Development of modified gas indices for early detection of spontaneous heating in coal pillars

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Synopsis

Extensive field studies have been carried out to investigate the pillar fire problems in one coal mine in India. A Thermal IR gun and a Thermovision camera have been employed for thermal scanning to assess the state of heating in selected pillars. Special sampling set-ups have been designed to collect gas samples from the holes drilled into the selected pillars and the multigas detector is used to analyse the composition of samples *in situ*. In order to predict the spontaneous heating in coal pillars, different gas ratios have been calculated and it has been observed that some of the established gas ratios, viz. Graham's ratio, Young's ratio etc. have resulted in negative values in samples containing high amounts of methane. The modified gas ratios have been proposed which will be useful for predicting the pillar fires. These ratios may also be used for assessing the condition of fires in sealed-off areas.

Introduction

In India bord and pillar method of mining contributes 90% of the coal produced from underground mines. In this method of work the coal-seam is developed in the form of pillars and these pillars remain for a long time before being finally extracted. In some cases fires occur in the developed pillars and as a result it affects production, productivity and safety in mines. This type of pillar fire is very common in Raniganj Coalfield of India. Therefore, in order to find some methodology for predicting the occurrence of fires in coal pillars, an extensive study has been undertaken in one coal-mine of this coalfield. Holes have been drilled in the pillars and with help of specially designed gas sampling set-up, gas samples have been collected at regular intervals.

The results of the study revealed some interesting observations with respect to some gas indices which are commonly used for early detection of fire in mines. It has been observed that in certain field situations these gas indices yield some anomalies and it is difficult to draw any meaningful conclusion in such conditions. Therefore, an attempt has been made in this paper to suggest some modified gas indices which will be applicable for assessing the fire in coal pillars under a variety of geo-mining conditions.

Selection of pillars for the study

All the coal-mines of Raniganj Coalfield are being operated by a coal company, Eastern Coalfields Limited. After discussion with the senior executives of this coal company, Satgram coal-mine, working in Dishergarh (RIV) seam was selected for carrying out the study. The basis for the selection of this mine was the proneness of coal of this seam to spontaneous combustion. Generally, the crossing point temperature value of this seam lies between 129°C and 134°C; and it is considered to be highly susceptible in Indian conditions. In addition, the volatile matter content of the coal is always more than 30% which makes it more liable to spontaneous combustion.

An in-depth study into the occurrences of pillar fires in this coalfield has revealed that such fires have occurred mostly in the pillars subjected to high ventilation pressure difference and are located between the main intake and main return of the mines. In addition, a number of such fires have also occurred in pillars near geologically disturbed zones. In all cases of pillar fires in this coalfield it has been observed that these fires occur within 2 to 3 m from the surface of coal pillars.

Considering the place of occurrence of pillar fires, two coal pillars in Satgram coal-mine were selected for this study. Details about the location and coal characteristics of the pillars, as determined in the laboratory by carrying out crossing point temperature and proximate analyses, are given in Table I(A).

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Table I(A)

Details of the location and characteristics of selected coal pillars

Sl. no.	Item	Pillar 1	Pillar 2
1.	Location	i) Between 22 and 23 level of 2nd and 3rd dip ii) Located between main intake and main return of the mine having high ventilation pressure differential	i) Between 45 and 46 level of 6th and 7th dip ii) Located near a fault zone and very close to the operating face
2.	Coal characteristics a) Crossing point temperature b) Proximate analysis (as received basis) i) Volatile matter content (%) ii) Moisture content (%) iii) Ash content (%) iv) Fixed carbon content (%)	 134°C 33.39 3.59 11.86 51.16	 129.5°C 34.68 2.54 9.34 53.44

Thermal scanning has been undertaken to ascertain the initial status and the subsequent condition of the pillars with respect to pillar fires or auto-oxidation. Therefore, this has been done before starting any field investigation and it has been continued at regular intervals while carrying out the gas emission studies. Thermal scanning is based on the principle that any surface at a temperature above absolute zero emits heat in the form of radiated energy. The radiant flux from the surface is directly related to its temperature by known physical laws. Two instruments, an infrared thermal gun (Figure 1: Infra trace 800, Kane-May Ltd., UK) and Thermovision camera (Figure 2: Thermovision 510, AGEMA Infrared System, UK) have been used for thermal scanning of the selected pillars.

In the thermal I. R. gun, the energy radiated by an object is processed to display temperature directly in degrees centigrade. This instrument is held and aimed like a pistol. The aperture of the front side should be aligned with the appropriate aperture in the rear side. The upper aperture provides optimum distance of 1 m from the instrument. The lower aperture provides a parallel sight line suitable for aiming at targets at a distance of greater than 5 m. For in-between distances of an object, any one of them can be used. For a distance of exactly 1 m, the minimum object size should be 20 mm and for greater distances, the distance to target size ratio should be a minimum of 40:1. This gun has been used to measure the temperature of different points on the sides of the pillars.

In order to determine the exact location of any heat build up area, the I. R. gun focused on the side of the pillars is traversed all around the pillars. If there is an appreciable increase in temperature in a particular area of the pillar compared to its surrounding, this area may be affected by fire and it gives a thermal status of the pillar. By using this gun, the temperatures on the sides of both the selected pillars were observed over a period of 35 days and are presented in Table I(B).

It may be observed from this table that the maximum temperature recorded in the intake side of Pillars 1 and 2 are 30°C and 33.6°C respectively. Similarly, on the return side, the surface temperature of Pillars 1 and 2 are 32.6°C and 34.9°C respectively. It may be mentioned here that this is the normal temperature of the strata at these locations.

The method of scanning by using a thermal I. R. gun is little bit tedious and there is a likelihood that one may miss the location of a heat build-up zone if it is small in area. Keeping this problem in view, the thermovision camera, i.e. an infrared thermal imaging system, has been used for thorough scanning of the sides of both the selected pillars. It maintains its high sensitivity and image resolution even when used in extremes of ambient temperature. It is merely focused at the object being scanned and high resolution thermal anomaly image is provided in the ocular adjustable viewfinder in real time. This instrument is provided with thermo-electrically-cooled 160 element lead-selenite (PbSe) infrared detectors which integrate the pixels in the form of a complete image. Therefore, the thermal anomaly, if it exists

