INVESTIGATION OF THE JHARIA COALFIELD MINE FIRES - INDIA[1]

by

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Abstract. In 1971, the Indian coal industry was nationalized and Bharat Coking Coal Limited was formed. The new company inherited about 600 poorly operated collieries, many on fire. Efforts to extinguish the fires have been partially successful. About sixty-five fires continue to burn in the 450-sq. km. coalfield. This is the largest complex of above and underground coal fires in the world. The fires have spread and grown to affect coal production, the environment and the health, safety, and well being of one million people living in the region. A 21-month long, two-part study, funded by the World Bank, began in 1994 and was completed in 1996. Part one was an analysis of the fires which included, their location, size, impact on the community, physical environment and coal reserves and possible remediation measures and their cost. Part two included an environmental and socio-economic survey of the coalfield and environs and the impact of implementing remediation measures. The investigations included the use of satellite and airborne remote sensing platforms, a Global Positioning System for surveying, drilling, software for mine planning and development, a field reconnaissance, laboratory testing, review of colliery records and data analysis. A counterpart staff of Indian professionals worked with the expatriates to acquire the training, procedures and methodologies required to continue the work. Technologies for extinguishing, containing and preventing fires and their cost were identified. Recommendations were made to extinguish or contain the fires.

Additional Key Words: coal, coal fire, mine fires, India.

Introduction

The Jharia Coalfield lies in the State of Bihar in northeast India, about 260 km. northwest of Calcutta. The arcuate coalfield, measuring about 40 km. in length and 12 km. in width, occupies an area of nearly 450 sq. km. of which Bharat Coking Coal Limited (BCCL) operates a leasehold of about 258 sq. km. (57 percent of the coalfield). Tata Iron and Steel Co. (TISCO) and the Indian Iron and Steel Co. (IISCO) hold another 32 sq. km., with industrial, forest, and agricultural areas comprising the remainder (Prasad 1989, Bharat 1991 and Sinha 1989). Towns, villages, and settlements are numerous throughout the coalfield.

Uncontrolled coal fires reportedly began in the Jharia Coalfield (JCF) in 1916, about 26 years after the start of mining (Munshi 1995). Most of the fires are reportedly caused by spontaneous combustion, resulting from poor mining practice, the nature of the coal deposits and the apparent susceptibility of the coal to self heating (Munshi 1995). Despite the efforts of independent operators before nationalization of coal mines (1971-73), and government sanctioned efforts following nationalization, new fires appear and many existing fires continue to expand (although a few fires have been extinguished and others greatly reduced in size). The JCF contains about one half of all the reported coal fires in India (Saxena 1995). Of the approximately 65 fires reported to be active, many have coalesced into much larger fires engulfing adjacent coal seams and collieries resulting in a staggering loss and isolation of coal reserves (Figure 1). The fire effects, including ground subsidence, have produced unprecedented havoc; loss of life, property and productivity of the land surface and disruption of the lives of people in the coalfield.

To date the fires have: 1) affected half of about 90 collieries, 2) affected over 17 sq. km. of the coalfield, 3) consumed 40 million tons of coal, and 4) isolated from recovery 1.45 billion tons of coal. BCCL currently supplies about 40 percent of the nations coking coal

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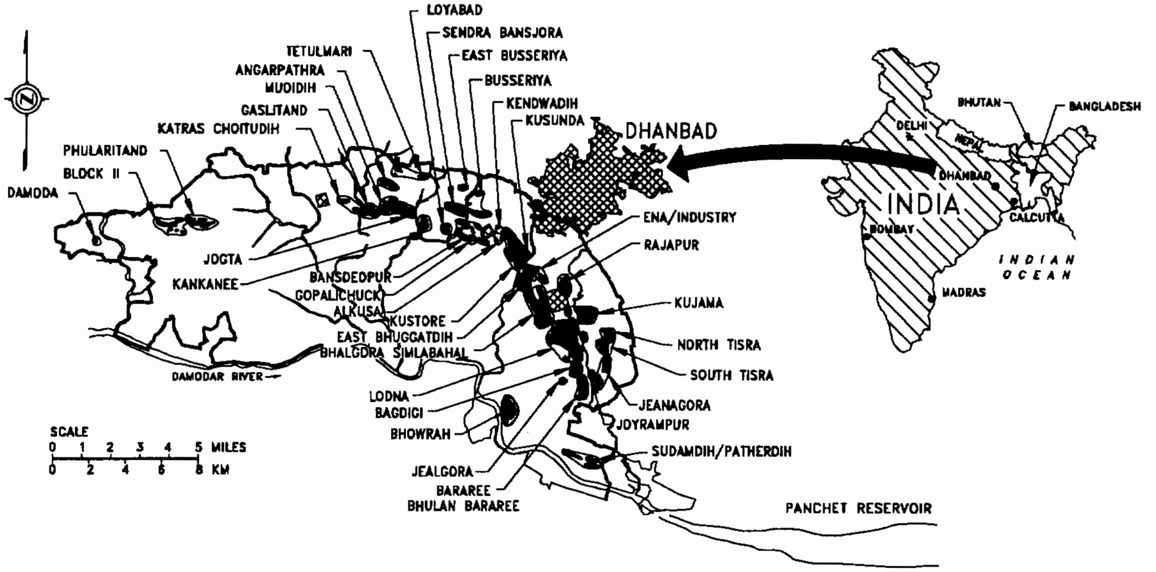

Figure 1. Plan of Jharia Coal Field

requirement or about eight million tons per year. Of the balance, about 23 percent is imported and 37 percent is mostly medium grade coking coal from other coalfields in India. The JCF is India's only source of prime coking coal.

