

Assessing the status of sealed fire in underground coal mines

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The paper highlights the different aspects of gas sampling in sealed mine fire area. Different fire ratios along with their limitations are also described, in detail. The paper also deals with different methods to determine the explosibility of gas mixtures with suitable examples. Recently obtained field data are also being analysed in respect of fire-ratios and explosibility diagram.

Keywords: Sealed fire, Gas sampling, Fire-ratios, Explosibility triangle

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Introduction

Fires represent one of the two most probable causes of major disasters in underground coal mining, involving loss of precious lives, hindrance in coal production, and loss of machinery involved in coal wining operation. An uncontrolled fire in an underground coal mine frequently can only be attacked by sealed off fire zone or the entire mine in the worse situations. The intent of sealing is to allow the fire to consume available oxygen eventually bringing to a halt any underground combustion. This sealed coal mine fire, which is also called concealed fire, generally has no connection with the main ventilation district. Normally concealed fire is caused by auto oxidation of coal (spontaneous heating). In this case the degree of pollution of mine atmosphere is limited and depends upon the amount of leakage from fire area to general mine atmosphere.

While dealing with coal mine fire the procedures mine management should adopt after sealing the fire area are correct sampling of the atmosphere within a sealed area, analysis of gas and temperature measurement. Gas analysis results are then interpreted with respect to relevant fire ratios. Explosibility of gas mixtures can then be determined with the help of Coward's diagram or USBM explosibility triangle or Ellicott's extension. This paper is devoted to all the above-mentioned steps while assessing the status of sealed coal mine fire. Recently obtained field data are also being analyzed in the light of fire-ratios and explosibility of gas mixture to assess the status of fire.

Gas Sampling

Why Gas Sampling?

When a fire breaks out the foremost thing a mining engineer should do is to seal the fire area from all sides and thereby isolate it from the main ventilation system. This isolation is necessary for probably two reasons; to cut off the supply of oxygen into the fire area and to know the status of fire through the sampling points provided in the isolation stoppings. Some researchers¹ have mentioned that while dealing with a mine fire the questions that come to a mining engineer's mind are as follows:

- Is the fire under control?
- Effectiveness of the methods of fire control which are being used.
- Are the workforce employed in underground in combating the fire in danger?
- Can these fire fighters move quickly to a safe area should an explosive mixture develop?

The only means available to answer these questions is the information regarding the composition of atmos-

phere in the fire area. This calls for proper sampling of air within the sealed area.

Procedure to be Followed

In order to obtain uniform results, various sampling procedures must be adopted. These are listed below.

- (i) Samples should be taken as frequent as possible. Comparisons of results should be made with the same sampling points.
- (ii) In order to judge the intensity of heating number of sampling points should be as much as possible.
- (iii) It should be the usual practice of a mine to take gas samples at regular intervals immediately after sealing until such results show that the situation is no longer dangerous. After that follow up samples are usually taken at less frequent intervals until no longer required.
- (iv) Samples drawn through the tube or pipe should contain the atmosphere that one requires to be sampled. Samples collected in sampling bag should always be ringed or should be made air free by suction pump before taking sample on it.
- (v) The pressure difference across each stopping should be measured before taking samples. Wherever possible, arrangements for pressure measurement should be kept ready.
- (vi) While sampling it should be ensured that no water is being injected into the fire area because this water injection may produce water gas leading to erroneous results in the gas analysis.
- (vii) If a seal is in a dipping road any possible leakage through it causes fresh air running inbye along the floor. In this it is advisable to erect sampling pipes at three levels.

Provisions are made for continual samples from a fixed sample point where there is high incidence of heating. It has been reported that in South Africa Mobile Gas Analysis Laboratory (MOGAL) have been utilized many a times to tackle heating in mines. Continual samples are being sent to the MOGAL via tube bundle system. The laboratory has many advantages viz. Gas analysis results obtained almost immediately, cost saving and accuracy².