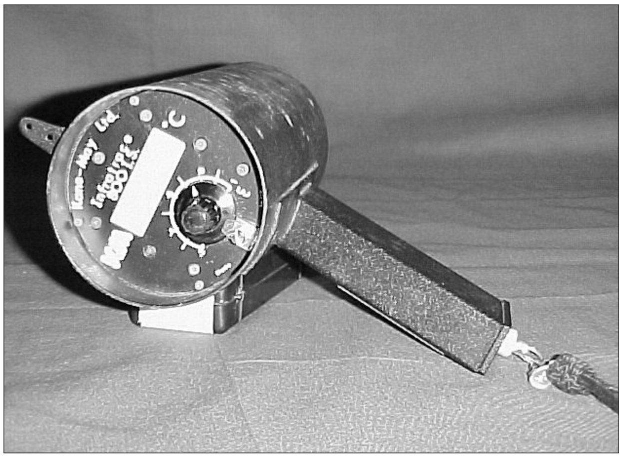

Figure 1—Infrared thermal gun

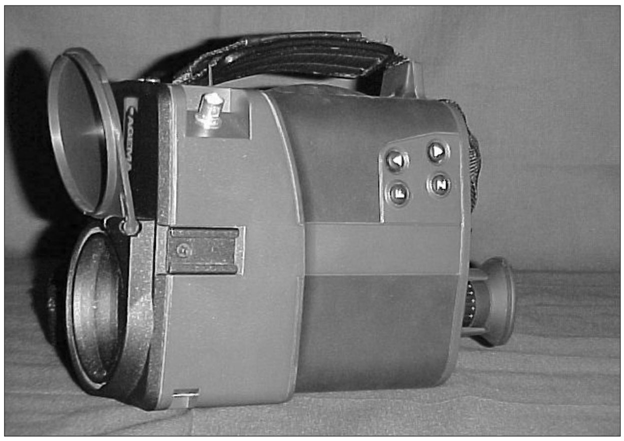

Figure 2—Thermovision camera

Table I(B)

Results of thermal scanning using I.R. gun

Pillar no.	Intake/ return	Observed temperature (° C) on different days					
		1st day	7th day	14th day	21st day	28th day	35th day
1	Intake side	29.6	29.8	29.8	29.6	30.0	29.8
	Return side	32.4	32.4	32.2	32.6	32.4	32.6
2	Intake side	33.2	33.4	33.5	33.6	33.4	33.6
	Return side	34.8	34.4	34.4	34.6	34.8	34.9

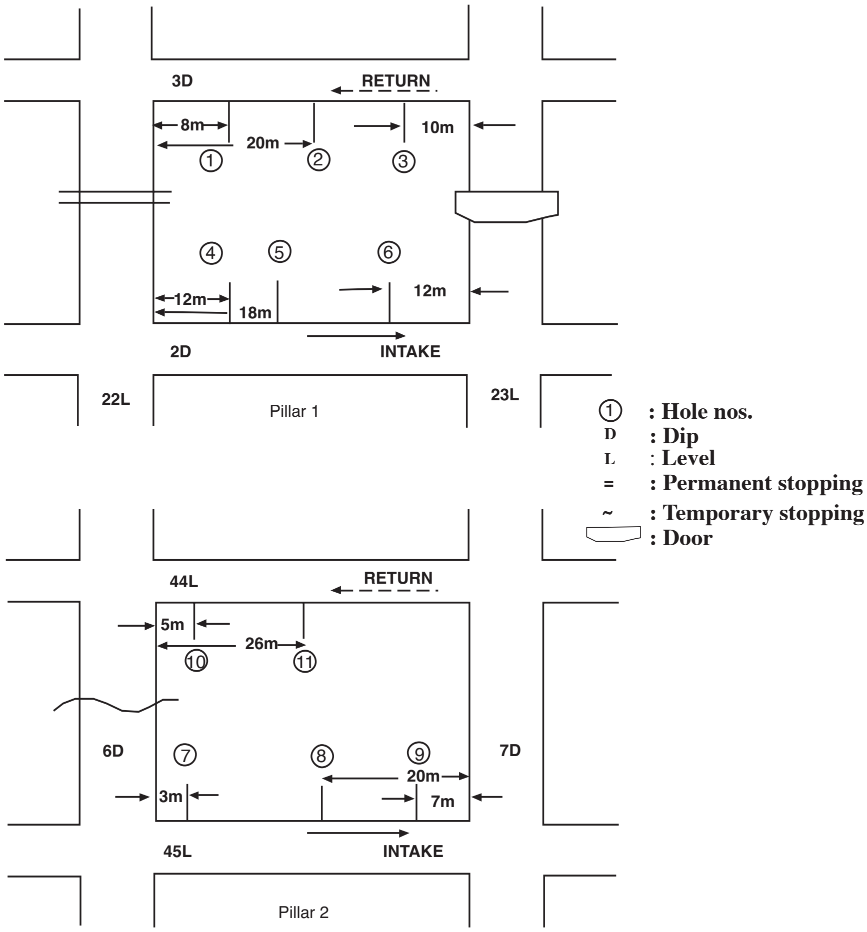

Figure 3—Position of holes in Pillars 1 and 2

in any small area of the coal pillar, can easily be detected and located. This camera has been used for finding a thermal anomaly, if present in both the selected pillars during the gas emission studies. It may be mentioned here that no thermal anomaly has been observed in any of the pillars.

From the results of temperature measurement by thermal I. R. gun presented in Table I(B) and the thermal scanning results by Thermovision camera, it may be concluded that there was no indication of fire in these pillars. In addition, air sample analysis around the pillars confirmed the absence of any heating in the selected pillars.

Experimental investigation

The occurrence of fire in a pillar to a significant extent depends upon the level of emission of CO_2 and other inert gases from the pillar. If the level of CO_2 emission from the pillar is very high, it has been observed that the pillar does not catch fire, possibly because of its extinctive nature. Therefore, to find out the level of CO_2 and other strata gases emitted from the pillars, holes were drilled on both intake and return sides of the pillars to a depth of 3.5 m, which is the vulnerable zone from the point of view of pillar fires. The position of these holes along with hole numbers in both the pillars are shown in Figure 3. Gas samples are collected from these holes once in a week to determine the level of these gases as well as the values of different gas indices commonly used for early detection of fire.

In order to collect gas samples from these holes, a special sampling set-up is developed in such a way that it does not allow the automatic entry of mine air into the hole unless it is deliberately allowed. Photographs of these set-ups are presented in Figures 4 and 5.

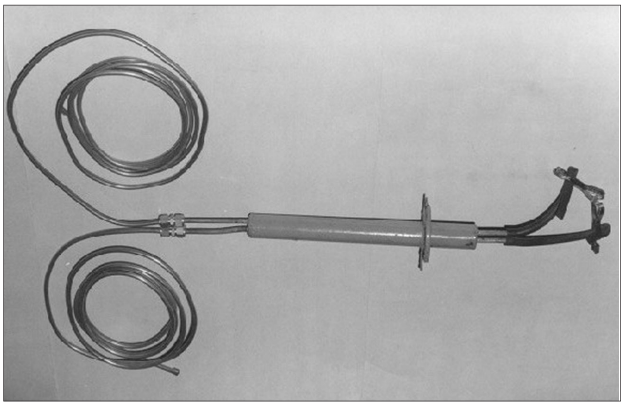

Figure 4—Sampling set-up with sampling pipe

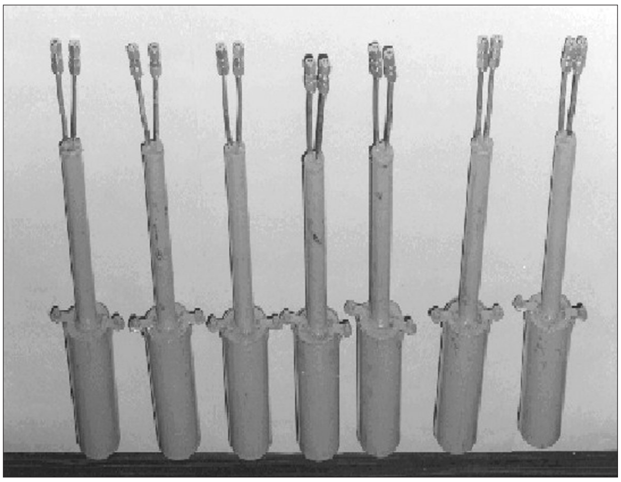

Figure 5—Sampling set-ups with jacket

It may be seen in Figure 4 that it consists of a circular plate through which a pipe passes. The diameter of the pipe is 37 mm. In this pipe two copper tubes of 6 mm diameter are fitted and approximately 150 mm length of these tubes project to both sides of the pipe. On one side of the copper tube, couplers are fitted to which longer lengths of the copper tubes can be attached for drawing samples from the back of the drill holes. In the other end of these two tubes, rubber hoses with clips are fitted to facilitate drawing of air samples. These rubber-hose ends of the set-up project outside the holes. To avoid tampering with these tubes and leakage of samples, a fabricated jacket is fitted with nuts and bolts as presented in Figure 5.

