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Coal fires burning out of control around the world: thermodynamic recipe for environmental catastrophe

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"From the day we sailed the Titanic was on fire, and my sole duty, together with eleven other men, had been to fight that fire. We had made no headway against it".

John Dilley, RMS Titanic Fireman (Report to U.S. Senate, 1912)

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Abstract

Coal fires burning around the world are an environmental catastrophe characterized by the emission of noxious gases, particulate matter, and condensation by-products. Underground mine fires and burning culm banks ignited by natural causes or human error are responsible for atmospheric pollution, acid rain, perilous land subsidence, the destruction of floral and faunal habitats, human fatalities, and increased coronary and respiratory diseases. Some of the oldest and largest coal fires in the world occur in China, the United States, and India. Techniques used to fight coal fires include slurry and ash injection, surface and tunnel sealing, aqueous foam technology, remote sensing, and computer software. Elusive, unpredictable, or cost prohibitive coal fires may burn indefinitely, choking the life out of a community and its environs while consuming a valuable natural resource.

Keywords: Coal fires; Coal gas; Spontaneous combustion; Pollution; Acid rain; Subsidence

1. Introduction

Fire is a force of nature that often demands human attention and resources; however, few people realize that fire is consuming coal seams and culm banks in major coal-producing countries including China, the United States, India, and Indonesia (Table 1). Numerous seams have been burning for decades and some in China for several centuries. Geological evidence for Pliocene coal fires includes fission-track dates obtained for zircons extracted from sandstone clinker found southwest of Forsyth, Montana and west of Colstrip, Montana (Coates and Heffern, 2000). Evidence for Pleistocene coal fires, some with temperatures exceeding 1000 °C, includes unconformable relationships among baked and unbaked sedimentary rocks southwest of Urumqi in the Xinjiang autonomous region of northwest China (Fig. 1) (Zhang and Kroonenberg, 1996; Kroonenberg and Zhang, 1997; International Institute for Geo-Information Science and Earth Observation (ITC), 2003). Although this evidence sug-

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Table 1
Ten major hard coal-producing countries and statistics on coal consumption

Major coal producing country[a]	Coal [b] production (Mt)	Coal consumed	
		Generating electricity (% production)	Steel production (Mt)
China	1294	78	152.3
USA	945	52	90.1
India	312.5	77	27.3
Australia	257	77	N.D.[c]
So. Africa	224.5	88	N.D.
Russia	168	N.D.[c]	59.0
Poland	104	96	N.D.
Indonesia	92.5	N.D.	N.D.
Ukraine	82	N.D.	33.1
Kazakhstan	73	N.D.	N.D.

Coal production and electrical data for 2001 (electricity for China and India, 2000), courtesy of the World Coal Institute, (2002). Steel production data for 2001, courtesy of the World Coal Institute, (2003).

[a] Total world hard coal production in 2001 (including countries not listed) was 3834 Mt. In 2001, Germany was the top producer of brown coal/lignite, with just under 20% of world production (903 Mt) (World Coal Institute, 2002).

[b] Mt = million tons.

[c] N.D. = no data.

gests that coal fires are a natural event, coal mining by humans has facilitated the proliferation of these fires and the environment is suffering.

Environmentally catastrophic effects from coal fires include the emission of noxious gases and particulate matter into the atmosphere and condensation products responsible for stream and soil pollution. Coal fires have killed people, forced entire communities to abandon their homes and businesses, destroyed floral and faunal habitats, and are responsible for perilous land subsidence.

This paper discloses the severity of the coal fires problem. The objectives of the analyses presented herein are to describe the origin of coal fires and related gases, discuss some of the world's most problematic coal fires and associated environmental hazards, and briefly consider techniques used to combat these fires.

2. Coal fires: the mining hazard

Although coal has been mined for over a thousand years as a heating and cooking fuel, large-scale mining, necessary to support the industrial revolution, did not begin until the 19th century (World Coal Institute, 2000). Since 1995, coal and oil reversed rankings; with oil overtaking coal as the primary resource for energy consumption (U.S. Department of Energy, 1995; World Coal Institute, 2000). As long as coal is *strip* or *deep* mined in order to stoke the electrical and steel fuel-hungry economies of industrialized and developing nations, the potential for uncontrollable fire exists.