The JCF contains as many as 46 coal seams averaging 4.5 m thick, but, locally, up to 55 m in thickness (Munshi 1993). It has one of the highest concentrations of thick coal seams in the world (Fox 1930). About 25 seams account for most of the coal mined. In ascending order, seams 1 through 8 produce boiler fuel whereas seams 9 and higher are best suited for coking purposes. Most of the fires are contained in the uppermost or coking coal seams in the eastern half of the coalfield (Figure 2). Most of India's coking coal reserves are contained in these seams. If the fires are left unabated, coal production is likely to dwindle until mining in the coalfield is abandoned.

The enormity of the problem and the impact on the economy of India and the health and safety of the local population justified an assessment to determine the extent of the fires, their rate and direction of propagation, potential effects in both the short and long term on continued coal production, and to identify abatement alternatives for extinguishing, controlling and preventing the fires.

Objectives

Immediate or short term objectives include reducing threats to the health and safety of people, infrastructure and waterways, and mitigation of certain social and environmental issues. In the former case, threats to the stability of public railroad lines and the potential collapse of perennial waterways is of first concern. Before fire abatement plans can be implemented, social and environmental issues must be resolved. These issues include: resettlement, the disposition of infrastructure, environmental quality (air, water and land), and mined land reclamation including restoration of farming potential.

The long term objective is to preserve the JCF coking coal reserves. Coking coal is required by the nation's steel industry which must resort to importation when domestic coking coal is unavailable. Substantial reserves of coking coal are actively burning, isolated from exploitation by fires or threatened to be isolated or consumed by fire. Coal fires have spread both laterally and vertically through adjoining mines and adjacent coal seams despite efforts expended to impede their progress. This situation has led to reduced production resulting from the mine fires. Importation of coking coal at world market prices is financially crippling to the beleaguered economy of India. Solutions to this problem include fire

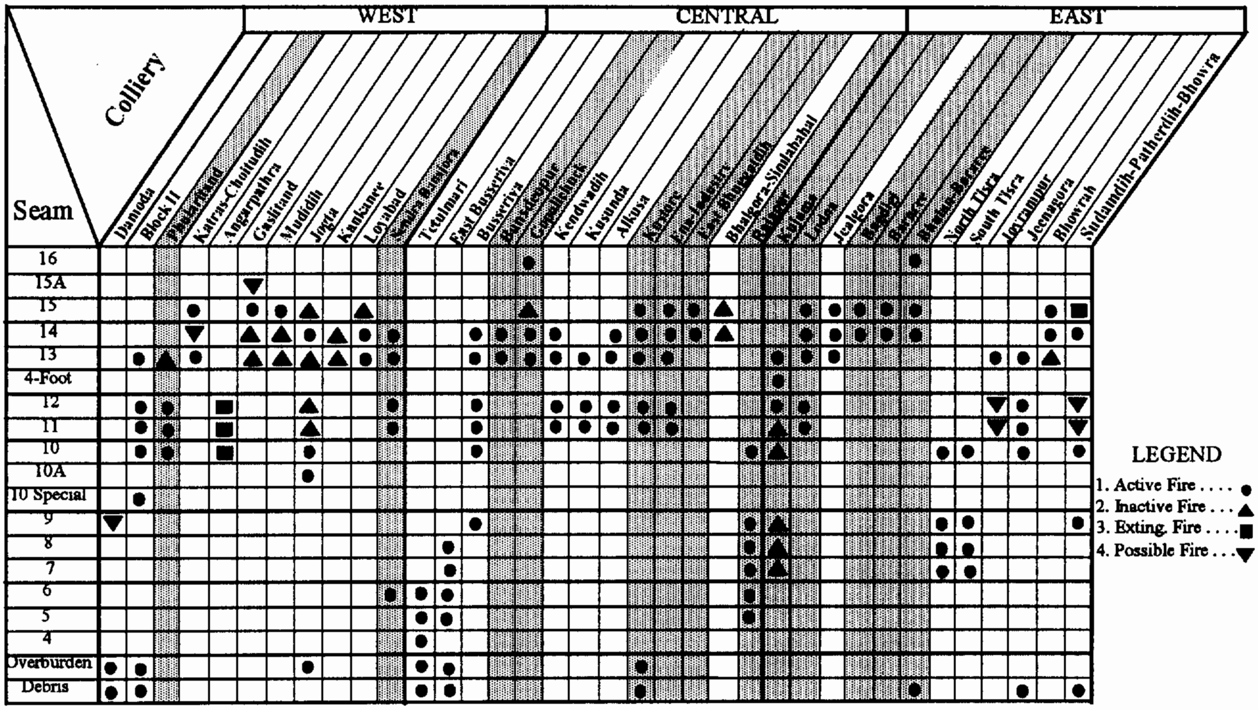

Figure 2. Matrix of Fires

extinguishment, fire abatement and control, fire prevention and fire management. Such solutions were considered within the context of available technologies, including power and equipment, that can be deployed in the JCF.

Cause of Fires

The origin of most coal mine fires in India is reported to be the result of spontaneous combustion. Although the coals of the JCF are not as susceptible to spontaneous combustion as some other coals in India (Banerjee 1985), irresponsible mining practice prior to nationalization resulted in enhancing self heating of the coal. Large volumes of fragmented coal in thick seams, crushed pillars, poor ventilation and surface subsidence fractures resulted in conditions ideal for spontaneous combustion to occur. A study conducted by the Central Mine Planning and Design Institute Limited (CMPDIL) of nearly one hundred fire sites in India resulted in identifying spontaneous heating as the cause of about 67 percent of the fires. About 33 percent were attributable to some form of neglect, accident or design (Malhotra 1989).