Determination of Optimal Gas Sampling Time and Location

Air moves in and out of sealed off areas with change in barometric pressure which is called breathing effect of stopping. Fan pressure may cause unidirectional leakage through sealed off areas. These two factors may have profound influence on results of gas samples taken from such areas. To study these factors pressure differential across seal should be measured at least for 12 h (if possible for 24 h) to find out the pressure behaviour of isolation stopping. Simultaneously the surface and underground barometric pressure is measured round the clock. It has been experienced that this optimal sampling time occurs just before the pressure differential across the seal changes from positive to negative and this prevails when the surface barometric pressure and hence the underground barometric pressure reaches a minimum point on its quasi-sinusoidal trough and starts rising³⁻⁵.

Figure 1 indicates optimal sampling period. Figure 2

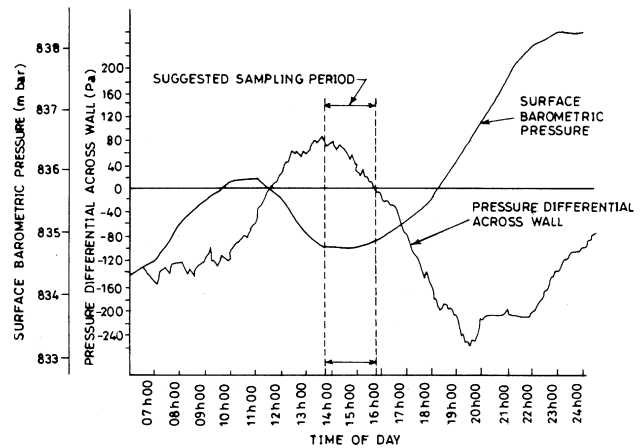


Fig. 1—Determination of sampling time from pressure graphs (after Fauconnier & Beukes⁴)

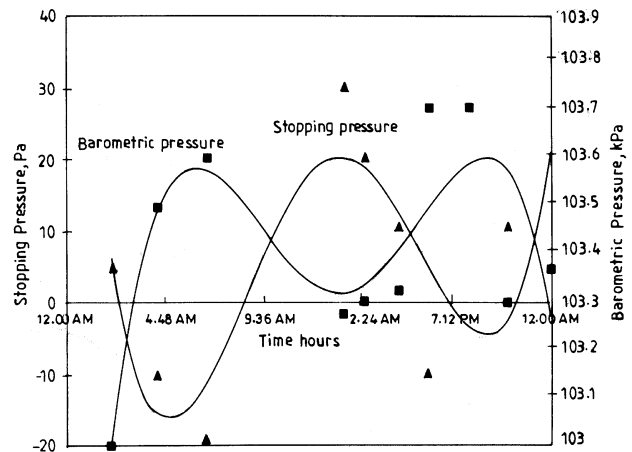


Fig. 2—Stopping pressure and barometric pressure with time in a mine of BCCL (after Sahay *et al.*⁵)

shows the stopping pressure behaviour with barometric pressure measured round the clock in a mine of Bharat Coking Coal Ltd. (BCCL).

Method of Gas Sampling as Practiced in India

Gas samples are taken through sampling pipes, meant for the purpose, that are inserted into the isolation stopping. Pipes made of iron are generally of 1.5 in. internal diam and 3-5 ft length. The length of the pipe depends upon the width of the isolation stopping and should be such that drawing air through it represents the whole fire area. Mouth of the pipe should be closed with a threaded cap having a rod fixed on it.

Sampling is done by suction pump / Air pump so as to get a true representative sample. It is advisable to draw samples from the fire area when stopping shows a positive pressure with respect to the gallery. Arrangements are being provided for Indian mines to measure the pressure of isolation stopping by keeping a U tube manometer attached to the sampling points. Suction pump always creates a suction pressure to make the isolation stopping in positive pressure while sampling. The effect of barometric pressure and fan pressure should be duly taken care of to achieve an actual gas sampling time.

