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CRITICAL APPRAISAL TO ASSESS THE EXTENT OF FIRE IN OLD ABANDONED COAL MINE AREAS – INDIAN CONTEXT

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ABSTRACT: Mine fires in Indian coal mines have a long history of over 140 years and major causes of fire are considered to be spontaneous heating of coal. Regular thermo compositional monitoring plays an important role for assessment of fire in abandoned coal mines and therefore different fire indices assist to categorise location and extent of fire. The paper highlights different methodologies to know extent of fire in old abandoned areas and reviews different fire indices for interpretation of status of mine fires with suitable case studies.

INTRODUCTION

Indian coal mines have a historical record of extensive fire activity in Raniganj coal field, 1865 (Dhar, 1996). The coal mine disasters in India revealed that fire and explosion contributed to about 41% of total fatalities (Sinha, et al. 2001). The major coal fires of India are located in Jharia, Raniganj, Singrauli and Singareni coalfields and about 160 mine fires had been detected in 1997. Out of these, more than 70 were reported from Jharia coalfield itself and total area affected extends over 6300 ha which threaten the township of Jharia (DLR 2005). It is estimated that 75 % of India's coal fires result from mining activities mainly due to the prolonged exposure of coal to atmospheric oxygen. The fires in Jharia and Raniganj Coalfield are mainly due to unprofessional mining and the past extraction of coal (Figure 1). The incidences of fire (about 70 %) in Indian coal mines are mainly due to spontaneous combustion of coal (Zutshi et al. 2001).

Spontaneous combustion in coal is an outcome of heating through oxidation processes, which may be aided by catalytic effects of other compounds (e.g. water, pyrite, etc.). In the process of oxidation, coal interacts with oxygen of air at ambient temperature, liberating heat, which if allowed to accumulate ultimately, would enhance the rate of oxidation and lead to devastating fire, known as spontaneous combustion. The oxidation of coal starts with exothermic chemical reactions and oxidation can be described as a process of three sequential steps. These are (i) physical adsorption, (ii) chemical adsorption or chemisorption, forming coal-oxygen complexes, and (iii) chemical reaction. The chemical reaction breaks down less stable coal-oxygen complexes and results in the formation of gaseous products such as CO, CO_2, and H_2; it can be simplified as follows :

$$COAL + O_2 \rightarrow CO_2 + \Delta H \uparrow$$

Coal fires include surface coal seam fires, underground coal seam fires, old abandoned coal mine fires and carbonaceous dump material, as well as fires in stored coal or coal which is being transported. If a coal seam catches fire and remedial measures fail to be taken at an early stage, the seam may continue to burn for tens to hundreds of years, the time depending primarily on the availability of oxygen. So, demarcation and delineation of coal fire is a major threat to Indian coal mining industries. The paper highlights different methodologies to know extent of fire in old abandoned areas and reviews different fire indices for interpretation of status of mine fires with suitable case studies.

AVAILABLE TECHNIQUES FOR DETERMINATION OF EXTENT OF FIRE

Abandoned coal mine fires in India were mainly due to spontaneous combustion of coal and unscientific mining before nationalization in 1971. The process of spontaneous heating in coal depends upon several inherent parameters, namely mining, geological and chemical. Other external factors, include conveyor belt frictions, electrical short circuits, and explosions, as well as Bantulsi conflagration, dumping of hot ash, and illicit distillation of liquor.

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Fires in abandoned mines and overburden dumps are a relatively common occurrence in coal-producing areas. Abandoned mine fires present serious health, safety and environmental hazards due to the emission of toxic fumes, subsidence and the deterioration in air quality. Such fires usually depress property values for affected land and for adjacent areas. Although there are several fire extinguishment methods, in many cases the high cost and low efficiency are related to the inability

(1) to accurately determine the location and extent of the combustion zones within an abandoned mine and
(2) to identify some point at which the fire can be reliably considered extinguished.

To locate this type of remote, subsurface fire, it is necessary that suitable methods should be adopted and available data are interpreted according to an appropriate algorithm. The different techniques available so far for demarcation and delineation for fire areas include:

1. Field observations and surface thermal mapping of the area,
2. Thermo-compositional studies,
3. Geophysical methods and remote sensing, and
4. Data analysis and interpretation.