Activities and Findings

This paper addresses the activities and findings of Part One, Fire Fighting Programme, which was conducted by a joint venture of GAI Consultants, Pittsburgh, Pennsylvania, USA and MET-CHEM Canada, Inc. of Montreal, Canada. The joint venture was formally known as the GAI/MET-CHEM Joint Venture. Part Two, an Environmental Programme, was conducted by NorWest Mine Services Limited, Salt Lake City, Utah, USA. Some of the activities described below overlapped both parts of the investigation. The activities included were selected on the basis of experience and usefulness in the analysis of large, complex underground coal mine fires elsewhere in the world (Michalski 1990).

A wide range of activities, some conducted concurrently, provided the basis from which to develop fire abatement procedures. The principal activities included: 1) Review of Existing Data, 2) Field Reconnaissance, 3) Topographical Mapping, 4) Remote Sensing (Satellite), 5) Airborne Thermal Infrared (TIR) Survey, 6) Colliery Interviews, 7) Borehole Drilling, 8) Monitoring Borehole Temperatures and Gasses,

9) Geological Modeling, Mine Planning, 10) Fire Abatement Measures and 11) Technology Transfer. A summary of findings under each of these headings is presented below.

Review of Existing Data

Colliery mining reports cover a range of topics including colliery location, access, land use, and a history of mine operation. Geology is presented with emphasis on exploration, coal seam data, in situ coal quality, and marketability of the coal. Colliery reports also include reserve estimates, production targets, mining development strategies, mine scheduling, mining methods and the projected remaining life of the mine. The location of fire and its potential impact on mine planning and fire abatement efforts were described when applicable.

Geological reports normally cover a portion of the coalfield described as a block. The size of the block may be limited by leasehold boundaries, faults, dykes and coal seam outcrops. The exploration phase of the evaluation of the block's potential includes surveying, geological mapping, and exploratory drilling. Information on geological structure, the number, thickness and continuity of the coal seams, and the extent and location of mica-peridotite intrusive dykes is also included. These data were then used to estimate the range of coal seam thickness, the location and displacement of faults, and the quantity and location of jhama (coal coked in situ by igneous intrusions).

The colliery mining and geological reports were examined to determine the thickness, quality, areal extent, and potential quantity of mined and unmined coal reserves prior to establishing a borehole drilling programme.

Other documents reviewed included engineering reports on proposed fire abatement projects and investigations, proposed fire control measures and many professional papers produced over the years.

Field Reconnaissance

The Global Positioning System (GPS) consists of ground based units which receive information from 24 satellites to locate specific features on the ground surface. The satellites operate under the auspices of the United States Department of Defense, who scramble satellite signals for security reasons. This scrambling results in limiting the system to 100 meter accuracy. By reading the distance and bearing from four or more satellites, the ground based units calculate the approximate position in latitude/longitude and elevation above datum. Use of a base station of known location, enabled operators to use computer software to calculate the lateral position of ground surface features to within approximately 10 cm. +/-. GPS post-processing software reduced the received data and generated maps of the ground surface showing the features located by the GPS roving units. A fully operational GPS system was in place before conducting the field reconnaissance.

A coalfield-wide reconnaissance was conducted in July and August 1995, and sporadically through to the end of the project in June of 1996. This effort provided data on the past position of surface fires, salient fire features and effects not detected by the TIR and data on the location of infrastructure, waterways, community and environment impacted by the fires.

Location and elevation of topographical features including boreholes, surface fire features (fissures, subsidence zones, elevated temperature anomalies), physical features (roads, railroads, streams which had changed over time), were obtained with the GPS equipment and added to the topographical database. The GPS automated data acquisition and maintained compatibility with other aspects of the project.

Topographical Mapping

Existing mapping in the JCF was not current or of appropriate scale to produce the best results for the western one third of the coalfield. Nevertheless, the Survey of India topographical maps (1:4000 scale) prepared in 1981 - 1983 were manually digitized or scanned into computer files to serve as the basis for the elevation contour background appearing on report maps and drawings. These topographical maps are based on latitude and longitudes in Everest 56 Geoid. For the remainder of this project, the Indian National Remote Sensing Agency (NRSA) prepared electronic topographical map files to provide the basis for the background elevation contour and surface features appearing on report maps and drawings. These digital topographical maps were also based on the Everest 56 Geoid, but updated on the basis of 1995 aerial photography and printed at a scale of 1:25000. These base maps were used to depict data from the TIR survey, reconnaissance, drilling and mine planning activities. These data were combined electronically to provide a uniform presentation (Figure 3).