These sampling set-ups are grouted at the mouth of the hole as soon as holes are drilled. The samples are drawn from these holes after one hour of drilling and plugging the holes. Subsequently gas samples are taken once a week and it is continued for up to five weeks. These samples are analysed on the spot by using a BM22 multiguard multigas detector of Oldham France and a photograph of the detector is presented in Figure 6. The multigas detector is calibrated at regular intervals to maintain its accuracy.

The results of the analysis of gas samples drawn from all 11 boreholes are presented in Tables II and III for Pillars 1 and 2, respectively.

Analysis of experimental results

The following gas indices are commonly used for early detection of fire as well as in the prediction of the status of spontaneous heating in coal:

$$\text{(a) Graham's ratio} = \frac{\text{CO produced}}{\text{O}_2 \text{ deficiency}} \times 100$$

$$\text{(b) Young's ratio} = \frac{\text{CO}_2 \text{ produced}}{\text{O}_2 \text{ deficiency}} \times 100$$

$$\text{(c) Willet's ratio} = \frac{\text{CO produced}}{\text{Blackdamp} + \text{Combustible gases}} \times 100$$

$$\text{(d) CO/CO}_2 \text{ ratio} = \frac{\text{Final CO} - \text{Initial CO}}{\text{Final CO}_2 - \text{Initial CO}_2}$$

$$\text{(e) Morris ratio} = \frac{\text{Excess N}_2}{\text{CO} + \text{CO}_2}$$

In addition to the above ratios, the blackdamp emission level in different pillars is also considered to be an important parameter for the occurrence of fire inside a pillar. The values of the above ratios and the percentage of blackdamp are calculated and presented in Tables IV and V for Pillars 1 and 2 respectively. It may be noted that for calculation of the above ratios, the percentages of O_2 and N_2 present in normal atmosphere are assumed to be 20.93 and 79.04 respectively.

Figure 6—BM22 Multigas detector

Table II

Gas analysis results of samples collected from boreholes of Pillar 1

Period of sample collection	CO %	CO_2 %	O_2 %	CH_4 %
Hole no. 1				
1st day	0.0028	1.28	8.00	61.0
7 days	0.0015	0.82	6.70	68.0
14 days	0.0008	0.50	6.90	54.0
21 days	0.0008	0.72	8.90	52.0
28 days	0.0009	0.52	7.10	41.0
35 days	0.0004	0.81	6.30	25.0
Hole no. 2				
1st day	0.0035	0.90	9.30	56.0
7 days	0.0039	1.00	7.50	68.0
14 days	0.004	0.92	7.10	45.0
21 days	0.0035	0.73	6.12	75.0
28 days	0.0035	1.35	5.80	70.0
35 days	0.0023	0.92	7.10	66.0
Hole no. 3				
1st day	0.0017	0.50	6.70	68.0
7 days	0.0021	1.00	7.10	43.0
14 days	0.0028	1.00	6.20	46.0
21 days	0.0031	1.00	5.30	45.0
28 days	0.0039	1.35	4.30	80.0
35 days	0.0039	1.22	4.20	69.0
Hole no. 4				
1st day	0.0024	0.80	16.50	7.4
7 days	0.0028	1.10	14.50	1.2
14 days	0.0022	0.90	12.20	0.0
21 days	0.0027	0.80	11.90	0.7
28 days	0.0029	0.66	11.50	1.7
35 days	0.0016	0.45	10.80	0.2
Hole no. 5				
1st day	0.0029	1.40	15.60	2.3
7 days	0.0034	0.50	14.30	9.3
14 days	0.0022	0.62	14.10	0.1
21 days	0.0028	0.52	13.80	2.2
28 days	0.0014	0.55	15.80	0.3
35 days	0.0004	0.69	15.00	0.1
Hole no. 6				
1st day	0.0012	1.25	16.20	0.3
7 days	0.0024	0.70	15.80	4.5
14 days	0.0031	1.20	14.20	0.1
21 days	0.0025	1.10	14.50	38.0
28 days	0.0029	0.84	9.80	0.1
35 days	0.0025	1.20	10.10	0.1

A study of Tables IV and V reveals that

- The values of Graham's ratio are negative on some of the days in case of hole nos. 1 to 3 and 6 to 11. In case of hole nos. 4 and 5 Graham's ratio is positive in all the cases
- The values of Young's and Morris ratios are also negative on the same days in same holes as in case of Graham's ratio
- The values of CO/CO_2 and Willet's ratios are positive on all the days in all the holes
- The percentage of blackdamp is negative on some of the days for hole nos. 1 to 3 and 6 to 11. In hole nos. 4 and 5 it is positive on all the days
- The CH_4 percentage is less in hole nos. 4 and 5 compared to other holes (Tables II and III)
- It may be observed that Graham's ratio, Young's ratio, Morris ratio and blackdamp percentage are negative on some days and CH_4 percentage on those days is also high. Negative values of Graham's, Young's and Morris ratios are not meaningful to interpret and draw any suitable conclusion. Thus, an attempt is made to nullify the effect of CH_4 by recalculating the composition of air on a CH_4 free basis.