Field observations and surface thermal mapping of the area

The emission of smoke, fumes and goaf stink smell at surface fractures and vents is the conventional indicator of an abandoned mine fire. Because hot gases follow the path of least resistance, the surface evidence of fires may not be related by straight line paths to the source of combustion. Aerial infrared photography, through thermal scanner or infra red gun, determines temperature variations within a few inches of the surface, but is inappropriate when heated areas lie about 40 m beneath the surface. Interpretation of aerial infrared can also be complicated by the presence of heat absorbing surface features.

Thermo-compositional studies

In thermo-compositional studies temperature and gas analysis are carried out to determine the state of fire in abandoned mines. Borehole temperature measurements were the principal tool for detection of subsurface coal fires until the 1960s. Temperature and gas samples taken at boreholes are point source measurements; their accuracy is limited to a very small volume of 0.03 to 0.06 m3 (1 to 2 ft^3), within a radial distance of 0.25 m (10 in) at the base of borehole. Their advantage lay in the fact that they could be performed in close proximity to the fire centre.

Subsurface changes in the concentration of O_2, CO_2, CO, CH_4, H_2 and other higher hydrocarbons have been used as the basis for geochemical combustion indicators. Although changes in the concentration of these gases may be related to combustion, they may also be produced by processes other than combustion. In contrast, previous work by the Bureau of mines USA has shown that the desorption of low molecular weight hydrocarbon gases from coal is strongly temperature dependent. A Mine Fire Diagnostic (MFD) Methodology was developed to determine the location and extent of combustion zones in abandoned underground coal mines. In Indian coal mines, carbon monoxide concentration is most widely used as an indicator for spontaneous heating/fire in combination with Graham's ratio. But, in the actual practice this is not the only ratio, on that basis the fire position can be interpreted and every ratio can't be used in all cases as it will vary case to case depending upon the extent and condition of fire. Always trends of fire ratios/indices are to be given due importance and not the absolute values.

Geophysical Methods

In geophysical methods remote thermal characteristics or variations in the gross composition of the mine atmosphere have not been routinely successful at locating isolated combustion zones. Core drilling and near-surface geophysical imaging techniques will produce adequate information on structural features, but are less reliable for indicating combustion areas. Elevated temperatures can alter the mineralogy of iron bearing rocks, but magnetic anomalies are more likely to be associated with areas that have been heated and cooled than with active combustion. Electrical terrain conductivity surveys may indicate water flow, i.e., areas where combustion is unlikely. Near surface seismic surveys and ground penetrating radar can indicate subsidence areas and changes in subsurface structure, but these are not necessarily related to combustion.

In the early 1960s, increasing availability of airborne and satellite-borne thermal scanner data made remote sensing a better tool for coal fire detection and monitoring on surface only. Infrared photography discriminates temperature variations only within a few centimeters of the surface, usually indicating heated vents and fractures. In-depth studies using Landsat TM and/or airborne thermal data were performed then in various countries. These studies applied an average emissivity value (0.96) to represent all land cover. Geographical information systems helped to store and analyse the data generated.

Data analysis and interpretation

The most common techniques of early detection of fire in Indian context are the thermo-compositional analysis. In order to locate a fire, it is necessary that (1) a fire have a measurable characteristic, (2) the characteristic be detectable through appropriate sampling methods, and (3) the sampling data are interpreted correctly. The procedure to determine the extent of fire consists of determining a unique feature for heated coal, a procedure for obtaining samples from abandoned mines and an algorithm for interpreting the data and relating it to a subsurface location. The diagnostic procedure used to locate underground fire zones is based upon two primary assumptions: (1) changes in the concentration of product of combustion gases are due to the presence or absence of heated coal and (2) the temperature recorded with depth in surface borehole near fire zone. The data obtained from these analyses are important for interpretation to know various stages of coal mine fire.

COLLECTION OF MINE AIR SAMPLES

Mine air generally contains CO_2, O_2, CH_4, N_2 and in special cases CO, H_2, H_2S, NO_x and other higher hydrocarbons. Sampling of mine air is required for qualitative assessment for safety of miners and mines. Composition of mine air samples not only indicates the presence of explosive or obnoxious gases but also enables adoption of safety measures in time and also provides valuable information about the condition of the mine during or after explosion. Determination of status of mine atmosphere depends mainly on the collection of representative samples and if sampling is faulty, the painstaking accuracy of the analysis is a waste. Proper sampling mainly depends upon the knowledge and alertness of the sampler, correct sampling procedure and proper preservation of the samples. In addition to this, sampling point, sampling site, sample container and sampling techniques are important in deciding the correctness of representative sample. In practice - sampling pipe becomes too large due to depth of mining. In such circumstances, purging should be at least fifteen times of the volume of the sampling pipe, so that stagnant gases within sampling pipe purge out properly. In fire areas it is very difficult and time consuming to collect representative samples in fire event analysis. So a large number of gas samples are required for an extended period for assessment of the area.