Mining in the JCF left a legacy of various co-ordinate systems for exploration and mining. Each exploration drilling campaign had a different origin and

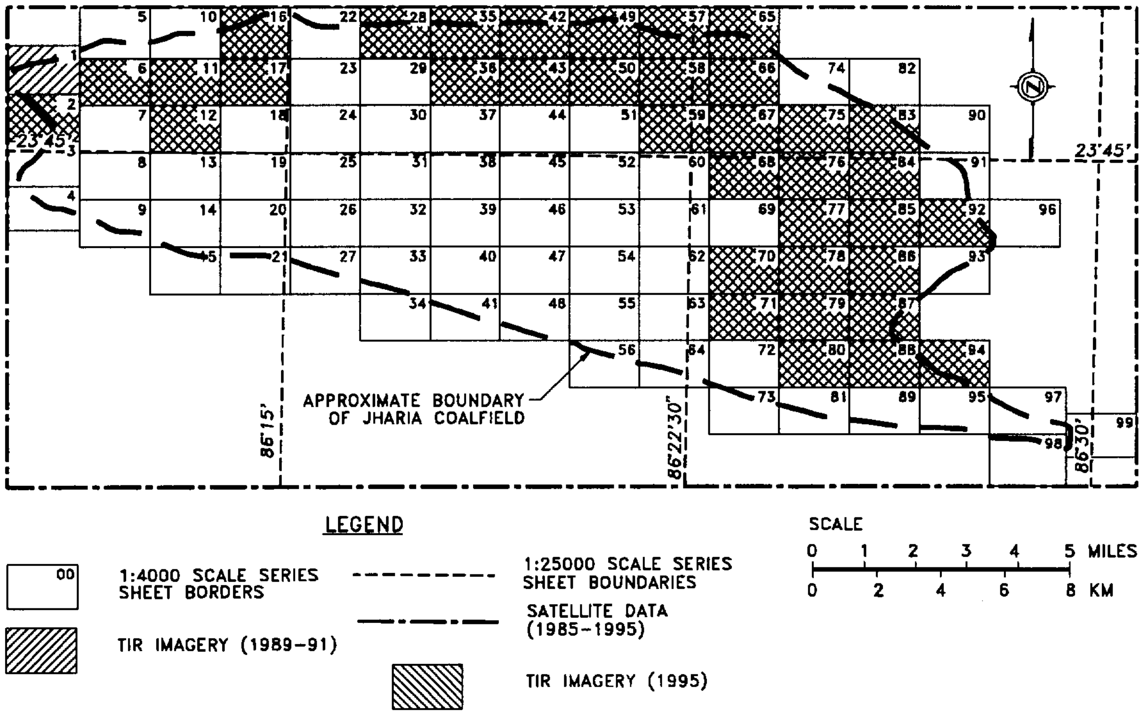

Figure 3. Index to Mapping

North direction, as did every colliery engaged in mining. Currently, it is BCCL's policy to convert all surveying to a standard grid. At present 19 collieries, and 3 CMPDIL report areas have been converted to a standard referred to as the Jharia Grid. All computerized geological models and topographical sheets used on this project have been converted to Jharia Grid.

Remote Sensing (Satellite)

Space based remote sensing utilizing the Thematic Mapper (TM) onboard Landsat-5 was used to observe ground surface heating and to determine fire spread throughout the coalfield between the years 1985 through 1995. The NRSA analyzed and compiled TM data, and submitted a summary report to BCCL in March 1995 NRSA 1995. A geographic information system was used to calculate the area of surface heating over the coalfield. Due to inherent low resolution, the data were most useful in presenting an overview of the fire problem. Such data can continue to be easily and inexpensively acquired periodically for comparison purposes. The results of this analysis showed a 56 percent reduction in fire area between the years 1991 and 1995 (Table 1).

Table 1
Jharia Coal Field Fire Area (1985-1995)[1]

YEAR	FIRE AREA[2] (Sq.km)
1985	5.57
1987	8.82
1989	14.50
1991	15.92
1993	8.79
1994	8.48
1995	8.92

Note: 1) Based on Landsat 5, Thematic Mapper (Thermal IR Band).

2) Pixel area temperature above 45 °C

This reduction in observed active fire is likely the result of reclamation and sealing of the mined surface over some of the fires. Fire activity also appears to decline as surface mining activity declines. Other possible factors may be the result of fires moving deeper underground and being less active at the surface and attenuation of the TM data by airborne dust which is evident in the visible bands.

Airborne Thermal Infrared (TIR) Survey

Airborne TIR imagery is a process where a low flying aircraft scans the subject area in the pre-dawn hours with an on-board thermal infrared scanner. The TIR product is a pictorial representation of temperature differences between objects at ground surface presented on a photographic medium. TIR primarily highlights an underground mine fire in areas where heated gases escape at the ground surface. These "hot spots" may be somewhat distant from the actual heat source, but interpreted in the context of the local geology, outcrop location and pattern, dip of rock, etc., can indicate the general source area for the escaping heat.

NRSA performed two aerial pre-dawn TIR mine fire mapping missions over the JCF utilizing an advanced Airborne Daedalus Thermal Infrared Digital Scanner.

First Mission. In February 1989, the Jharia Coalfield was scanned with the Daedalus scanner, and black and white aerial photography made at the same time, was used to update existing 1:4000 scale topographic maps (NRSA 1992 and Figure 3). Although all of the JCF was scanned during this survey, only a small area in the eastern side of the coalfield was selected for detailed study (Bhattacharya 1994). Studies with the data were developed at this time to develop procedures to detect and determine the depth of subsurface fires (Mukherjee 1991).

Second Mission. The second TIR mission was flown in March 1995 (Figure 3). This mission was performed in three concurrent phases. Phase I required the preparation of 1:50000 scale mapping utilizing satellite based TM data and Phase II required the preparation of mine fire maps at a scale of 1:4000 scale utilizing airborne TIR scanner data (NRSA 1996). Fire areas depicted to be radiating heat on the TIR images were transferred to the work plans. These areas were planimetered. Phase III required preparation of selected maps at the 1:4000 scale of the 1989 TIR data (first mission) (Figure 3). This 1989 data was not available in the early stages of the project, but did become available later on. Technical problems resulting from the use of older or different hardware and software resulted in some data corruption. Nevertheless, most of the 1989 TIR data was useful for comparison purposes with 1995 TIR data, to determine the rate and direction of fire spread.