Table III

Gas analysis results of samples collected from boreholes of Pillar 2

Period of sample collection	CO %	CO_2 %	O_2 %	CH_4 %
Hole no. 7				
1st day	0.0021	0.71	7.16	18.4
7 days	0.0022	0.40	12.4	38.0
14 days	0.0024	0.80	11.4	45.0
21 days	0.0016	0.90	13.9	33.0
28 days	0.0012	0.90	13.4	36.0
35 days	0.0003	1.00	16.1	23.0
Hole no. 8				
1st day	0.0018	0.81	6.90	33.0
7 days	0.0015	1.00	5.80	77.0
14 days	0.0011	1.00	7.80	63.0
21 days	0.0009	1.30	9.20	76.0
28 days	0.0008	1.10	11.10	46.0
35 days	0.0004	0.80	12.00	43.0
Hole no. 9				
1st day	0.0014	0.42	2.96	49.0
7 days	0.0004	0.80	5.10	87.0
14 days	0.0004	0.90	6.60	59.0
21 days	0.0004	1.30	7.70	64.0
28 days	0.0004	0.70	7.20	85.0
35 days	0.0004	0.60	7.50	21.0
Hole no. 10				
1st day	0.0008	0.93	5.60	46.0
7 days	0.0008	0.80	5.90	88.0
14 days	0.0006	0.90	7.80	49.0
21 days	0.0004	1.10	11.2	88.0
28 days	0.0004	0.85	10.9	51.0
35 days	0.0004	1.20	11.0	70.0
Hole no. 11				
1st day	0.0012	1.12	3.48	61.0
7 days	0.0009	1.00	6.10	71.0
14 days	0.0007	0.80	7.80	63.0
21 days	0.0006	0.90	8.96	86.0
28 days	0.0004	0.90	11.0	48.0
35 days	0.0004	1.10	10.8	46.0

CH_4 free method

In order to make the air composition CH_4 free, the CH_4 percentage is made zero and other constituent gases are proportionately increased. The calculation of N_2 by this method is given below:

$$N_2 \text{ \% in } CH_4 \text{ free method} = \frac{N_2 \text{ \% present in the sample}}{(100 - CH_4\%)} \times 100$$

A similar calculation has been done for CO, CO_2 and O_2. A sample calculation for air composition data of one borehole is given below :

Composition of air sample of hole no. 7 on 14th day (%)		Composition of the same sample on CH_4 free basis	
CO	0.0024	CO	0.0044
CO_2	0.8	CO_2	1.4545
O_2	11.4	O_2	20.7273
CH_4	45	CH_4	0
N_2	42.7976	N_2	77.8138

Table IV

Values of gas indices and blackdamp percentage for different holes in Pillar 1

Period of sample collection	Graham's ratio	Young's ratio	CO/CO_2 ratio	Morris ratio	Willet's ratio	Blackdamp %
Hole no. 1						
1st day	-2.141	-955.6046	0.0022	-0.3790	0.005	0.743
7 days	-0.688	-362.3375	0.0018	-1.0200	0.002	-0.038
14 days	0.024	14.1516	0.0016	26.6750	0.001	12.987
21 days	0.063	54.6356	0.0011	6.9349	0.001	5.434
28 days	0.014	7.5323	0.0017	50.0788	0.001	25.013
35 days	0.003	6.6796	0.0005	56.5267	0.001	44.811
Hole no. 2						
1st day	-0.998	-248.1475	0.0039	-1.4902	0.006	-0.472
7 days	-0.305	-75.8897	0.0039	-4.9378	0.006	-3.861
14 days	0.075	16.6686	0.0043	22.5734	0.006	21.016
21 days	-0.266	-53.2417	0.0048	-7.0368	0.005	-4.261
28 days	1.401	528.3946	0.0026	0.7233	0.005	2.261
35 days	-1.041	-402.6481	0.0025	-0.9164	0.003	0.048
Hole no. 3						
1st day	-1.275	-352.4694	0.0034	-1.0335	0.003	-0.039
7 days	0.036	16.5860	0.0021	22.7369	0.003	23.015
14 days	0.045	15.6653	0.0028	24.0526	0.004	24.316
21 days	0.041	12.7714	0.0031	29.4879	0.004	29.612
28 days	-0.778	-263.4126	0.0029	-1.4216	0.005	-0.563
35 days	0.152	46.2564	0.0032	8.1458	0.005	10.899
Hole no. 4						
1st day	0.070	22.3902	0.0030	16.8651	0.011	13.679
7 days	0.037	14.2082	0.0025	26.5419	0.009	29.420
14 days	0.020	8.0475	0.0024	46.8413	0.005	41.601
21 days	0.024	6.9802	0.0034	53.9494	0.006	42.334
28 days	0.026	5.5706	0.0044	67.5243	0.006	43.245
35 days	0.013	3.3207	0.0036	113.3520	0.003	48.086
Hole no. 5						
1st day	0.050	23.7484	0.0021	15.8953	0.011	23.070
7 days	0.059	8.1068	0.0068	46.3211	0.011	22.285
14 days	0.026	6.9779	0.0035	53.9757	0.007	32.429
21 days	0.034	5.9001	0.0054	63.7094	0.008	31.763
28 days	0.022	8.2922	0.0025	45.4918	0.006	24.112
35 days	0.005	9.0424	0.0006	41.7922	0.001	28.133
Hole no. 6						
1st day	0.022	21.8650	0.0010	17.2863	0.005	22.203
7 days	0.047	13.0891	0.0034	28.8049	0.010	19.917
14 days	0.038	14.3119	0.0026	26.3457	0.010	31.951
21 days	-0.113	-48.3327	0.0023	-7.7627	0.008	-7.327
28 days	0.021	5.8545	0.0035	64.3030	0.005	52.960
35 days	0.019	8.7569	0.0021	43.0534	0.005	51.529

Accordingly, all the ratios are recalculated and presented in Tables IV(A) and V(A).

It may be observed from Tables IV(A) and V(A) that:

- ➤ The values of Graham's, Young's and Morris ratios continued to be negative on the same days of observation as earlier
- ➤ In addition, the values of Willet's ratio on some of the days have become negative, because CH_4 is made free in this method and the blackdamp percentage in the denominator is negative
- ➤ Therefore, the CH_4 free method is also not suitable for drawing any meaningful conclusion from the values of different gas ratios.

In the next stage of analysis it is thought that the CH_4 is diluting different gases present and accordingly CH_4 may be distributed proportionately on the basis of fresh air composition.

CH_4 distribution method

In this case CH_4 is distributed between N_2, O_2 and CO_2 according to their percentage in normal air, i.e. 79.04, 20.93 and 0.03 respectively. The calculation of N_2 by this method is as follows:

N_2% in CH_4 distribution method = N_2% present in the sample + 0.7904 CH_4% present in the sample

A similar calculation has been done for O_2, CO and CO_2. A sample calculation for the same air composition data as given in the CH_4 free method is as follows:

Composition of air sample of hole no. 7 on 14th day %		Composition of the same sample by CH_4 distribution method %	
CO	0.0024	CO	0.0024
CO_2	0.8	CO_2	0.8135
O_2	11.4	O_2	20.8185
CH_4	45	CH_4	0
N_2	42.7976	N_2	78.3656

