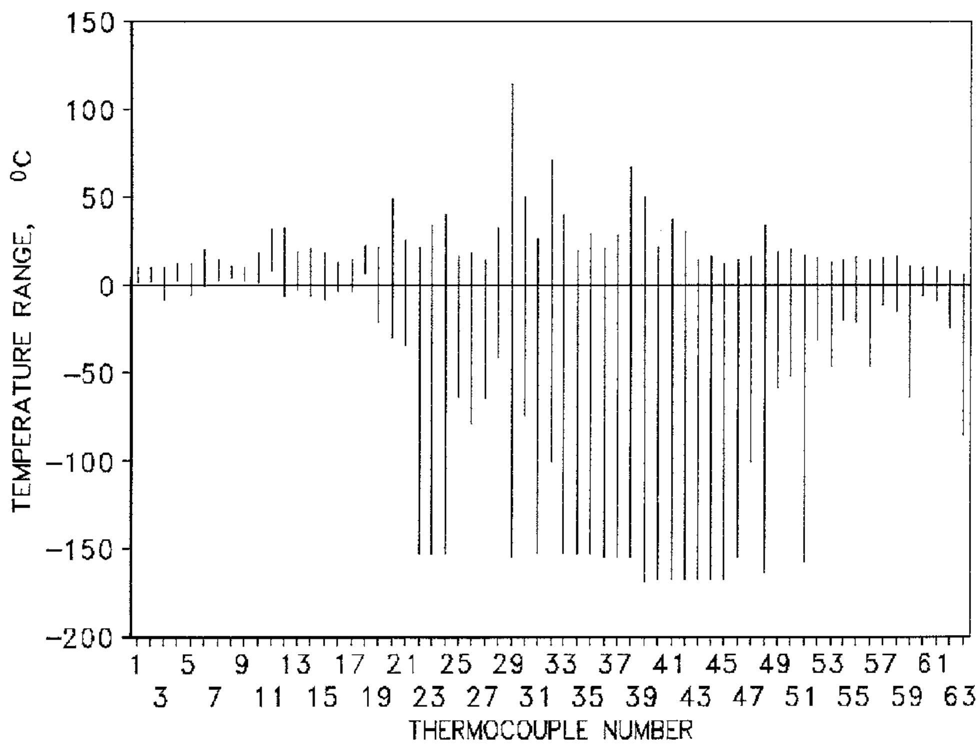

Figure 59.—High and low temperatures during injection of liquid nitrogen.

The use of cryogenic gas as the extinguishing agent in waste bank fires assumes that freezing the water normally present in the bank will enhance the uniform distribution of the extinguishing agent and that as the liquid vaporizes, the expansion of the cold gas will distribute the extinguishing agent upward to the surface. Tests with liquid nitrogen have shown that the injected liquid causes a relatively quick cooling of surrounding material and that the expansion of the evaporating gas maintains the cool atmosphere for an extended period. To overcome the flow constraints, an apparatus[11] has been designed to produce a pumpable slurry of liquid nitrogen and carbon dioxide (fig. 60). This

[11]Patent applied for.

slurry has the distribution properties of a liquid. As the nitrogen evaporates, the carbon dioxide remains in place. Using a batch injection system, 300 gal of the cryogenic slurry reduced temperatures in the trench from 400° C to below the reignition point (fig. 61). Further development of this technique involves scale-up of the equipment and a field trial (*75*). The potential applicability of this novel technique cannot be determined until research is completed, but appears to be promising. Eventual use will depend upon the cost and the availability of cryogenic liquids.