2.1. Origin of coal fires

Most coal mine-related fires are ignited by: (1) mine-related activities such as cutting and welding, explosives and electrical work, and smoking, which may ignite gases such as methane and hydrogen (Mine Safety and Health Administration, 1996; Pennsylvania Department of Environmental Protection, 2001a); (2) surface fires transmitted to culm banks or coal seams by lightning, forest or bush fires, and burning trash (DeKok, 1986; Geissinger, 1990; Discover, 1999); and (3) spontaneous combustion induced either by coal fines, oil-soaked rags, lumber,

Fig. 1. Coal fires across China: provinces are outlined. Anthracite reserves are concentrated in the Xinjiang and Ningxia Hui provinces (autonomous regions). Urumqi, capital city of Xinjiang, is one of the most polluted cities in the world. Coalfield fires are surface fires in seams, some of which occur in open-pit mines. Coal mine fires include underground and surface fires in government and private mines. Courtesy of Anupma Prakash, Geophysical Institute, University of Alaska, Fairbanks and ITC (2003), with modifications.

hay, or manure in culm banks or by exothermic oxidation reactions catalyzed by oxygen circulating through coal seam joints (Jones and Scott, 1939; Anthony et al., 1977; U.S. Department of Energy, 1993; International Institute for Geo-Information Science and Earth Observation, 2003). One such oxidation reaction is (Limacher, 1963)

$$FeS_2 + (7/2)O_2 + H_2O \rightarrow FeSO_4 + H_2SO_4. \quad (1)$$

This reaction exemplifies the fact that moisture is conducive to spontaneous combustion (U.S. Department of Energy, 1993).

According to the U.S. Department of Energy, (1993), many spontaneous fires start in storage facilities including open-air stockpiles, coal bunkers, and silos. The DOE attributes combustion to numerous factors. These include improperly loaded and compacted storage in facilities that promote the diminution of coal into highly combustible fines and also storage for prolonged periods of time, which promotes exothermic oxidation reactions in high-sulfur coals. Spontaneous fires in storage bins have been extinguished by injecting N_2 or CO_2 into the bins. Water has also been used, but with extreme caution, because of the risk of steam explosions. The U.S. Department of Energy (1993) has published guidelines for preventing spontaneous combustion in coal-storage facilities. These include recommendations for the shape, height, and composition of stockpiles.

The significance of spontaneous coal fires in storage facilities was conveyed in the testimony of John Dilley to the U.S. Senate (1912). Dilley, of Southampton, England, was a survivor and fireman in the engine department on the RMS Titanic that sank about 640 km south of Newfoundland on Monday, April 15, 1912 (U.S. Senate, 1912). According to Dilley, the bottom of a coal bunker containing hundreds of tons of coal was on fire from the time the ship departed Southampton for New York City on April 10, until the iceberg that the Titanic hit on the evening of April 14 tore open this bunker and the incoming water put out the fire.

Although coal fires often start at storage facilities where they can be extinguished relatively easily, larger and more problematic fires frequently start in the excavations of the *abandoned workings* or *workings* of a coal mine (Pennsylvania Department of Environmental Protection, 1965). Fires in abandoned underground workings are the most problematic because they are difficult or impossible to locate precisely. According to the latest estimate of the U.S. Department of the Interior, more than $651 million is needed to control these fires in the U.S. alone (Office of Surface Mining, 1999).

2.2. Coal gas

Carbon dioxide concentrations exceed those of other gases produced by coal fires; however, CO_2 concentrations are not entirely controlled by the coal itself. The concentrations are also determined by (Mitchell, 1996): (1) *blackdamp* (chokedamp) produced by the respiration of miners and working animals (formerly used in the U.S.), cellulose-decomposing monerans in wooden supports, and the oxidation of wood, pyrite, or coal; (2) CO_2 associated with coal, gypsum, potash, and salt-bearing strata encountered during mining; and (3) chemical reactions between acidic water and carbonate rocks, rock dust, or inclusions in strata.