Table V

Values of gas indices and blackdamp percentage for different holes in Pillar 2

Period of sample collection	Graham's ratio	Young's ratio	CO/CO_2 ratio	Morris ratio	Willet's ratio	Blackdamp %
Hole no. 7						
1st day	0.017	5.5001	0.0030	68.4739	0.003	47.293
7 days	0.350	58.9447	0.0055	6.4487	0.005	2.700
14 days	-3.578	-1147.8336	0.0030	-0.2926	0.005	0.485
21 days	-2.059	-1119.3120	0.0018	-0.2985	0.005	0.532
28 days	-0.501	-363.0643	0.0013	-1.0018	0.003	-0.076
35 days	-0.126	-406.8761	0.0003	-0.8881	0.001	0.014
Hole no. 8						
1st day	0.020	8.8640	0.0022	42.5270	0.003	33.956
7 days	-0.099	-64.2131	0.0015	-5.8576	0.002	-4.728
14 days	-0.330	-291.4164	0.0011	-1.2752	0.002	-0.297
21 days	-0.016	-22.5762	0.0007	-16.6982	0.002	-19.963
28 days	-2.543	-3400.9452	0.0007	-0.0861	0.002	0.921
35 days	-0.135	-260.2850	0.0005	-1.4128	0.001	-0.381
Hole no. 9						
1st day	0.015	4.0416	0.0033	93.1210	0.002	36.792
7 days	-0.012	-23.9130	0.0005	-15.7682	0.001	-11.370
14 days	0.018	38.3128	0.0004	9.8704	0.001	9.427
21 days	-0.073	-230.7267	0.0003	-1.6217	0.001	-0.817
28 days	-0.008	-12.5940	0.0006	-29.9421	0.001	-19.401
35 days	0.004	5.0557	0.0007	74.6750	0.001	43.075
Hole no. 10						
1st day	0.011	12.9125	0.0009	29.2349	0.001	27.183
7 days	-0.018	-17.1234	0.0010	-22.0127	0.001	-16.189
14 days	0.018	25.5808	0.0007	14.7739	0.001	13.683
21 days	-0.004	-9.4862	0.0004	-39.7694	0.001	-41.496
28 days	-0.039	-79.1347	0.0005	-4.7379	0.001	-3.117
35 days	-0.006	-18.6110	0.0003	-20.2618	0.001	-22.566
Hole no. 11						
1st day	0.021	19.3644	0.0011	19.4880	0.001	22.328
7 days	-0.299	-322.1942	0.0009	-1.1559	0.001	-0.168
14 days	-0.250	-275.2058	0.0009	-1.3467	0.001	-0.297
21 days	-0.008	-11.0632	0.0007	-34.0864	0.001	-28.803
28 days	-0.105	-228.0350	0.0004	-1.6250	0.001	-0.598
35 days	0.115	307.3963	0.0004	1.2522	0.001	2.354

Accordingly, all the ratios are recalculated and presented in Tables IV(B) and V(B).

In this method, the values of different ratios as presented in Tables IV(B) and V(B) continued to be negative on the same days of observations as in the CH_4 free method.

It may be observed from the previous analysis that the gas ratios under the conditions investigated in this study fail to give any meaningful conclusion for early detection of fire. It may also be noted here that the different attempts made to recalculate the composition of air samples and gas ratios by different approaches have also failed for application to real life situations.

An in-depth critical study to find out the reasons for failure of all these approaches reveals that:

- The presence of a high percentage of methane may not only be responsible for making the values of these ratios negative. It has also been reinforced by the observation that even with a high percentage of methane in some of the boreholes, the values of different ratios are positive
- When the O_2 deficiency is negative, the Graham's, Young's and Morris ratios are negative. In some of these cases the percentage of blackdamp is also negative. In cases whereO_2 deficiency is negative and the percentage of blackdamp is positive, it has been observed that N_2 content of the blackdamp is negative.
- The oxygen deficiency is calculated on the basis of available nitrogen in the sample. It becomes negative only when the air is nitrogen deficient
- As nitrogen is non-reactive and inert there is no loss of nitrogen due to any reaction. There can be only deficiency of nitrogen in the borehole because of diffusion into the strata
- The diffusion of nitrogen into the strata is mainly influenced by the following factors:
  - liberation of methane from the strata resulting in empty pore spaces favouring diffusion of nitrogen and
  - the coal characteristics and other site conditions existing in the coal pillars.
- In addition to diffusion of nitrogen, the strata also adsorbs oxygen at normal temperature
- Therefore, it is difficult to establish a direct relationship between the percentage of methane liberated and diffusion of nitrogen and adsorption of oxygen into the strata

Table IV(A)

Values of gas indices and blackdamp percentage for different holes in Pillar 1 by CH_4 free method

Period of sample collection	Graham's ratio	Young' ratio	CO/CO_2 ratio	Morris ratio	Willet's ratio	Blackdamp %
Hole no. 1						
1st day	-2.1406	-978.54	0.22	-0.37	0.361	1.986
7 days	-0.6880	-376.10	0.18	-0.99	-11.568	-0.041
14 days	0.0241	15.05	0.16	25.79	0.006	28.331
21 days	0.0633	57.01	0.11	6.78	0.015	11.409
28 days	0.0138	7.99	0.17	48.85	0.004	42.503
35 days	0.0034	6.94	0.05	55.99	0.001	59.866
Hole no. 2						
1st day	-0.9983	-256.70	0.39	-1.46	-0.800	-0.994
7 days	-0.3051	-78.24	0.39	-4.84	-0.102	-11.993
14 days	0.0749	17.23	0.43	22.24	0.019	38.315
21 days	-0.2662	-55.52	0.48	-6.82	-0.082	-16.975
28 days	1.4010	540.40	0.26	0.71	0.153	7.617
35 days	-1.0406	-416.22	0.25	-0.90	3.063	0.221
Hole no. 3						
1st day	-1.2749	-374.97	0.34	-0.99	-12.911	-0.041
7 days	0.0359	17.10	0.21	22.44	0.009	40.483
14 days	0.0452	16.15	0.28	23.72	0.011	45.138
21 days	0.0408	13.17	0.31	29.08	0.010	53.953
28 days	-0.7783	-269.40	0.29	-1.40	-0.711	-2.743
35 days	0.1516	47.42	0.32	8.01	0.036	35.256
Hole no. 4						
1st day	0.0698	23.26	0.30	16.82	0.017	14.863
7 days	0.0372	14.61	0.25	26.53	0.009	29.877
14 days	0.0204	8.33	0.24	46.84	0.005	41.708
21 days	0.0245	7.25	0.34	53.93	0.006	42.740
28 days	0.0256	5.84	0.44	67.47	0.007	44.102
35 days	0.0127	3.56	0.36	113.34	0.003	48.294
Hole no. 5						
1st day	0.0503	24.27	0.21	15.89	0.013	23.708
7 days	0.0586	8.62	0.68	46.05	0.015	24.668
14 days	0.0260	7.33	0.35	53.97	0.007	32.563
21 days	0.0337	6.26	0.54	63.62	0.009	32.580
28 days	0.0223	8.77	0.25	45.48	0.006	24.282
35 days	0.0055	9.45	0.06	41.79	0.001	28.260
Hole no. 6						
1st day	0.0215	22.40	0.10	17.29	0.005	22.365
7 days	0.0469	13.68	0.34	28.75	0.012	20.951
14 days	0.0379	14.68	0.26	26.34	0.010	32.084
21 days	-0.1129	-49.69	0.23	-7.68	-0.034	-11.744
28 days	0.0210	6.07	0.35	64.30	0.005	53.127
35 days	0.0187	8.98	0.21	43.05	0.005	51.693

- If the diffusion of nitrogen is proportionately more than the adsorption of oxygen, the calculated values of oxygen deficiency based on the following formula will be negative :
  - O_2 deficiency = 0.265 N_2% available in the sample - O_2% available in the sample
- The diffusion of N_2 is more favoured compared to O_2 present in air for three reasons:
  - Lower molecular weight and density of N_2 compared to O_2, which may facilitate better diffusion of N_2 into the strata as per Graham's law (density of O_2: 1.331 g/l, and density of N_2: 1.165 g/l)[1]
  - Size of N_2 molecule (covalent radius: 0.549A^0)[1] is smaller compared to O_2 molecule (covalent radius: 0.603A^0)[1], thus it may easily migrate into the pore spaces vacated by liberation of CH_4
  - The percentage of N_2 present in normal air is nearly four times that of O_2. As a result, the partial pressure of N_2 is higher than O_2, which favours diffusion of N_2.