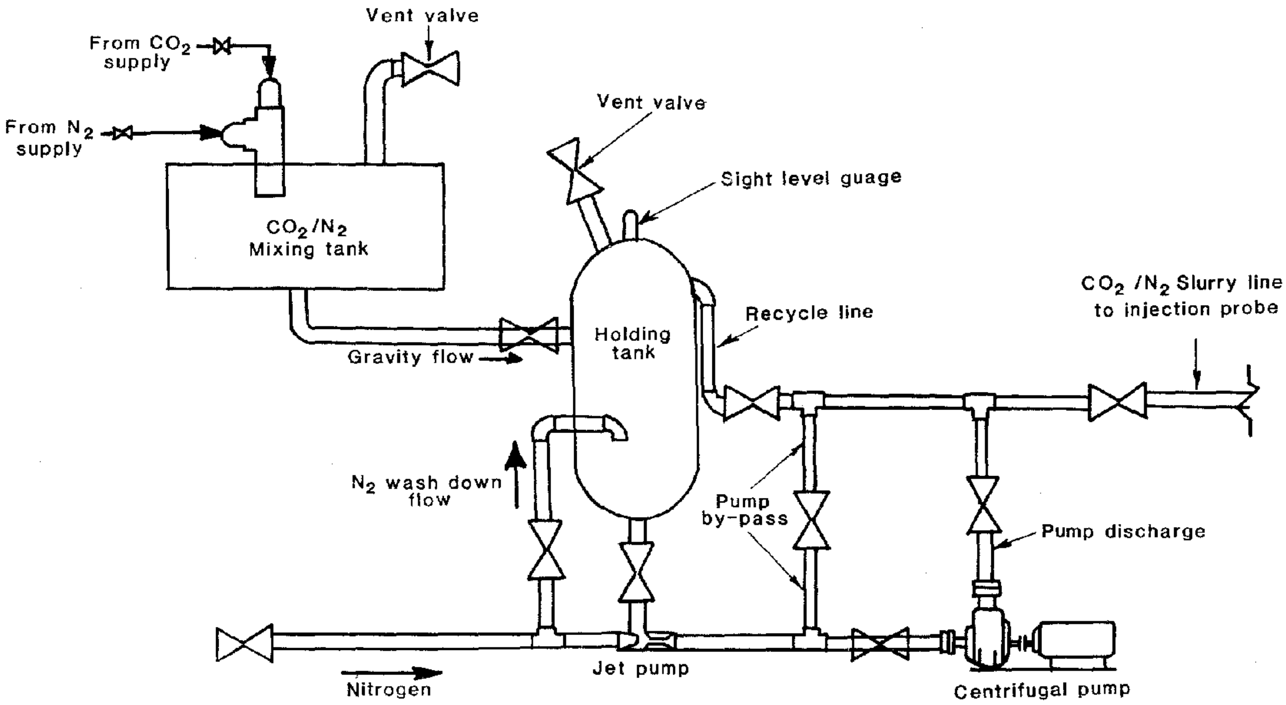

Figure 60.—Schematic of equipment to produce cryogenic slurry.