Data processing and analysis of the 1995 and 1989 TIR data sets resulted in the production of 74, 1:4000 scale geocoded (gray scale) image maps. These maps were the basis for planning the drilling campaign, reconnaissance survey and fire analysis (Figure 3).

The data was used to determine the rate of fire expansion or contraction between 1989 and 1995, where possible. Fire areas as reported by BCCL were planimetered from existing maps and colliery plans to show fire area in the past. Similarly, fire perimeters based on drilling, TIR and reconnaissance were also planimetered to show current fire area. A comparison of both data sets indicated the fires to be in various stages of development. Some are contracting both on the surface and underground whereas others are stable or very rapidly advancing. A 25 percent reduction in fire area between 1989 and 1995 was determined by this comparison. These findings were further corroborated by the drilling and reconnaissance programs.

Colliery Interviews

Interviews with BCCL staff members included colliery general managers, project officers, safety officers and surveyors and were made prior to and during the planning and execution of the drilling program. The focus of the interview was to obtain current information on the state of the fire for each fire area investigated. This information included mine level temperatures, gas analysis and water levels, among others and recorded on a standard form. Colliery personnel reviewed selected drilling positions which might better define the current fire position. Colliery surveyors were also enlisted to verify that proposed boreholes sites could be drilled at the planned locations.

Borehole Drilling

Non-sampled drilling was performed to assess subsurface conditions in the seams where burning was reported by colliery personnel. The objective was to determine subsurface conditions and provide more or less permanent monitoring points to periodically sample mine level air temperatures and gases. Borehole data provided site specific subsurface information to aid in mine planning, plotting fire perimeters and, over the longer term, the direction and rate of fire propagation.

Borehole locations were selected after review of available geological and colliery data, a preliminary site reconnaissance and following numerous consultations with various colliery personnel. Data for existing fire boundaries were supplied by the individual collieries, including the location of underground stoppings in the mine workings. Historical temperature, gas analyses and mine pool elevation data were collected, where available.

Boreholes were located outside reported fire boundaries for monitoring the rate and direction of movement of the fire. Several boreholes encountered fire or evidence of fire during drilling, indicating some of the fires have extended beyond the estimated perimeters. Six hundred thirty one non-sampled boreholes were drilled with a total of 33,531 lineal meters of drilling.

Sampled core borings were drilled to: 1) resolve stratigraphic anomalies encountered during the drilling program, 2) to permit physical examination of the strata, and 3) to provide accurate thicknesses of overburden, interburden, and the seams. These data were useful in the mine planning and consideration of fire abatement options. Ten core borings were drilled with a total of 757 lineal meters of drilling.

Monitoring Borehole Temperatures and Gasses

The analysis of the JCF fires was augmented by the collection of mine level gasses and temperature data in conjunction with remote sensing and visual observations at ground surface.

Temperature Testing. Borehole temperature data was collected with the use of temperature sensing probes (thermistor and thermocouple) that were lowered down a borehole. More commonly, a temperature profile was created for most boreholes with a portable ANSI Type K: Chromel/Alumel thermocouple. Temperature measurements were recorded at 1.5 meter intervals (minimum) beginning at the ground surface. Other pertinent data included whether the borehole was drawing (sucking) or venting (blowing) air, steam, smoke, or odors of combustion, and depth to water, if present. Three sets of data were obtained from most of the boreholes to determine if fire was present, advancing or retreating from a particular borehole location. A truck mounted thermistor, provided by CMPDIL, was used to speed data acquisition, particularly from the cold boreholes. This instrument provided a continuous analog temperature profile beginning at the ground surface, and extending to the bottom of the borehole. A portable digital thermistor was also periodically utilized, recording temperature data at 1.0 meter intervals. A severe limitation of the thermistor temperature sensor is that insertion into a hot borehole will damage the instrument. Technicians using this instrument therefore, tend to avoid boreholes known to have above normal temperatures. This results in few or no high temperature readings. Analog plots of thermistor data were prepared by CMPDIL and manually digitized to the same format for presentation purposes.

The spacing between boreholes was insufficient to prepare contour diagrams of mine level temperatures or other indices. Nonetheless, sufficient data was collected to infer the locations of burning zones in the respective coal seams and plot fire perimeters.

Gas Testing. The composition of the mine atmosphere can change with time. Roof falls and other ground adjustments may redirect air flow so as to dilute or drive off blackdamp from areas where flaming combustion cannot occur. Reactions, some subtle, others violent, may chemically alter the constituents of the mine atmosphere. Like temperature, the composition of the mine atmosphere is transient and must be monitored on a regular and periodic basis.

Gas sampling was performed at the top of the boreholes and testing for mine fire gasses was performed by local laboratories. The gas sampling and testing programme did not yield significant findings. This conclusion was based on: 1) the relatively few number of boreholes at each fire site, 2) the wide spacing between boreholes and 3) insufficient sampling frequency to determine trends. The gas analytical data did not influence the conclusions and recommendations of this study.

Geological Modeling, Mine Planning

Mine modeling and planning was done with microLYNX mine planning software, utilizing stratigraphic information from CMPDIL and data gathered during the present study. Geological modeling evolved into the development of preliminary mine planing that evaluated the open cast mining potential of coal reserves, and the impact the fires have on this mining potential. Preliminary mine plans were developed evaluating the nine most promising open cast and underground coal blocks. Results of the geological modeling and mine planning indicate five potential opencast mines. Their development does not impact immediate fire control options, although eventual excavation of the fires within their ultimate quarry boundaries would be required.