This also supports the earlier observation that the higher the gassiness of the seam, the lower its susceptibility to spontaneous combustion[2]. This may be due to diffusion of N_2 into the strata and creation of an inert atmosphere in the macro-pores and micro-pores retarding low temperature oxidation. In addition, some researchers[3–5] observed that emission of CH_4 from strata or goaf reduces the percentage of O_2 and makes the atmosphere inert to some extent, thus reducing the chances of spontaneous combustion.

In view of these observations, the following modification is suggested to calculate the gas ratios and blackdamp percentage:

$$\text{(1) Modified Graham's ratio} = \frac{\text{CO Produced}}{\frac{20.93}{79.04}\left(N_2 + CH_4\right) - O_2} \times 100$$

Table V(A)

Values of gas indices and blackdamp percentage for different holes in Pillar 2 by CH_4 free method

Period of sample collection	Graham's ratio	Young's ratio	CO/CO_2 ratio	Morris ratio	Willet's ratio	Blackdamp %
Hole no. 7						
1st day	0.0170	5.74	0.30	67.92	0.004	58.074
7 days	0.3505	63.72	0.55	6.26	0.080	4.440
14 days	-3.5777	-1192.55	0.30	-0.29	0.453	0.964
21 days	-2.0585	-1157.91	0.18	-0.30	0.273	0.875
28 days	-0.5008	-375.58	0.13	-0.99	-4.972	-0.038
35 days	-0.1258	-419.46	0.03	-0.88	0.392	0.100
Hole no. 8						
1st day	0.0205	9.20	0.22	42.00	0.005	50.793
7 days	-0.0993	-66.20	0.15	-5.72	-0.032	-20.491
14 days	-0.3305	-300.43	0.11	-1.25	-0.410	-0.725
21 days	-0.0160	-23.11	0.07	-16.40	-0.005	-83.154
28 days	-2.5428	-3496.30	0.07	-0.09	0.083	1.788
35 days	-0.1352	-270.43	0.05	-1.39	-0.120	-0.587
Hole no. 9						
1st day	0.0145	4.35	0.33	89.75	0.004	72.267
7 days	-0.0124	-24.84	0.05	-15.25	-0.004	-87.441
14 days	0.0176	39.63	0.04	9.67	0.004	23.088
21 days	-0.0727	-236.18	0.03	-1.60	-0.051	-2.194
28 days	-0.0075	-13.16	0.06	-28.84	-0.002	-129.339
35 days	0.0035	5.32	0.07	73.86	0.001	54.640
Hole no. 10						
1st day	0.0115	13.34	0.09	28.79	0.003	50.451
7 days	-0.0178	-17.79	0.10	-21.28	-0.005	-134.917
14 days	0.0176	26.46	0.07	14.53	0.004	26.926
21 days	-0.0035	-9.75	0.04	-38.81	-0.001	-345.934
28 days	-0.0386	-82.03	0.05	-4.65	-0.013	-6.283
35 days	-0.0064	-19.09	0.03	-19.90	-0.002	-75.188
Hole no. 11						
1st day	0.0213	19.90	0.11	19.17	0.005	57.364
7 days	-0.2989	-332.16	0.09	-1.13	-0.618	-0.502
14 days	-0.2502	-285.93	0.09	-1.31	-0.261	-0.724
21 days	-0.0076	-11.44	0.07	-33.11	-0.002	-205.785
28 days	-0.1048	-235.90	0.04	-1.60	-0.072	-1.070
35 days	0.1149	316.01	0.04	1.24	0.017	4.443

$$\text{(2) Modified Young's ratio} = \frac{CO_2 \text{ Produced}}{\frac{20.93}{79.04}(N_2 + CH_4) - O_2} \times 100$$

$$\text{(3) Modified Blackdamp \%} = \text{Excess } N_2 + \text{Excess } CO_2$$
$$= \left\{(N_2 + CH_4) - \frac{79.04}{20.93} \times O_2\right\} + \left\{CO_2 - \frac{0.03}{20.93} \times O_2\right\}$$

$$\text{(4) Modified Willet's ratio} = \frac{\text{CO Produced}}{\text{Blackdamp}}$$

$$\text{(5) Modified Morris ratio} = \frac{(N_2 + CH_4) - 3.774 \times O_2}{(CO + CO_2) \text{ produced}}$$

In these cases, CH_4 is considered to be inert because it oxidizes in the presence of an igniting source only above 550°C. Therefore, in the denominator of all gas indices and in the excess N_2 content of blackdamp, CH_4 is taken along with N_2 for calculating O_2 deficiency and excess inert component. In the calculation of Willet's ratio, the blackdamp in the denominator includes the CH_4 as inert gas and therefore the combustible gases should not be accounted for twice.

After incorporating all these modifications, the gas ratios and the blackdamp percentage for all 11 holes have been calculated and presented in Tables IV(C) and V(C).

It may be observed from these tables (Tables IV(C) and V(C)) that the values of blackdamp percentage and gas ratios are positive and can be suitably interpreted for early detection of fire in coal pillars.

Conclusions

This study into the prediction of pillar fire problems in coal-mines reveals the following:

- The commonly used gas indices are not suitable for application in an atmosphere containing high percentage of methane.
- The modified gas ratios have been proposed and should be used for early prediction of fires in pillars of all coal-seams.
- If the temperature inside a sealed-off fire area is less than 550°C, i.e. the ignition point temperature of

Table IV(B)

Values of gas indices and blackdamp percentage for different holes in Pillar 1 by CH_4 distribution method