Carbon monoxide, hydrogen, and the hydrocarbons ethylene (C_2H_4), propylene (C_3H_6), and acetylene (C_2H_2) are monitored as *coal-fire detector gases* because they are released sequentially as temperature increases during heating. Consecutive temperatures at which release begins in medium volatile-bituminous coal, for example, are about 110 (CO), 170 (H_2), 240 (C_2H_4), and 300 °C (C_3H_6) (Chamberlain, 1971). Combustion occurs between about 110–170 °C, and flames appear at about 200 °C (Chamberlain and Hall, 1973).

The late D.W. Mitchell, 1996 (p. 45–61, 64–97), a leading authority on mine fires, discussed gas collection devices, concentration detectors, and the complexities associated with using coal-fire detector and *wood-fire detector gases* such as formaldehyde (CH_2O), formic (CH_2O_2) and acetic ($C_2H_4O_2$) acid and glyoxal ($C_2H_2O_2$) for identifying mine fires.

Other gases associated with coal fires include: (1) N_2, Ar, and trace amounts of other noble gases, all mainly from air; (2) O_2 mostly from air; occasionally from coal strata; (3) hydrogen sulfide or *stinkdamp* (H_2S), oxides of sulfur (SO_x), and nitrogen (NO_x) from oxidation and combustion processes; and (4) the hydrocarbons ethane (C_2H_6), propane

(C_3H_8), and methane (CH_4) released in increasing amounts during heating, and consumed once flames erupt (Mitchell, 1996; Álvarez et al., 1997; International Institute for Geo-Information Science and Earth Observation, 2003; World Coal Institute, 2000; Pennsylvania Department of Environmental Protection, 2001a).

Methane is the most combustible gas associated with blasting and burning coal, but CO and H_2 also contribute to combustion hazards (Pennsylvania Department of Environmental Protection, 2001a). Methane, a component of virgin coal, accumulates in underground mines, especially in poorly ventilated shafts. Oxygen supports combustion and the amount necessary for burning is a function of the proportion of any combination of methane, carbon monoxide, and hydrogen to other gases. Five to fifteen percent methane in air, for example, is highly combustible (Pennsylvania Department of Environmental Protection, 2001a).

Condensation products associated with burning coal form as gas exhaled from surficial vents, cracks, coal seams, and culm banks first cools and then condenses (Christie, 1926; Rost, 1937; Limacher, 1963; Lapham et al., 1980; Stracher, 1995). The exhalation–condensation process is analogous to the way minerals form in fumarolic environments (Lindgren, 1933; Stoiber and Rose, 1974; Smithsonian Institution, 2003). Using an analytical technique called *thermodynamic loop analysis*, Stracher, 1995 derived a $P-T$ stability diagram for the condensation of orthorhombic sulfur from anthracite gas associated with the Centralia, Pennsylvania mine fire. The significance of any such stability diagram is that it serves as an environmental indicator of conditions that tend to favor the condensation of gaseous exhalations as opposed to the absorption of those exhalations into the atmosphere. In addition, such diagrams reveal information about gas composition.

Fortunately, thermodynamic data is available for additional condensates associated with the Centralia fires, as well as coal fires in Russia. Consequently, the authors are currently deriving $P-T$ stability diagrams for these materials. In addition, samples collected from coal fires in La Plata County, Colorado, and condensates from Indonesia and Northern China have the potential to serve as environmental $P-T$ indicators. The authors would appreciate receiving samples of coal-fire condensates from their readers for chemical analysis and further study.

3. Largest coal fires in the world

Some of the oldest, largest, most prevalent, and environmentally catastrophic coal fires in the world are described below. Environmental hazards associated with these fires and techniques used to control them are briefly discussed.

3.1. Northern China

China leads the world in coal production (Table 1); with one third of the global output, coal accounts for about three-fourths of China's total energy consumption (Williams, 1999; World Coal Institute, 2000). Its reserves are concentrated in the Xinjiang Uygur and Ningxia Hui autonomous regions of northwest and north-central China, respectively. Coal fires burning throughout these regions and across northern China (Fig. 1) started by lightning, spontaneous combustion, and mining operations on all scales. The fires consume up to 200 million tons of coal per year (Rosema et al., 1993; Discover, 1999) and account for as much as 2–3% of the annual world emission of atmospheric CO_2 from burning fossil fuels (Cassells and van Genderen, 1995; Zhang and Kroonenberg, 1996). This is equivalent to the CO_2 emitted per annum from all vehicles in the United States (Discover, 1999) and does not include CO_2 emissions from coal or other fuels used by China's industrial and residential sectors.