Analysis of mine air samples

The normal atmospheric air consists of N_2, O_2 and CO_2 in the proportion of 79.04%, 20.93% and 0.03% respectively. The deviation of the proportions of these gases in mine-air is very useful for early detection of spontaneous combustion or assessment of fire in underground areas. During any incidence of fire the thermal splitting of coal is set-up and carbon monoxide together with other gases and smokes are produced at their characteristic temperature. The hierarchy and order of appearance of gases may vary from coal to coal. For old abandoned mines there is no distinct technology used in Indian condition except thermo compositional analysis from boreholes. Different gases such as CO, CO_2, CH_4, H_2 and few other lower unsaturated hydrocarbons, which are product of the combustion due to mine-fire activity, are collected from the fire areas and are analysed.

Since the beginning of the twentieth century a number of fire indices/ratios have been suggested to assist in the interpretation of status of fires in underground coal mines *(J. L. Graham, 1914, Timko et al. RI-9362, Litton, C.D RI-9031, Ghosh and Banerjee et al. 1967, Jones & Tricket, 1954, Mitchell, D.W, 1984, Morris, R, 1986, Willet, H.L, 1961, Tripathi et al. 1996)*. A brief description of different fire indices/ratios used worldwide for detection and assessment of mine fire are given in Table 1. All the fire indices/ratios are mainly based on different gases produced during fires. These ratios are based on two assumptions

1. The air which has been supplied to mine having 20.93% O_2, 79.04 % N_2 and 0.03 % CO_2 (excluding other gases)

2. Nitrogen is neither added to the air nor taken from the air concerned in the oxidation.

CASE STUDY

Satgram Fire Project

Sitaldas Opencast Project under J. K. Nagar Fire Project of Satgram, Area, ECL, is located in the central part of Raniganj Coalfield for extraction of 6 – 6.5 m thick Nega Seam (R-VIII). The major outcrop of the Nega seam is exposed in Nimcha Village (population approximately 3000) and average gradient of seam varies between 2^o to 5^o towards S44^{o}E. The dip side of Nega seam (R-VIII) was worked out using bord and pillar method of mining under shallow depth cover surrounding Nimcha village before nationalisation in 1971. Cracks and fractures were developed because of unscientific extraction of coal under shallow cover and resulted in spontaneous heating/fire and subsidence in the area, due to air ingress. It was observed that fire was within 60 to 90 m of the periphery of Nimcha village. So, trench cutting to floor of Nega seam encircling the Nimcha village was appropriate technology instead of normal blanketing and was filled with incombustible material. Maximum width of the trench was 195 m at top and 145 m at the bottom where trench was divided into three patches along the length namely patch 1, patch 2 and patch 3. Patch 1 and patch 2 could not be completed due to middle district road connecting to grand trunk road. The gestation period of trench cutting of patch 2 made a scope for illegal miners to enter into Nega seam towards Nimcha village and galleries were developed towards Nimcha village to extract coal at different places of the trench. A pothole of 10 m diameter took place on 4th of January 2008 near southern part of Nimcha village. Smoke and toxic gases were coming out from potholes, which is endangering the village and affecting environment. Thermal mapping was carried out by Heat Spy Infra red thermometer in early morning near the subsided area and surrounding village. The temperature variation of 5^o to 7^o was found near by pothole and some of places surrounding to Nimcha village. In the first phase nine boreholes 150 mm (6") diameter with casing and leads, at least up to 3 m were made at judiciously selected location (Figure 1). The location of maximum boreholes were drilled where temperature was found more than ambient by thermal mapping and giving due importance to periphery of Nimcha village. Subsequently two more boreholes were drilled near borehole no. 3 t and observed no symptoms of fire.