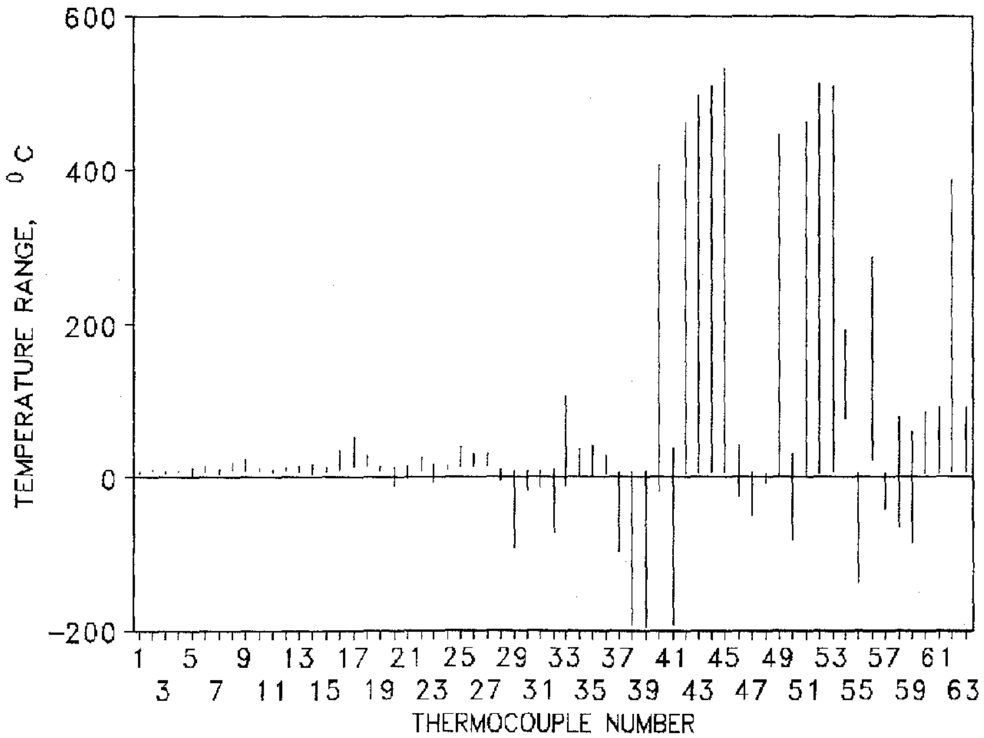

Figure 61.—High and low temperatures during injection of cryogenic slurry.

OXYGEN EXCLUSION (FIRE BARRIERS)

Recently, foaming grouts have been used as underground fire control agents. These have been normal cementitous grouts mixed with a preformed foam and foaming mud cements that use local soil as an aggregate (*56, 76*). The foamed grouts are light in weight and can be pumped through boreholes. The thermal conductivity is low, and decreases with the amount of air in the slurry. The thermal conductivity can be increased by adding an appropriate aggregate to the cement slurry. The foamed concrete when pumped into the voids of an abandoned mine is believed to flow over burning material, encapsulating it, and preventing further combustion by oxygen exclusion. The foaming grout has the additional property of filling voids, providing subsidence control.

In many abandoned mines, the roof has collapsed and voids are relatively small. The configuration of an abandoned mine can more accurately be described as a nonhomogeneous, porous bed. Whether foaming grouts can be forced to flow through such a bed has not been determined. Also, although the grouts can reach the mine roof, there is no data on how well it will fill cracks or how far it can be made to migrate along roof fractures. Presently, the suggested method of using foaming grouts presupposes that they are introduced at or near the combustion. If this assumption does not hold, their effectiveness is unknown.

RESEARCH AREAS

Diagnostics

The primary need in any AML fire effort is to know where the fire is and what area it affects. The Bureau's mine fire diagnostic technology is a significant improvement; however, it requires extensive drilling and gas analysis. The need for repeated tests and possibly additional rounds of drilling are time consuming and add to the overall cost. It does have the advantages of being more accurate than other methods, of determining cold boundaries, and of being useful for long-term monitoring.

Two methods are being considered to improve the mine fire diagnostic technique. The first, ventilation analysis, is being tested. This bases the location of fire zones on pressure changes and anisotropic resistances between borehole pairs. It eliminates the need for hydrocarbon gas analysis. The second improvement would be the use of an on-site sampling and analysis system to replace laboratory gas analysis, paired with a semi-automated computerized data evaluation.

A remote reconnaissance method to determine the location and extent of subsurface AML fires would improve the evaluation and control of these fires by several orders of magnitude. Ideally, such a method would be simple, quick, inexpensive, and require no drilling. Although methods based on geochemical or geophysical prospecting may be applicable, the use of such a method would require extensive research, including design and development, controlled testing, field testing, and comparative evaluation. Development of any remote reconnaissance method must consider that the strata between the surface and the fire are not homogeneous, that permeability is influenced by the presence of fracture zones and that the energy released by the fire and the gaseous products of combustion are not limited to straight line migration paths. Remote reconnaissance is probably the area of greatest need in AML fire research; it is also, at present, the area least likely to produce immediate results.

Another evaluation technique, which could be more extensively used in AML fire projects, is the borehole camera. The use of a camera in open entries is obvious. However, if the mine has collapsed, could the borehole camera be used to evaluate the condition of the mine, including such factors as size and distribution of voids, the height of the combustible zone, size distribution of rubble, condition of the overburden, directions of normal water flow, and gross differences in permeability? Can the borehole camera be used to observe the emplacement of a barrier or extinguishing agent to estimate potential effectiveness? The borehole camera is an available instrument and has potential for use in improving the effective application of available fire control techniques.

Extinguishment

With respect to extinguishment techniques, excavation is currently the most effective. The implementation of excavation could be improved by the use of diagnostics, more comprehensive project planning, and the inclusion of post-project monitoring. More attention to safety considerations would probably be of value.