Geological reserves blocked by fire are remaining coal in developed and in undeveloped portions of the seams that lie beneath a seam fire. Most of the coal that is burning is in developed or goafed areas. Underlying seams that fall within the zones of influence of the fires are blocked from mining until the fires are extinguished. This coal is considered inaccessible by current mining practice. A detailed calculation utilizing microLYNX software was performed to estimate the geological reserves blocked by fire. The results of this calculation show a total blocked reserve of 1.45 billion metric tonnes.

Extinguishment releases blocked coal for mining -- by excavation, in a relatively short time period (3 to 5 years), and by surface sealing or flooding, in a considerably longer time period (perhaps 25 to 100 years). Clearly, any mining project to be conducted in the near future must achieve extinguishment by excavation. Containment (isolation) of a fire without extinguishment releases no blocked coal, but does protect coal reserves laterally adjacent to the fire.

Underground coal gasification technology may allow blocked reserves to be exploited before surrounding fires are fully extinguished. or possibly without their having to be extinguished (Singh 1985). This method merits further consideration as an energy recovery method in the JCF.

Fire Abatement Measures

Possible fire control, abatement and extinguishment procedures include conventional techniques (excavation, surface sealing, etc.) and other techniques (water curtains, inert gasses, cryogenics, etc.) Conventional techniques are tried and proven technologies that require state-of-the-art equipment, procedures and methodology to be successfully implemented and environmentally sound. A mix of available technology, deemed appropriate to existing conditions in the JCF, was considered in developing fire abatement options. Options were prioritized on the basis of: 1) the health, safety and general welfare of the population, 2) the physical environment, 3) the existing infrastructure where deemed non-relocatable, 4) the existing mining of an area, and 5) the remaining coal reserves.

Technology Transfer

To maintain continuity following the close of the current investigation, a permanent fire management and investigation office consisting of BCCL and CMPDIL engineers, geologists and technicians was established. The high technology equipment, investigatory procedures and methods were transferred to the group which can continue to conduct fire investigation, abatement and mining activities more efficiently.

Summary

Fire Statistics

Statistics from the present study attest to the considerable number and extent of fires on BCCL properties. ('Fire' in the present context refers to burning conditions that occupy a portion of a colliery site and involve one or more coal seams, overburden strata and/or overburden debris. The majority of colliery sites have more than one fire, and the majority of fires involve more than one coal seam.)

Number of Fires Project-Wide. Sixty-five fires have been identified within the project area. (This number is based on a tally of groups of burning coal seams in accordance with the definition in the previous paragraph. Alternative tallies yield other fire counts. Approximately 135 fires are identified project-wide if all burning areas of each coal seam are counted; approximately 85 fires, if individual "hot" spots appearing on the TIR and fire perimeter maps are counted; and approximately 50 fires, if preferred fire control/abatement options are counted. In the last-mentioned case, contiguous and/or interrelated fires are grouped together and treated as larger composite fires.)

Geographic Distribution. Eighteen of the fires are in the western half of the coalfield whereas 47 fires are in the eastern half.

Frequency of Occurrence by Colliery. Only about one-third of the collieries (12) contain a single fire. The remaining two-thirds contain two to four fires each (15 collieries, two fires; 5 collieries, three fires; and 2 collieries, four fires).

Fire Type. The great majority of fires (56 of 65, or 85 percent) involve a series of burning underground coal seams partially exposed in open pits (quarries). Of these, at least five include burning overburden strata, and three, burning overburden debris. Three additional fires involve debris only. The fire is extinguished at one of the six remaining fire sites and dormant at the other five.

Number of Coal Seams. About one-third of the fires (22) involve a single coal seam and the remaining fires, two to six seams each (19 fires, two seams; 13 fires, three seams; 5 fires, four seams; and 2 fires, six seams).

Coal Seam. Stratigraphically, the fires span the interval from the 4 seam to the 16 seam. Two-thirds of the fires lie wholly or largely within the interval from the 11 to the 15 seam. The fires are primarily in the upper seams that contain coking coal.

Areal Extent at Ground Surface. Individual fires occupy areas in plan (map view) from 0.007 to 1.79 sq. km, and average 0.29 sq. km (neglecting those fire sites where no burning is seen at ground surface).

Aggregate Burning Area at Ground Surface. Taking all fires together, active burning conditions extend over 9.4 sq. km. This is the sum total ground surface area over which fire has been observed (1995) and approaches four percent of BCCL's leasehold.

Maximum Depth Below Ground Surface. Individual fires extend to maximum depths of 15 to 140 meters below ground surface, and average a maximum depth of 50 meters.

Fire Spread. Over time, the majority of fires have migrated and changed in size. Comparison of the 1989/1991 TIR imagery with that of 1995 shows that for the 34 collieries for which data were available, the fire area decreased in 27 cases (79 percent), increased in 6 cases (18 percent), and did not change in one case (3 percent).

Where the fire decreased in size, it reduced, on average, to about half the area occupied in 1989/1991. Where the fire increased in size, it doubled in area, on average.

These data suggest that a number of fires might shrink sufficiently and are manageable with only limited intervention. Although the TIR fire areas reflect only ground surface manifestations of burning conditions while the seam area on fire reflect burning conditions in all seams at depth, the trends are similar and bear further watching and evaluation.

A comparison of the BCCL seam area on fire (generally from the 1980's) with those in 1995 shows that for the 35 collieries for which data were available, the seam area on fire decreased in 26 cases (74 percent), increased in 8 cases (23 percent), and did not change in one case (3 percent). Where the seam area on fire decreased in size, it reduced, on average, to 34 percent of its earlier value. Where the seam area on fire increased in size, it expanded, on average, by about half.