Result and discussion

Thermo-compositional studies from all the borehole shows that fire does not exist except at borehole no. 3. With the exception of borehole no. 3, all the boreholes were full of strata water. The temperature was found to be ambient (Table 2). High percentage of CH_4 (14%) and CO (1400 ppm) was found in borehole no. 3 which showed that a moderate fire existed in localised area. The temperature in borehole no. 3 was found to be 80^0C and Graham's ratio, CO_2/O_2 ratio indicated that fire existed in the localized area surrounding it (Figure 2). The decreasing trend of oxygen percentage during investigation period along with marked presence of CO and CH_4 in borehole no. 3 confirmed that the extent of fire towards Nimcha village was up to the borehole no. 3 during the investigation period. About 9000 m^3 of top soil was used for blanketing the surface area and edges of trench as per site specific condition. Fire fighting operation was carried out through borehole no. 3 to control and combat fire in the localised area by chemical means, subsequently filling with incombustible material to stabilize the area outside the trench limit line. The remaining part of the trench i.e. North East side of trench towards village was also completed for the safety of village.

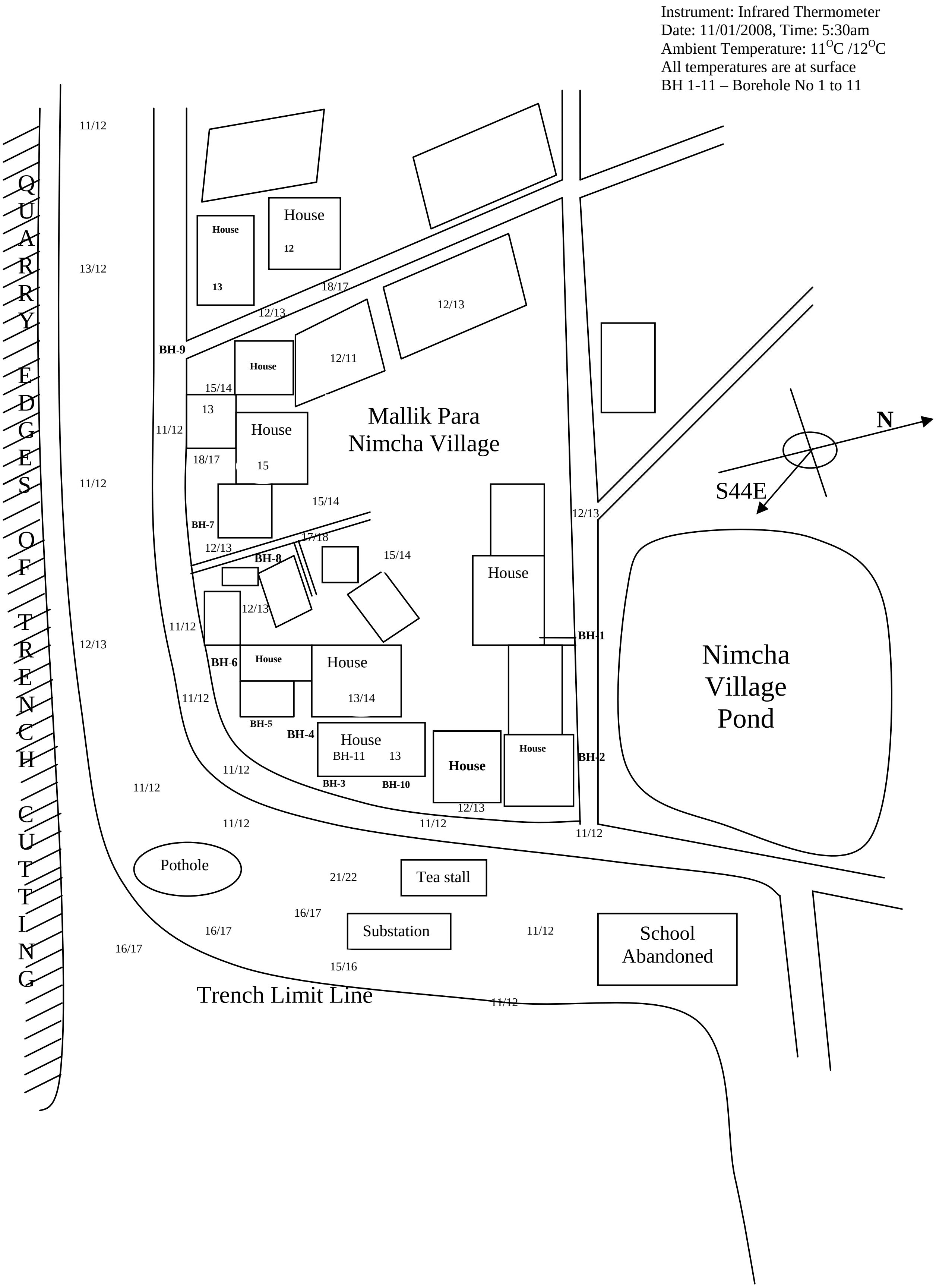


Figure 1 - Location of boreholes and thermal mapping of the area towards Nimcha village