Xinjiang contains some of the largest untapped coal reserves in the world. Underground coal fires in the Liu Huangou coalfield have been burning for over 20 years and possibly as long as 40 years. Chinese officials suspect the fires started by accidents inside small illegal mineshafts dug by local farmers. Particulates and noxious gases released by combustion are blown by winds over the region's capital city, Urumqi (Fig. 1), one of the 10 worst polluted cities in the world. The estimated cost of extinguishing the fires over a four-year period is at least \$10 million (U.S.) (Wingfield-Hayes, 2000).

In the Rujigou coalfield of Ningxia, underground coal fires are responsible for land subsidence and the

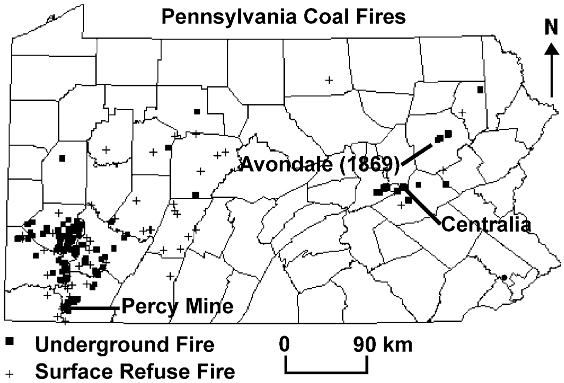

Fig. 2. Coal fires across Pennsylvania: state counties are outlined. Centralia, Percy, and Avondale mine fires of Columbia, Fayette, and Montgomery counties, respectively, are illustrated. Anthracite reserves are concentrated in the east and bituminous reserves in the southwest. Courtesy of Michael Klimkos (Pennsylvania Department of Environmental Protection, 2001c), with modifications.

release of hydrogen sulfide into the atmosphere (Discover, 1999). The length, width, and depth of surficial cracks induced by subsidence are as much as several kilometers long, tens of meters wide, and hundreds of meters deep. These cracks promote subsurface burning by providing a conduit through which oxygen can circulate to support combustion. Subsidence due to underground fires in northwest China has been identified with thermal, microwave, and optical satellite data (Prakash et al., 2000). Research using synthetic aperture radar (SAR) to identify subsidence is currently being conducted at ITC (Prakash, 2003).

Optical and thermal images acquired by the Beijing Remote Sensing Corporation (BRSC) and heat measurements from surface and subsurface detectors have been used to determine coal fire size, depth of greatest intensity, and burning direction (Vekerdy et al., 1999; International Institute for Geo-Information Science and Earth Observation, 2003, and references therein). Temperatures exceeding 800 °C for surface fires have been recorded with ground-based thermal detectors (Prakash and Gupta, 1999). Combining the information acquired for numerous fires with Global Positioning System (GPS) and geologic data, ITC scientists in cooperation with the BRSC, the Netherlands Institute of Applied Geo-Science, and the Environmental Analysis and Remote Sensing firm in the Netherlands designed the PC-based geographic information system, COALMAN (Vekerdy et al., 1999; 2000). COALMAN is used to assist Chinese fire fighters in the field by generating a time series of fire fighting maps and subsurface images of the fire. The COALMAN project was funded by the Dutch and Chinese governments and the PC system can be user updated as new information about a fire becomes available (Vekerdy et al., 1999).

Once the various forms of technology are used to locate the greatest intensity of an underground fire, fire fighters either inject a water-mud slurry into cracks created by subsurface burning or drill a series of holes into underground shafts, drifts, and slopes and pump in the slurry to smolder the flames. The surface is then covered with thousands of tons of soil to prevent oxygen from circulating back into the ground and rekindling the fire (Discover, 1999, Wingfield-Hayes, 2000). Surface fires are extinguished by burying burning coal under a one meter layer of soil (Discover, 1999) or by removing the coal and carrying it away by truck to an area in which it is flooded with water or community sewage (Vekerdy, 1999). Extinguishing all such fires, however, is cost prohibitive, and fires not likely to spread to nearby coal seams are sometimes allowed to burn (Prakash, 2003).