Fire Impacts. Fires at twenty-three collieries jeopardize villages; at twelve collieries, water ways; at eight collieries, railroad rights-of-way; and at four collieries, main roadways. (Fires at eight of these collieries jeopardize more than one entity, e.g. both a stream and a village.)

A systematic evaluation of fires at the 36 collieries on the basis of type, size, location and activity of burning, site conditions, and apparent threat to human life/infrastructure has involved determining: 1) where the fire resides in the earth both vertically and horizontally; 2) the directions and pathways through which it might travel; 3) the geologic/mining/site features, such as mine pool or barrier pillar, that would contain the fire; 4) the surface features (water ways, railway lines, villages) that might be impacted by the fire; and 5) the anticipated effectiveness of the technical option in meeting its objective.

This analysis determined the following conditions for each fire site: 1) Fire Status -- whether extinct, dormant, or actively burning; 2) Urgency of Implementation -- whether or not (a) immediate action is warranted to avert a disaster caused by the mine fire itself or the conditions it has produced, or (b) a potential future threat exists over the long term; and 3) Appropriate Fire Control Measures -- a selection of the most promising options to achieve containment or extinguishment. Each of these three categories is summarized below.

Fire Status

The fire status is based on the observed conditions at each colliery during the period of active investigation and temperature monitoring.

- One fire has apparently expired *(**Angarpathra**)*.
- Five fires are inactive: (***Gaslitand***, one of two fires; ***Kankanee***, one fire; ***Gopalichuck***, one of two fires; and ***Bhalgora-Simlabahal***, two fires).
- Fifty-nine fires are actively burning.

Urgency of Implementation

Emergency conditions at thirteen sites warrant *immediate* action due to a threatened passenger railway line, stream, or village.

- ***Phularitand (Block III)*** -- Threat to stability of Adra-Gomoh passenger railway line.
- ***Sendra Bansjora*** -- Threat to stability of Ekra Jore channel (a water way).
- ***Bansdeopur*** -- Threat to town of Kirkend.
- ***Gopalichuck*** -- Threat to populated area and stability of Ekra Jore channel.
- ***Kustore (SE)*** -- Threat to populated area and roadway.
- ***Ena*** -- Threat to stability of Kari Jore channel.
- ***East Bhuggatdih*** -- Threat to adjacent Jharia town and populated area.
- ***Rajapur*** -- Threat to Jharia Town and populated area and roadway.
- ***Kujama*** -- Threat to Jharia Town and populated area.
- ***Lodna*** -- Threat to Jharia Town and populated area and stability of Dhanbad-Patherdih railway line.
- ***Bagdigi, Bararee and Bhulan Bararee to Bagdigi*** -- Threat to stability of Dhanbad-Patherdih railway line.

Conditions at fifteen additional sites are such that a railway line, a stream, or a village could potentially be threatened in the future if fire control measures are not undertaken and the fire continues to spread.

Appropriate Fire Control Measures

For a fire to initiate and be sustained, three components must be present: fuel, oxygen, and heat. Eliminating one or more of these three requisites for combustion -- the legs of the "fire triangle"-- is the basis for all fire control measures (Figure 4). Although methods of extinguishment and containment are much the same, differences in speed of implementation, maintenance requirements, and long term effectiveness make some measures suitable for confinement purposes, but unsuitable for extinguishment.

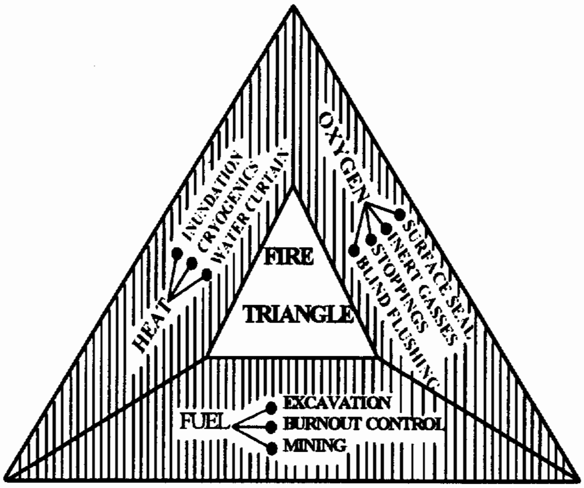

Figure 4 - Fire Triangle

Fire control concepts formulated for the 65 fires are based on the following premises:

1. *Excavation, blanketing (surface sealing), and flooding are the only potentially viable methods available to extinguish a fire in an underground mine, an opencast mine, or opencast overburden.* Flushing is also a potentially viable method for underground mine workings. (The injection of inert gases into underground mine workings is not considered a reliable extinguishment method given the great uncertainties regarding underground ventilation patterns.)

2. Of the three potentially viable methods, excavation is the only *certain* means to extinguish a fire (McElroy 1939). Excavation and cooling the over excavated material to a temperature at which combustion cannot continue is the sole method that can assure a fire has been extinguished.

   Were total excavation to be employed throughout the JCF, no less than 490 million cubic meters of overburden strata and coal would have to be removed within a series of about 60 open pit excavations, some of them measuring as much as 800m in diameter and some up to 140m in depth. An earth moving and extinguishment operation on that scale could approach a cost of $2.4 billion, if accomplished at today's prices, and could take decades to complete. Apart from the very significant cost, the extended length of time needed to complete the removal of all fires makes total excavation an unacceptable option except on a project-by-project basis.