Period of sample collection	Graham's ratio	Young's ratio	CO/CO_2 ratio	Morris ratio	Willet's ratio	Blackdamp %
Hole no. 1						
1st day	-2.141	-992.53	0.216	-0.349	0.361	0.775
7 days	-0.688	-385.45	0.178	-0.952	-11.568	-0.013
14 days	0.024	15.54	0.155	25.843	0.006	13.032
21 days	0.063	58.25	0.109	6.819	0.015	5.477
28 days	0.014	25 8.18	0.169	48.896	0.004	25.077
35 days	0.003	7.00	0.049	56.004	0.001	44.899
Hole no. 2						
1st day	-0.998	-261.50	0.382	-1.431	-0.800	-0.437
7 days	-0.305	-79.83	0.382	-4.802	-0.102	-3.838
14 days	0.075	17.48	0.428	22.262	0.019	21.073
21 days	-0.266	-57.23	0.465	-6.767	-0.082	-4.244
28 days	1.401	548.81	0.255	0.738	0.153	2.285
35 days	-1.041	-425.18	0.245	-0.860	3.063	0.075
Hole no. 3						
1st day	-1.275	-390.27	0.327	-0.921	-12.911	-0.013
7 days	0.036	17.32	0.207	22.461	0.009	23.075
14 days	0.045	16.37	0.276	23.740	0.011	24.375
21 days	0.041	13.34	0.306	29.107	0.010	29.674
28 days	-0.778	-274.19	0.284	-1.367	-0.711	-0.549
35 days	0.152	48.23	0.314	8.036	0.036	10.929
Hole no. 4						
1st day	0.070	23.33	0.299	16.822	0.017	13.763
7 days	0.037	14.61	0.254	26.534	0.009	29.519
14 days	0.020	8.33	0.244	46.841	0.005	41.708
21 days	0.024	7.25	0.337	53.935	0.006	42.441
28 days	0.026	5.84	0.439	67.471	0.007	43.352
35 days	0.013	3.56	0.356	113.336	0.003	48.198
Hole no. 5						
1st day	0.050	24.28	0.207	15.888	0.013	23.163
7 days	0.059	8.67	0.676	46.059	0.015	22.374
14 days	0.026	7.33	0.355	53.973	0.007	32.530
21 days	0.034	6.27	0.538	63.626	0.009	31.863
28 days	0.022	8.77	0.255	45.484	0.006	24.209
35 days	0.005	9.45	0.058	41.790	0.001	28.232
Hole no. 6						
1st day	0.022	22.40	0.096	17.285	0.005	22.298
7 days	0.047	13.70	0.342	28.751	0.012	20.008
14 days	0.038	14.68	0.258	26.345	0.010	32.052
21 days	-0.113	-50.20	0.225	-7.663	-0.034	-7.281
28 days	0.021	6.07	0.345	64.301	0.005	53.074
35 days	0.019	8.98	0.208	43.052	0.005	51.641

methane, the modified ratios presented in the paper may also be used for assessing the condition of fire in such sealed off panels. However, applicability of the modified ratios may be tested in subsequent studies for assessing the condition of fire in sealed-off panels.

Acknowledgement

The authors thank to the Director, Indian School of Mines, Dhanbad for permission to publish the paper. The views expressed are of the authors and not necessarily of the organisation to which they belong.

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Table V(B)

Values of gas indices and blackdamp percentage for different holes in Pillar 2 by CH_4 distribution method

Period of sample collection	Graham's ratio	Young's ratio	CO/CO_2 ratio	Morris ratio	Willet's ratio	Blackdamp %
Hole no. 7						
1st day	0.017	5.79	0.293	67.938	0.004	47.389
7 days	0.350	65.54	0.535	6.307	0.080	2.753
14 days	-3.578	-1212.68	0.295	-0.259	0.453	0.530
21 days	-2.059	-1170.65	0.176	-0.276	0.273	0.587
28 days	-0.501	-380.09	0.132	-0.969	-4.972	-0.024
35 days	-0.126	-422.35	0.030	-0.870	0.392	0.077
Hole no. 8						
1st day	0.020	9.32	0.220	42.016	0.005	34.031
7 days	-0.099	-67.73	0.147	-5.683	-0.032	-4.713
14 days	-0.330	-306.11	0.108	-1.219	-0.410	-0.268
21 days	-0.016	-23.51	0.068	-16.374	-0.005	-19.957
28 days	-2.543	-3540.16	0.072	-0.064	0.083	0.965
35 days	-0.135	-274.79	0.049	-1.362	-0.120	-0.334
Hole no. 9						
1st day	0.015	4.50	0.322	89.811	0.004	36.856
7 days	-0.012	-25.66	0.048	-15.197	-0.004	-11.367
14 days	0.018	40.41	0.044	9.707	0.004	9.466
21 days	-0.073	-239.67	0.030	-1.573	-0.051	-0.790
28 days	-0.008	-13.64	0.055	-28.784	-0.002	-19.401
35 days	0.004	5.38	0.066	73.877	0.001	43.166
Hole no. 10						
1st day	0.011	13.54	0.085	28.819	0.003	27.243
7 days	-0.018	-18.38	0.097	-21.228	-0.005	-16.190
14 days	0.018	26.90	0.066	14.556	0.004	13.732
21 days	-0.004	-9.99	0.036	-38.772	-0.001	-41.512
28 days	-0.039	-83.51	0.046	-4.621	-0.013	-3.079
35 days	-0.006	-19.42	0.033	-19.875	-0.002	-22.557
Hole no. 11						
1st day	0.021	20.22	0.105	19.194	0.005	22.372
7 days	-0.299	-339.23	0.088	-1.095	-0.618	-0.146
14 days	-0.250	-292.68	0.085	-1.274	-0.261	-0.268
21 days	-0.008	-11.77	0.065	-33.057	-0.002	-28.810
28 days	-0.105	-239.67	0.044	-1.571	-0.072	-0.557
35 days	0.115	319.98	0.036	1.258	0.017	2.399

Table IV(C)

Values of gas ratios and blackdamp percentage for different holes in Pillar 1 with CH_4 as inert

Period of sample collection	Graham's ratio	Young's ratio	CO/CO_2 ratio	Morris ratio	Willet's ratio	Blackdamp %
Hole no. 1						
1st day	0.0175	7.99	0.22	47.18	0.0045	61.77
7 days	0.0084	4.61	0.18	81.79	0.0022	67.99
14 days	0.0045	2.84	0.16	132.90	0.0012	67.03
21 days	0.0053	4.79	0.11	78.79	0.0014	57.48
28 days	0.0052	3.00	0.17	125.90	0.0014	66.08
35 days	0.0022	4.43	0.05	85.28	0.0006	69.90
Hole no. 2						
1st day	0.0242	6.22	0.39	60.54	0.0063	55.56
7 days	0.0233	5.98	0.39	62.95	0.0061	64.16
14 days	0.0232	5.33	0.43	70.54	0.0061	66.07
21 days	0.0189	3.94	0.48	95.50	0.0049	70.76
28 days	0.0186	7.19	0.26	52.43	0.0048	72.29
35 days	0.0133	5.33	0.25	70.67	0.0035	66.08
Hole no. 3						
1st day	0.0095	2.80	0.34	134.57	0.0025	67.99
7 days	0.0122	5.80	0.21	64.97	0.0032	66.08
14 days	0.0152	5.44	0.28	69.20	0.0040	70.37
21 days	0.0159	5.13	0.31	73.47	0.0042	74.67
28 days	0.0189	6.53	0.29	57.70	0.0049	79.45
35 days	0.0187	5.85	0.32	64.32	0.0049	79.93
Hole no. 4						
1st day	0.0296	14.82	0.20	25.48	0.0076	21.16
7 days	0.0268	14.01	0.19	26.93	0.0068	30.72
14 days	0.0204	8.33	0.24	45.28	0.0053	41.71
21 days	0.0267	7.13	0.38	52.79	0.0070	43.14
28 days	0.0271	4.32	0.63	86.88	0.0071	45.05
35 days	0.0283	3.54	0.80	105.79	0.0074	48.40
Hole no. 5						
1st day	0.0455	21.95	0.21	17.19	0.0114	25.46
7 days	0.0412	6.05	0.68	62.03	0.0107	31.67
14 days	0.0259	7.31	0.35	51.53	0.0067	32.63
21 days	0.0315	5.85	0.54	64.26	0.0082	34.06
28 days	0.0220	8.66	0.25	43.56	0.0057	24.51
35 days	0.0055	9.42	0.06	40.12	0.0014	28.33
Hole no. 6						
1st day	0.0212	22.09	0.10	17.11	0.0053	22.60
7 days	0.0380	11.09	0.34	33.98	0.0098	24.51
14 days	0.0378	14.63	0.26	25.77	0.0096	32.15
21 days	0.0319	14.02	0.23	26.92	0.0081	30.72
28 days	0.0209	6.06	0.35	62.13	0.0055	53.17
35 days	0.0187	8.96	0.21	42.06	0.0048	51.74