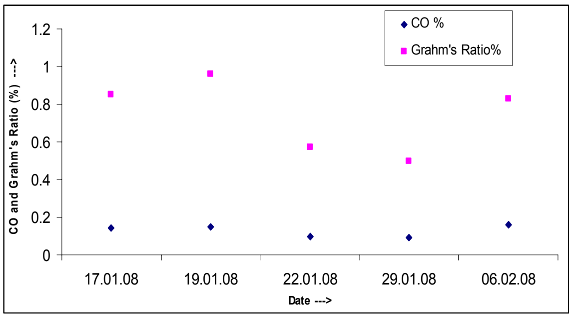
Table –1 Different fire indices/ ratios to assess the status of fire

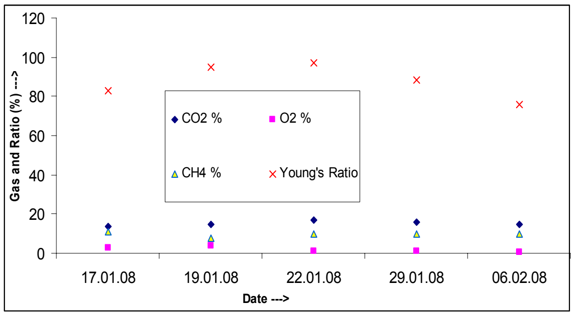
Fire Indices/Ratios	Significance/Interpretations	Advantages	Limitations
Graham's Ratio (GR) =100CO/(0.265*N_2-O_2) and (J. L. Graham, 1914-15, 1920-21) In case of failure of GR, where CO extinction is not indicative of status of fire, than the CO/CO_2 def.* Ratio can also be applied. CO/O_2de* = 100CO_2/(0.265*N_2-O_2)	< 0.5 - Normal >0.5 - < 1.0 - Existence of Heating >1.0 - < 2.0 - Advance Stage > 3.0 - Active Fire > 7.0 - Blazing Fire	• Since both numerator and denominator are affected, so the ratio remains independent to dilution of air or methane. • Gives early detection of fire if it increases continuously. • Assessing the status of fire.	• Does not give extent of fire i.e. amount of coal involved. • Disappearance of CO does not mean complete extinction of fire • If the products of combustion are diluted by black damp (N_2) or O_2 deficient air, the ratio would be affected.
Young's Ratio (YR) =100(CO_2 - 0.03) /(0.265*N_2-O_2) (CMRI Report, 1991)	< 25 - Normal 25-50 - Superficial Heating > 50 - High Intensity Fire	• CO_2 found, where fire exists in advance stage.	• Extraneous origin of CO_2 and its solubility in water render misinterpretation.
JTR=(CO_2+0.75 CO-0.25H_2) /(0.265N_2-O_2) (Jones &Tricket, 1954)	< 0.4 - No fire 0.4 – 0.5 – Methane Burning 0.5 - 1.0 - Coal, Oil, Conveyor Belt Burning 0.9 - 1.6 – Timber Burning > 1.6 – Error in Analysis	• It can differentiate the nature/type of fire.	• Does not provide status of fire. • Cannot provide the early detection of fire.
Willets Ratio= CO/(Excess N_2+CO_2+Combustible) Excess (N_2 +Ar) = Sample (N_2+Ar) – (3.8* Sample O_2) (Willet, H.L, 1951-52)	Actual figure vary from seam to seam. The ratio increases as temperature increases. It also depends upon the magnitude and extent of fire.	• Gives early detection of fire in presence of production of CO.	• Does not provide status of fire. • If CO disappears then prediction of the status of fire is very difficult.
C/H Ratio = 6(CO_2+CO+CH_4+2C_2H_4)/ 2(0.265*N_2-O_2-CO_2+CH_4+C_2H_4+H_2-CO) (Ghosh & Banerjee et al., 1967)	0 – 2.0 - Normal 3.0 – 4.0 - Superficial Heating > 5.0 - Active Fire > 20.0 - Blazing Fire	• It can characterise intensity and extensity of fire. • Can distinguish between coal and wood fire. • Large range of value provide a better tool for characterisation of a fire	
Morris Ratio= N_2 - C_{NO} O_2 /(CO + CO_2) and N_2/(CO+CO_2) (Morris, R, 1986)	Actual figure vary from seam to seam. The ratio increases as temperature increases. It is sensitive to change in the state of the gases within a sealed fire zone.	• For a particular seam it is very useful • It is used to estimate the temperature of a heating. It may be used to warn mine personal that an explosion may occur within the fire seals.	• Does not provide status of fire. • Ratio varies randomly with high temperature depending upon the production of CO and CO_2.
Litton's Ratios (R) =1/3*CO_s *$R_g^{-3/2}$ 8 $O^{-1/2}$ R_g=100-4.774O_2-CH_4-C_2H_2 CO_s= CO in ppm (Litton, C.D, 1986)	≤ 1.0 – Equilibrium Exists for 30 days then ambient temperature reached > 1 – Smouldering combustion or above ambient temperature (oxidation takes place)	• Provides better information for sealed-off area. • Very useful for reopening of sealed-off area.	• Does not provide status of fire. • It cannot provide the early detection of fire.