For extinguishment techniques other than excavation, the delivery system is the primary problem. Water is an effective extinguishing agent if it can be placed in contact with the burning coal. There is no indication that extinguishing agents other than water are more effective in quenching AML fires. The use of foam and of cryogenic liquids are methods to improve the delivery system, to keep the extinguishing agent within the fire zone. Research on the use of fire retardant chemicals in subsurface fires is unwarranted unless there is an effective method of getting the extinguishant to the fire.

Control-Containment

The use of barriers, either as independent fire control devices, or as a corollary to excavation is another fertile area for research. Foaming grouts or cellular concretes (*77-78*) have been considered for use as fire barriers. The use of stable, nontoxic chemical agents, i.e., plasticizers or gelling agents, also could be considered for heat-absorbing barriers or toxic fume barriers. Slurry walls, either for fire isolation (rectangular trench barriers) or as containment devices for inundation, are potentially applicable to fire problems. These are currently used for seepage control and for isolating contaminated ground water. In some circumstances, these may apply to AML fire problems.

It should be recognized that under certain conditions, it may be unnecessary to completely eliminate an AML fire to solve the fire problem. If the problem is the emission of noxious odors, the possible migration of toxic fumes or subsidence caused by the fire, these can be addressed by methods that treat the symptoms. As examples, if the fire is in an isolated and inaccessible area, but vents are producing noxious odors that can be detected in populated areas, it may be possible to construct a surface seal and insert a tall chimney and wind turbine to disperse the fumes. A seal suppresses surface evidence of a fire, but may not extinguish it unless the fire is relatively small, and has limited sources of oxygen. If the fire is in an abandoned mine with extensive workings, the seal can force the movement of hot gases into another area of the mine, actually spreading the fire. The use of a chimney or other pressure balancing method to control the movement of heat and fumes may significantly improve the effectiveness and longevity of a seal. Pressure balancing can be accomplished by creating either a high or low pressure area. Even creating an area of higher permeability (i.e., a French drain) may control the migration of toxic fumes.

The subsurface injection of polyurethane has been used to control subsidence and water infiltration (*79*). It may also be useful for forming an impermeable barrier to toxic fumes and as an improvement in surface sealing. Its expansive characteristics, its strength, and its compatibility with water make it suitable for barriers. Its combustibility can be modified by combining the polyurethane with other materials, such as sodium silicate. The near surface injection of polyurethane grout to increase the shear strength of unconsolidated materials (*80*) may be effective in improving the longevity of surface seals.

Blasting has been suggested as a means of collapsing the overburden and limiting oxygen in subsurface fires. In most cases, the overburden is already collapsed; mine fires burn in a low oxygen environment (<3%) and the explosive fragmentation of combustible material increases the surface area. Because of these factors, it is unlikely that blasting would extinguish fires and it could lead to enhanced propagation rates. In the case of some outcrop fires, however, properly placed explosives might be used to remove the burning material from the rest of the seam. The use of the foregoing methods assumes that there is a valid method for determining the degree of risk, the extent to which a subsurface fire may be hazardous to people on the surface. If that hazard can be evaluated, it may be appropriate to control the symptoms and simply monitor the fire. At present, there are no guidelines for making this assessment, and certainly, careful consideration would have to be given to all factors in any project attempting to protect surface features without controlling the fire.

The above discussion of research needs is intended to indicate that there are many areas and technical approaches that can be considered. The cost of conducting research or of implementing new technical approaches has not been a factor in this discussion. However, given the cost of AML fire control projects, the historically poor success rate and the few available options, it is apparent that money spent on AML fire research would be a good investment in more effective, more efficient reclamation of AML lands.

SUGGESTED APPROACH TO AML FIRE PROBLEMS

The foregoing information on AML fires should indicate that there is no typical fire and certainly no standard control or extinguishment method. The methods currently in use are generally expensive and not routinely successful. In an attempt to improve the efficacy of current methods and to limit costs, the Bureau suggests an approach to AML fires involving an assessment of the hazard and selection of the appropriate response. The steps in this approach are as follows:

1. Determine the location and extent of the fire.
2. Assess the degree of risk.
    - Nature of hazard.
        - Toxic fumes.
        - Subsidence.
        - Noxious odors.
    - Size and distribution of affected population.
3. Select appropriate strategy.
    - Extinguishment.
    - Control-containment.
    - Surface amelioration-cosmetics.
    - Do nothing.
4. Select method most likely to succeed.
5. Monitor completed project.