Table VC

Values of gas ratios and blackdamp percentage for different holes in Pillar 2 with CH_4 as inert

Period of sample collection	Graham's ratio	Young's ratio	CO/CO_2 ratio	Morris ratio	Willet's ratio	Blackdamp %
Hole no. 7						
1st day	0.0122	4.12	0.30	91.43	0.0032	65.79
7 days	0.0206	3.74	0.55	100.45	0.0054	40.75
14 days	0.0203	6.75	0.30	55.80	0.0053	45.53
21 days	0.0185	10.39	0.18	36.31	0.0048	33.59
28 days	0.0129	9.68	0.13	38.98	0.0033	35.98
35 days	0.0051	17.09	0.03	22.13	0.0013	23.08
Hole no. 8						
1st day	0.0103	4.62	0.22	81.61	0.0027	67.03
7 days	0.0079	5.30	0.15	71.20	0.0021	72.29
14 days	0.0067	6.12	0.11	61.69	0.0018	62.73
21 days	0.0062	8.97	0.07	42.11	0.0016	56.04
28 days	0.0066	9.05	0.07	41.70	0.0017	46.97
35 days	0.0036	7.21	0.05	52.36	0.0009	42.67
Hole no. 9						
1st day	0.0062	1.86	0.33	202.77	0.0016	85.86
7 days	0.0020	4.04	0.05	93.52	0.0005	75.63
14 days	0.0022	5.03	0.04	75.07	0.0006	68.47
21 days	0.0024	7.93	0.03	47.63	0.0006	63.21
28 days	0.0023	4.07	0.06	92.70	0.0006	65.60
35 days	0.0024	3.56	0.07	105.92	0.0006	64.17
Hole no. 10						
1st day	0.0042	4.86	0.09	77.71	0.0011	73.24
7 days	0.0043	4.25	0.10	88.70	0.0011	71.81
14 days	0.0037	5.50	0.07	68.69	0.0010	62.73
21 days	0.0033	9.15	0.04	41.29	0.0009	46.49
28 days	0.0032	6.82	0.05	55.40	0.0008	47.92
35 days	0.0033	9.80	0.03	38.56	0.0008	47.44
Hole no. 11						
1st day	0.0055	5.14	0.11	73.37	0.0014	83.37
7 days	0.0049	5.41	0.09	69.81	0.0013	70.85
14 days	0.0043	4.88	0.09	77.38	0.0011	62.73
21 days	0.0040	6.04	0.07	62.54	0.0010	57.19
28 days	0.0032	7.30	0.04	51.74	0.0008	47.44
35 days	0.0032	8.78	0.04	43.02	0.0008	48.40

Electra Mining Africa 2004: the biggest and the best*

Africa's premier mining, industrial, construction and electrical show, Electra Mining Africa, has exceeded the 500 exhibition booking mark—net space sold to date is over 27 000 m^2 compared to 24 795 m^2 sold in 2002, when the last show was held.

As a result, Specialised Exhibitions, organizers of the event, are expecting visitor numbers to exceed the previous years' average of 30 000 visitors.

John Kaplan, Specialised Exhibitions MD and exhibition director of Electra Mining Africa, says 'Electra Mining Africa is once again proving that, as the second biggest mining show worldwide and one of the best of its kind internationally, it is a strong catalyst for new investment opportunities in the mining, industrial, construction and electrical industries. As the biggest exhibition in southern Africa, and Africa's premier mining and mining-related show, it is the gateway into Africa for investors around the world.'

Government has committed to the show with the South African Department of Minerals and Energy (DME) again running Mining Week concurrently with Electra Mining Africa. The Department of Trade and Industry (DTI) will host a stand in Hall 8, with a conference and events programme for the duration of the show. Its export arm, the Capital Equipment Export Council, has also advised Specialised Exhibitions that they have invited and subsidized over 40 major buyers and specifiers from Africa and all parts of the world to attend Electra Mining Africa 2004.

In addition, a delegation of 12 mining engineers, from Teniente Mine of Codelco, Chile, the largest copper mine in the world, will also attend Electra Mining Africa. There will be representation from all the major mining and mining-related countries, including Australia, Canada, the Ukraine, Saudi Arabia, India, and China.

'Many new products are launched at the show, and this year will be no different,' says Kaplan. 'The show offers visitors the perfect opportunity to view all the latest technology, while it gives the exhibitor the opportunity to meet with the people in the buying chain and for them to meet with the technical team of the exhibitor, including international experts, to discuss their needs and problems face to face.'

Both Elenex, the collocating show at Electra Mining Africa 2004, and the newest addition to the show, Machine Tool and Accessories, are virtually booked out.

'Electra Mining Africa 2004 really is a mega event that covers the mining industry, the electrical industry, the construction industry, the manufacturing industry, the materials handling industry, transport industry and IT, and that is not to be missed,' concludes Kaplan.

Specialised Exhibitions, which is affiliated to Montgomery Exhibitions (UK), has over 30 year's experience in leading the exhibition industry on the African continent by staging world-class events. Its exhibitions meet the needs of the industries it serves, and provides value-added opportunities for exhibitors and visitors alike.

This will be Bell's 10th consecutive Electra Mining Africa, and the company will be celebrating two 50 milestones at the show: the company's 50th anniversary and the production of its largest Articulated Dump Truck, the B50D, a 50 ton 6 x 6.

Barloworld Equipment, whose stand was the talk of the show in 2002, will again be one of the biggest and most comprehensive stands at the exhibition. The company's theme for this year is Smart Technology—Smart Partner, which will be demonstrated to the visitor via an interactive journey.

Babcock Equipment has a 1 600 square metre stand in the outside area. It is launching its new product range at the show and looking to repeat success of the 2002 show, when the company sold three units valued at R2.5 million.

KH Diesel Electrical cc located in Hall 5 will be launching the well-known and reputable Australian Hella mining product range at this year's show. This follows the company's recent appointment as distributors of Hella Mining Product division's mobile equipment lighting range and 230–240 v fixed lighting range in southern Africa.

The Electrical Equipment Exhibition is a group of electrical and engineering businesses incorporating electrical instrumentation and electronics industries. The group has booked a total of 220 m^2 in Hall 7.

Iscar, a major player in the machine tool and accessories market, is looking forward to seeing their customer base at the show.

Another player in this market, Multitrade Distributors will be using the opportunity to launch a new technology threading tool.

Further information: The Exhibition Director, Specialised Exhibitions, Tel: +27 11 835 1565; Fax: +27 11 496 1161. ◆

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