Desorbed Hydrocarbon Ratio (RI) = $\{1.01*(CH_4+C_2H_2+C_2H_4)- CH_4/(CH_4+C_2H_2+C_2H_4) +0.01\}*1000$ (Kim, A.G, 1988)	For Bituminous Coal 0 – 50 - Normal 50 - 100 – Possible Source of Heating > 100 - Hot Zone	• Can asses the status of fire. • Gives a better result for sealed-off area having a no of sampling locations. • Can find out the location of fire if sampling point is evenly distributed.	• It cannot provide the early detection of fire. • Without hydrocarbons the value will be zero, which gives sometimes no indication of fire.
Oxides of Carbon Ratio = CO/CO_2 (Kuchta et al. Al. 1982, Mitchell, D.W, 1989)	< 2.0 - Normal 2.0 – 13.0 - Superficial Heating > 13 - Blazing Fire	• Gives early detection of fire if it increases continuously. • Assessing the status of fire.	• Extraneous origin of CO_2 and its solubility in water render misinterpretation
H_2/CH_4 (Mitchell, D.W, 1990)	The ratio increases as temperature increases. It also depends upon the magnitude and extent of fire.	• Gives better information when fire is in advance stage or blazing fire.	• Cannot provide the early detection of fire.
RI/RE Ratio Relative Efficiency (RE)= $(0.265N_2-3.83O_2)/ (CO+CO_2)$, Relative Intensity (RI)=$\{(1-3.83O_2)/N_2\}/[CO/0.265*N_2-O_2]$(Mitchell, D.W, 1984)	Increase in RI/RE value indicates fire is an ascending order of moving towards the sampling locations or conversely.	• Gives better result in locating the proximity of fire, when sampling locations spread throughout the area.	• Does not provide status of fire. • Cannot provide the early detection of fire.

Table – 2 Temperature measurements in different boreholes

Date	Time	Borehole Number (temperature in °C)											Ambient Temperature
		1	2	3	4	5	6	7	8	9	10	11	
17.01.08	10.30am	--	31	89	--	--	--	--	--	--	--	--	31
19.01.08	12.10pm	32	32	83	34	36	--	36	--	36	--	--	32
22.01.08	11.30am	--	--	82	28	26	--	27	--	24	28	26	27
29.01.08	11.55am	21	22	81	28	26	28	27	28	27	28	27	27
06.02.08	11.15am	24	24	81	16	14	22	31	17	29	31	31	30





(a) (b)

Figure 2 - (a) Graham's ratio and CO percentage of borehole no 3
(b) Young's ratio, CO_2, O_2 and CH_4 percentage of borehole no 3