The first step in an AML fire project should be to determine the extent and location of the fire. Determining that within a 10-acre site, the fire is limited to 1 acre can considerably reduce the cost of the project. Conversely, discovering that a supposed outcrop fire extends into an abandoned mine will affect how much money must be allocated to control a fire. And discovering in the middle of a fire project that what was assumed to be the limit of the work area passes through a hot zone can have a significant impact on the expenditure of time and money, particularly if it is necessary to obtain additional rights of entry. Time and effort put into finding where the fire is and how big it is will usually result in a less costly, more efficient fire control effort.

The second step is to assess the degree of risk, including the type of risk and the population affected. Is the hazard the migration of toxic fumes, subsidence under or near inhabited structures, smoke and noxious odors in a community, subsidence in a remote, but accessible area, fumes in a remote area, etc.? Estimating the probable direction of propagation is also a factor in the degree of risk. If the problem is currently minor, will it in time affect more people or be significantly more costly to control? This type of evaluation is essential to cost-effective planning.

The next step is to select an appropriate strategy. Based on the location and extent of the fire and on the hazard it presents, a variety of options may be available. It may be that the degree of risk imposes a responsibility to extinguish the fire. It's possible that some fires, if properly contained or controlled, will burn themselves out or at least cease to be hazardous. In some situations, cosmetic alterations to the surface, i.e., filling in sinkholes or suppressing vapors, will resolve the problem. And in some situations, a do nothing option is the correct choice.

Once the strategy has been selected, the method of implementation should be planned carefully. Since most fires have unique characteristics, and since there is no standard method, the project, including the technique, its implementation and the cost, must be tailored to the fire. Designing a fire control or extinguishment project based on the amount of money available limits the available options and decreases the probability of success. For example, the first three attempts to control the Centralia mine fire were stopped before the fire was controlled, because funds had been expended. At least twice, work was delayed until additional funding could be approved, and twice, the control method believed to be most effective was rejected in favor of a less costly alternative (*27*). The availability of funds was a factor in the failure to control the Centralia mine fire. As a corollary observation, successful projects are 2 to 10 times more expensive than the original unsuccessful project.

Some simple precautions during an extinguishment project may limit the probability of reignition. For example, determining the temperature of quenched material before it's used as backfill may seem like additional work, but it may prevent hot material being returned to the excavation. As another example, in many projects, it is probably worth the additional effort to work from an interior cold boundary toward the surface. This simple step limits the possibility of propagating a fire beyond the original fire zone.

The final step in improving the probability of a successful fire project is postproject monitoring. Although it is natural to be optimistic, experience shows that many AML fires are neither extinguished or controlled at the end of a fire project. Periodic monitoring at least permits appropriate remedial action to be taken.

CONCLUSIONS

The problem of AML fires is serious. It may not be as pervasive as acid mine drainage, but on a local level AML fires can involve a greater degree of hazard and can be less amenable to solution. AML fires are usually remote and may involve outcrops, waste banks, and abandoned workings. Because of the nature of these fires, it is unlikely that the the extent of the problem or the cost of solutions will decrease in the near future. Although new techniques for locating fires, and for controlling and extinguishing fires have been or are being developed, the majority of current AML fire control projects utilize conventional methods and techniques. Despite the seriousness of the problem, in some cases, costs are prohibitive and current methods are inadequate. In many cases, however, evaluation, assessment, and planning can improve the implementation and cost effectiveness of a fire control effort. Wasted coal fires have occurred in this country for over 200 years. Considering the extent of abandoned mined lands, they may continue to occur for the next 200 years. Experience has shown that they are difficult and expensive to control. Most methods currently used to control AML fires are less than 70% effective. Research in new technology and in the adaptation of technology available in other fields may significantly improve the effectiveness of fire control methods, and is essential to reducing the cost of AML fire control.

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