Atmospheric pollution in China, primarily from coal combustion, is among the highest in the world (Johnson et al., 1997). Acid rain from SO_2 and NO is a problem in 88 major Chinese cities and the problem has spilled over into Taiwan, Japan, Korea, and the Philippines (World Resources Institute, 1999, pp. 63–67; United Nations Development Program, 2000). The economic loss from burning coal resources in China alone is estimated to be as high as $125–250 million (U.S.) (Prakash, 2003). These problems are compounded by the rise of lung cancer, bronchitis, stroke, pulmonary heart disease, and chronic obstructive pulmonary disease in China linked to coal gas and particulate emissions; in some cases, directly linked to coal emissions from indoor cooking and heating (Johnson et al., 1997, p. 19; World Resources Institute, 1999, pp. 63–67). In Guizhou Province alone, over 10 million people have contracted arsenosis and fluorosis from eating foods such as corn and chili peppers dried over coal-burning stoves (Finkelman et al., 1999; 2001; 2002).

3.2. Pennsylvania, USA

Coal mining in Pennsylvania began in the mid-1700s in response to colonial America's demand for iron. Since then, Pennsylvania coal has supplied energy to the United States and countries abroad. This includes 60% of the fuel used to generate the state's electricity (Pennsylvania Department of Environmental Protection, 2001b). Although Pennsylvania ranks fourth at 6.7% of U.S. coal production after Wyoming, West Virginia, and Kentucky, more than a third of U.S. abandoned mine-related problems occur in Pennsylvania and coal fires are among the worst such problems (Piposzar and Jones, 2000; Pennsylvania Department of Environmental Protection, 2001b). Coal fires in Pennsylvania have been recorded since 1772 (Glover, 1998) but the first major fire occurred in 1869 when a ventilating furnace ignited wooden supports in the Avondale mine in Plymouth (Fig. 2), suffocating 110 men trapped below ground. Fortunately, the fire self extinguished about a year after attempts to put it out with water failed (Roy, 1876, pp. 134–137). Since the Avondale catastrophe, coal fires burning across Pennsylvania have destroyed floral and faunal habitats, consumed buildings, emitted toxic fumes into houses, contributed to respiratory illnesses, induced land subsidence over mine tunnels, burned precariously close to natural gas lines, and contributed to making Pennsylvania the leading acid rain producing state in the U.S. (Glover, 1998; Piposzar and Jones, 2000; Pennsylvania Environmental Network, 2003). According to data from The National Abandoned Land Inventory System of the Pennsylvania Department of Environmental Protection (2001c), there are currently 140 underground coal mine fires and 58 burning refuse piles in Pennsylvania (Fig. 2).

In Pennsylvania, coal fires have been fought using the slurry-flushing and surface-sealing techniques used in China. In some underground fires, mine tunnels have been sealed with brick, tile, cement blocks, or clay barriers to cut off the oxygen supply and reduce the risk of explosion (Glover, 1998; Pennsylvania Department of Environmental Protection, 2001a). Aqueous foam fire-fighting technology is currently under consideration (Pennsylvania Department of Environmental Protection, 2001b) as well as pneumatic injection of dry fly ash (Magnuson, 2003). Unfortunately, numerous underground coal fires in Pennsylvania are burning unchecked because they are elusive, unpredictable, and cost prohibitive to extinguish. One of the worst underground fires in the U.S. is the Centralia mine fire (Fig. 2), burning since May 1962 (Geissinger, 1990; Memmi, 2000).