3. Surface sealing is a viable fire extinguishment method only when: a) the blanket is sufficiently thick to limit air intrusion to negligible levels; b) the blanket is noncombustible; c) the blanket does not develop fissures from mine-related differential settlement or desiccation (or alternatively, is continually maintained to seal off fissures and cracks); and d) there are no underground sources of air to sustain the fire and compromise the effectiveness of the blanket. Sealing must generally be assumed imperfect due to the likelihood of mine-level air circulation and potential lapses in maintenance over the several decades generally required for latent heat to be dissipated and a fire to be extinguished.

   Consideration to blanketing selected parts of the coalfield with silt from Panchet Reservoir is warranted as a means to hasten the demise of the JCF fires by smothering (Banerjee 1986).

4. Surface sealing may be beneficial for fire containment when used in combination with other methods, such as barriers constructed in open entries.

5. Extinguishment by flooding, requires a long term, essentially permanent, raising of the mine pool to dispel latent heat in the rock mass. Short term flooding is generally inadequate for this purpose, but can sometimes be used for containment.

6. Flushing of incombustible granular or grout materials into underground mine workings can theoretically extinguish a fire by sealing off oxygen, but cannot be assumed totally effective because of probable incompleteness of the backfilling process. Flushing can be beneficial for containment.

7. Water cannons can be effective in quenching burning material exposed in highwalls or on debris faces immediately prior to excavation. An adequate delivery system must be in place to make the system viable. An infiltration pond can serve a similar purpose.

8. A water curtain is useful strictly as a stop-gap measure deployed where proximity to the fire and the need to block the fire quickly compels its use until other more permanent containment can be achieved. The water curtain requires considerable quantities of water on a continuous basis, as well as a dependable, reliable delivery system, and continuous operation. To count on its use for more than a short term application is inadvisable.

9. The suitability of high technology fire diagnostics and fire extinguishment methods varies from useful to impractical. Certain applications are viable, such as remote sensing from space and aircraft platforms, temperature monitoring, and computerized data management. Other uses of high technology are less practical because of the complexity of a particular fire situation and difficulty of implementation. Less practical uses may include gas sampling, where results may be uninterpretable, or cryogenics for fire extinguishment, where cost is high and the likelihood for success is low. In these cases, a simpler and more direct approach may be more appropriate given the complex nature of past mining techniques, ventilation patterns, fracturing and subsidence, among other considerations.

In defining technical options, the first concern was in halting the fire -- limiting the fire to an area as small as possible in a time as short as possible -- and the second, to extinguishment.

For each fire, two or more technical options were generally evaluated and from them a preferred option selected that was judged most rational and cost-effective in view of prevailing conditions. The options and associated costs were, by necessity, conceptual owing to less than complete information being available. A mix of technologies ranging from filling old workings to construction of isolation trenches were identified to hold the line with the fires and provide some measure of control. These measures resulted in a cost of $260 million for the 65 fires.

Conclusions

1. Although certain JCF fires investigated in the present study may expire without outside

intervention, most are expected to burn indefinitely. New fires may develop.

2. Fire fighting technologies are available, however, nearly heroic measures would be required to extinguish many of the fires. Containment is generally a more achievable, but still an extremely costly, proposition.

3. Action must be taken to remove the fire threat from certain railway lines, streams, and villages either by containing/extinguishing the fire and stabilizing as necessary or by relocating what is endangered.

4. Fire conditions change rapidly with time. Site-specific strategies for fire control and extinguishment should be reevaluated and refined before they are implemented to account for possible changed conditions and new information.

5. The extinguishment of fires would unblock some coal reserves for future exploitation. The benefits realized would not generally offset the cost of fire fighting.

6. Several particular blocks of Jharia coal reserves may be minable by open cast methods so as to realize a net profit, with one or more fires being extinguished as an ancillary benefit.

7. Some fire areas have shown a reduction in size over the past several years and may expire without outside intervention.

8. Underground coal gasification may offer a means to exploit energy resources from certain blocked reserves despite the presence of existing mine fires.

9. The JCF fire problem can potentially be moderated by:

   a) Practicing fire prevention in all mining activities, and providing technical assistance and training on fire prevention and control measures to operating personnel.

   b) Attacking mine fires in a systematic and timely manner, while the fires are of manageable size and before they jeopardize villages and infrastructure (e.g. railroad rights-of-way and water ways).

   c) Dedicating a complement of equipment including staff training to fire control activities.

   d) Concentrating fire-fighting activities at existing fires to locations where impacts on villages and infrastructure are greatest.

   e) Reclaiming opencast pits in a timely and systematic manner so as to reduce air circulation to underground mine workings, with consideration being given to the use of reservoir sediments for blanketing and sealing.

   f) Developing sources of water for fire control purposes, including water catchment basins created by grading during the course of reclamation, as well as mine pool pumping systems.

   g) Maintaining a vigorous fire investigation team to collect and analyze fire data and formulate options for fire control on a site-by-site basis and modifying plans as appropriate to properly account for changes in fire conditions over time.

This paper has focused on the fire fighting programme. Concerns in the socio-economic arena will require resolution before serious measures are undertaken to ameliorate the effects of the fires. Relocation of population, compensation to property and home owners, and cooperation among government and non-government organizations are prerequisite to an effective fire control programme. The common goal should be aimed at improving living conditions, the health and safety of the population, and insuring continued and long term economic stability. Regardless of what remediation activities are carried out, the JCF fires will continue to burn for many decades, be a menace to the health and safety of people living in the region, a strain on BCCL's ability to produce coking coal and on the financial resources of the nation.

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