Mudidih Colliery

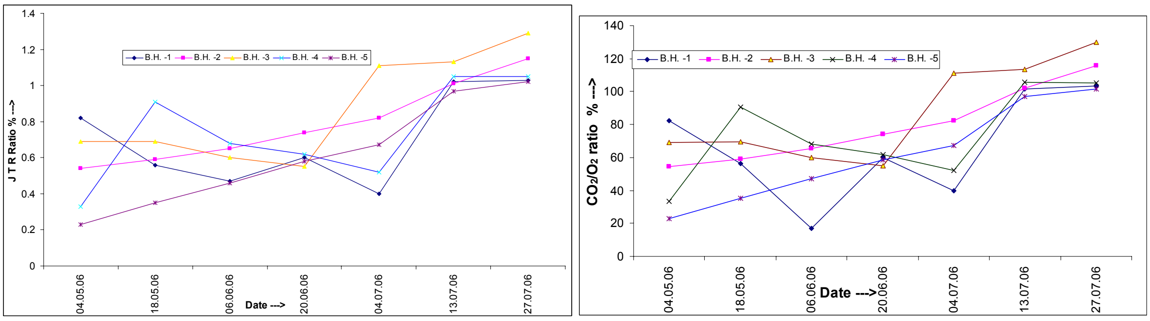
Mudidih colliery lies in Sijua Area at a distance of about 15 km towards west from Dhanbad railway station and this colliery consists of three sections namely Tetulmari, Mudidih and Jogta, which were amalgamated during take over by BCCL in 1971. Numbers of major faults of 3.36 m to 128.0 m of throw are passing through the colliery properties. Besides these major faults, large numbers of localized faults of small throw are also found frequently. All seams were developed on board and pillar mining. Fire in IX (T) and IX (B) seam in the adjoining colliery has been in existence since 1960s. In the dip side, the smoke and fume were seen in the recent past in adjoining area beyond western boundary of 7/8 incline of Mudidih colliery. In the year 2000, isolation stoppings of VIII seam goaf area below the above area of Tetulmari colliery were reported for temperature increase. Suddenly huge amount of black smoke coming out of the incline mouth and accordingly stoppings were erected. It was suspected that fire was coming from an old isolation stopping. Accordingly all the openings of the VIII seam leading to the incline were sealed, and inspection to the fire/stopping was ceased. Also, the progress of fire towards the boundary of 7/8 incline of Mudidih colliery from Tetulmari colliery became difficult to monitor.

Result and discussion

Five boreholes (Borehole No. 1 to 5) were available in the western side of the incline of Mudidih colliery. Borehole No. 2 was drilled up to IX (T) seam at a depth of 27.64 m and borehole No. 1, 3, 4 and 5 were drilled up to VIII seam at a depth of 50, 43, 53 and 60 m respectively. Huge amount of hot gases were observed coming out from borehole No.2, indicating positive pressure, while borehole No. 1, 3, 4 and 5 were showing negative pressure. After carrying out thermo-compositional investigation of the different boreholes, no CO trace was detected in the borehole, but CH_4 has been found in the borehole Nos 1 to 5, which indicated the presence of heating/fire. The ratio of CO_2/O_2 def. value indicates that heating is in advanced stage in the sealed off area. Also, Jonnes Tickett Ratio (JTR) value was between 0.4 to 1.1 in different boreholes indicating that the fire was due to coal and wood burning. It was concluded that the gas sample data indicates that fire is present in the surrounding area.

Table – 3 Temperature measurements in different boreholes

Date	Borehole Number (temperature in °C)					Ambient Temperature
	1	2	3	4	5	
04.05.06	44	63	50	48	36	36
18.05.06	38	59	33	37	35	35
06.06.06	37	54	34	36	36	34
20.06.06	39	65	35	40	38	36
04.07.06	33	68	35	32	39	30
13.07.06	35	86	35	35	32	31
27.07.06	36	98	36	35	34	32



(a) **(b)**

Figure 4 - (a) JTR ratio in different borehole (b) Graham's ratio in different borehole

CONCLUSION

The abandoned coal mine fires blazing in the Indian coalfields are not only consuming huge quantity of coal but also preventing exploitation of coal in the adjoining areas and in the underlying coal seams. Mine fires also affect the environment, due to release of noxious and toxic gases from abandoned coal mine fire areas. Also emitted are greenhouse gases (GHG) which contributes to global warming.

In Indian coal mining industry, the general trend for assessment and extent of fire is determined from thermo-composition studies i.e. interpretation of Grahams ratio i.e. CO/O_2 def. ratio only if sampling from fire area is proper. The trends of fire indices/ratios are to be given due importance for determination of extent of fire in abandoned coal mine and not the absolute values. Every ratio can't be used in all cases, as it will vary case by case, depending upon the extent and condition of fire.

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