The Centralia fire began when the Centralia Borough Council decided to burn trash to reduce the volume of and control rodents in an abandoned strip-mining cut used as an unregulated dump at the edge of town. Burning trash ignited anthracite in the Buck Mountain seam concealed behind the refuse and the fire spread along the seam to tunnels beneath Centralia (DeKok, 1986, p. 20; Geissinger, 1990; Memmi, 2000). Between 1985 and 1991, the U.S. Congress appropriated $42 million for Pennsylvania to relocate the 1100 residents of Centralia and its businesses. About 20 people, mostly in their 60s or older, are left in a town and its environs damaged by toxic gases, subsidence, smoke filled valleys, polluted streams, scorched woodlands dusted with sulfur, highways cracked by temperatures as high as 455 °C, surficial fires induced by heat from subsurface burning, and an underground fire that may burn for another hundred years (Memmi, 2000; Schogol, 2001). Because of deteriorated living conditions and the state's declaration of eminent domain in 1992, these people, now living in a town with an unmanned firehouse, may be forced to relocate (Schogol, 2001).

The Percy mine fire in Youngstown, Pennsylvania (Fig. 2), has been burning underground for over 30 years. Like the Centralia fire, it apparently started when people ignited trash near a coal seam. Although fly ash has been used to plug conduits to the fire, the town also appears to be destined for the same fate as Centralia, with an estimated cost of $30 to $40 million (U.S.) necessary to extinguish the fire. Neither the state nor federal government has offered to extinguish the fire or relocate the town's residents, whose homes are worthless (Glover, 1998).

3.3. Bihar, India

Commercial coal mining in India began in 1774. Production was at first slow, but it increased with the advent of steam locomotives in 1853 (Ministry of Coal and Mines, 2003a). In order to improve safety standards and develop coal resources judiciously, coal mines were nationalized between 1971 and 1973 (Bharat Coking Coal Limited, 2003; Ministry of Coal and Mines, 2003a). Consequently, ninety percent of Indian coal is currently mined by subsidiaries of Coal India Limited, a holding company headquartered in Calcutta (World Bank, 1997; Ministry of Coal and Mines, 2003b). Singareni Collieries, co-owned by the state of Andra Pradesh and the central government of India, in addition to privately owned companies, mine the remaining 10% (World Bank, 1996; Ministry of Coal and Mines, 2003a). Today, India is the third largest coal-producing nation in the world. Two-thirds of its energy requirements are supplied by coal, 77% of which is used to generate electricity (Table 1). The remainder is used to produce steel and as boiler fuel in industrial plants (World Bank, 1997).

Fires have beset Indian coalfields since the earliest days of mining (Sinha, 1986; Bharat Coking Coal Limited, 2003). Surface and subsurface fires burning throughout the Jharia coalfield (JCF) (Fig. 3) comprise one of the largest coal mine-fire complexes in the world (Gupta and Prakash, 1998; Western Pennsylvania International Business Newsletter, 1998). The JCF is located in the Dhanbad district, north of the Damodar River, in the state of Bihar. It is the largest coalfield in India and the country's primary source of coking coal (Gupta and Prakash, 1998; Prakash and Gupta, 1998). Mining in the JCF began in 1894, and the first coal fire broke out at Bhowrah in 1916. By the 1960s, numerous fires spread throughout the entire coalfield, with flames locally reaching heights of 20 m (Bharat Coking Coal Limited, 2003). Today, about 70 fires are burning in the JCF (Pennsylvania Department of Environmental Protection, 2001d; Bharat Coking Coal Limited, 2003; Fig. 4).

Most fires in the JCF were ignited by the spontaneous combustion of coal subsequent to opencast and deep mining. Exploitation without fire-prevention codes prior to nationalization was responsible for these fires (Bharat Coking Coal Limited, 2003). In addition, the illegal distillation of alcohol in abandoned underground mines is purported to be the origin of some JCF fires (Stracher et al., 2002). At present, approximately 37 million tons of coal has been lost to JCF fires and approximately 1453 million tons are locked up under fire (Bharat Coking Coal Limited, 2003).

As in China and Pennsylvania, JCF fires are responsible for environmental degradation and human suffering. Noxious vapors and toxic fly ash that pollute air, water, and soil promote human disease including lung and skin as well as asthma and chronic bronchitis. In addition, land subsidence, endangered and inoperable rail lines, displaced communities of people, increased mining hazards, overburden dumps, the destruction of floral and faunal habitats, and the loss of coal as a valuable resource are products of these fires (Saraf et al., 1995; Gupta and Prakash, 1998; Sierra Club, 2003; Bharat Coking Coal Limited, 2003). According to the National Center for Atmo-

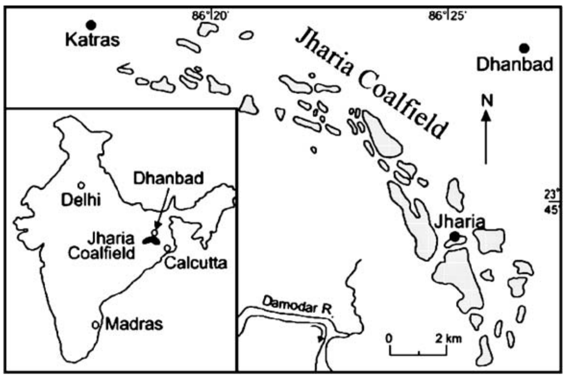

Fig. 3. Coal fires burning across the Jharia coalfield, India. Courtesy of Anupma Prakash et al. (1997).

Fig. 4. Coal fire in an exposed seam (left) in the Jharia coalfield, India. Excavated material (right) is backfilled to seal goafs (openings) left after mining. Smoke is high in particulate matter as well as oxides and dioxides of nitrogen, carbon, and sulfur (Stracher et al., 2002). Courtesy of Anupma Prakash, Geophysical Institute, University of Alaska, Fairbanks.

spheric Research in Boulder, Colorado, JCF fires contribute to atmospheric sulfate aerosols derived from industrial emissions. These aerosols absorb or scatter solar radiation, thereby reducing the amount of sunlight that reaches earth's surface. This amounts to as much as a 15% reduction for the Indian subcontinent (Collins, 2000; Perkins, 2001).

Several forms of technology have been used to investigate JCF fires. Multi-spectral and temporal data from the Landsat Thematic Mapper (TM), for example, reveal that subsurface fires are more extensive than surface fires (Prakash et al., 1997). Surface thermal anomalies (25.6–31.6 °C) detected with TM-6 thermal infrared data signify subsurface fires at depths of 45–55 m (Saraf et al., 1995; Prakash et al., 1997). Alternatively, subpixel corrections for TM-5 and TM-7 short wave-infrared data reveal surface fires ranging in temperature from 342 to 731 °C. IR pointing thermometers and ground-based thermal detectors confirm such surface fire temperatures (Prakash and Gupta, 1999). In addition to remotely acquired TM data, Bharat Coking Coal Limited (2003) has integrated GPS data into a Geographic Information System (GIS) to locate, map, and monitor surface fires, ground subsidence, and borehole temperatures.

In the JCF, the population density is much higher than in the coalfields of northern China (Prakash, 2003), thereby necessitating the relocation of large communities of people from endangered regions to newly constructed townships in non-coal producing areas. Fortunately, the Ministry of Coal and the Government of India have provided relocation funds for this purpose (Bharat Coking Coal Limited, 2003).

Once highly problematic coal fires in the JCF are identified with the available technology, a number of techniques are used to contain or extinguish them. For surface fires, these include trenching, analogous to a forest firebreak, and surface sealing with soil or some other non-combustible material to cut of oxygen from the fire. Inert gas injection, sand-bentonite slurry flushing, and surface sealing have been used for subsurface fires. In spite of the success with these techniques, the fires continue to burn in large areas where subsidence and inaccessible underground workings present a high risk and impasse to fire fighters (Bharat Coking Coal Limited, 2003).

4. Conclusions

Regardless of origin, coal fires consume a valuable natural resource and constitute a thermodynamic recipe for environmental catastrophe. Fires in China, Pennsylvania, and India exemplify this. Industrial smokestacks and motorized vehicles are usually cited in the news as the primary sources of pollution including acid rain and greenhouse gases. The enormous amount of toxic gases and particulate matter emitted by coal fires burning around the world over many years contribute significantly to the global destruction of the environment and the health of its inhabitants. However, little media attention has focused on these devastating fires. The overall effects of coal fires on the earth's atmosphere, hydrosphere, biosphere, geosphere, and cryosphere are worthy of intense study because of their sizeable contribution to the myriad environmental pollutants induced by human activities.

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