Temperature Measurement

Temperature in and around the seat of fire is an important parameter while dealing with sealed coal mine fire. Digital temperature recorder is extensively used in Indian coal mines. From the sampling points the temperature is measured at a distance of 15ft (5 m) inbye of isolation stopping. The temperature recorder is attached with a cable of 5m length and probe. The cable that is attached with the probe is being tied with 5mm diam steel rod of 3ft length. This rod is threaded at its both end. Likewise arrangements in five rods are there, each being threaded at both ends in such a way that one can be fitted with the other one. Thus, all the five rods are inserted in the sampling pipe and temperature at a distance of 5m can be known. It is worthwhile to mention here that one should always calibrate the temperature recorder before actual measurement takes place in the mine.

Temperature in sealed areas can also be measured utilizing different types of sensors available in the market or clinical type maximum thermometers. Infra-red thermometers (IR gun) are used to locate the hot spots accurately even from a distance. It has been experienced that one may miss the information on progress of heating in a mine, if the temperature-measuring device does not reach the hot zone, which is likely in the case of vast mine. The temperature measurement study is therefore to be always supplemented with gas survey studies of the fire environment.

Analysis of Sample Results

Sample gas results are analyzed with the basis of Fire ratios or Explosibility triangle or with both.

Fire Ratios

Interpretation of gas analysis results systematically calls for a powerful tool known as fire indices. Since the beginning of the twentieth century many ratios and composites of gas concentration have been suggested to assist in the interpretation of fire gases.

Graham's Ratio^{6,7}

This ratio is widely used in Indian mines as a criterion of the state of heating and fires in the early as well as later development stages. The production of CO in relation to the oxygen consumed by the oxidized material is a function of temperature and therefore indicates the average intensity character of a fire. This ratio, generally expressed as a percentage, represents the fraction of the oxygen absorbed as a result of heating or fire which appears as carbon monoxide.

As a thumb rule it can be taken that:

- 0.4 per cent or less indicates normal value.
- 0.5 per cent indicates necessity for a thorough check-up.
- 1 per cent indicates existence of heating.
- 2 per cent indicates serious heating approaches active fire.

- 3 per cent and above indicate active fire with certainty.

Values of Graham's ratio ≥ 7 may occur for blazing fire. With rise in intensity of the fire the ratio may even go up to as high as 10 per cent or more due to formation of water gas (CO and H₂) or producer gas (CO and N₂). This ratio has the significant advantage that it is almost independent of dilution by leakage of air as this effects both numerator and denominator equally.

This ratio possess the following disadvantages:

- The absence of CO is not a safe criterion that a fire has been extinguished but rather than active combustion has ceased.
- CO may be lost due to dilution, oxidation by wet coal or bacteria or it may not diffuse throughout the entire area.
- In some cases the CO produced by normal oxidation in goaves or wastes may not disappear at all or fall at a very slow rate.
- If the oxygen deficiency is less than 0.3 per cent.
- Finally, it will be affected by sources of carbon monoxide other than the fire, i.e. if the air supplied to the fire is not fresh. This can occur if the fire is fed, partially, by air that has migrated through old workings and contains blackdamp (deoxygenated air).

Young's Ratio

Carbon dioxide produced as a percentage of oxygen absorbed is considered as Young's ratio or CO₂/O₂ def. Ratio. As the fire progresses from smouldering to open flame, the burning of carbon monoxide will produce an increase in carbon dioxide. Hence, a simultaneous rise in [CO₂]/ΔO₂ and fall in [CO]/ΔO₂ indicates further development of the fire. However, as both ratios have the same denominator, the straightforward plot of carbon monoxide and carbon dioxide show the same trends. If the value of this ratio is below 25 it is considered to be indicative of superficial heating. If it is more than 50 it should be corroborated with other fire indices to rule out or confirm a high intensity fire⁷.

This ratio suffers from various limitations

- Its accuracy becomes suspect if very little oxygen has been consumed, i.e. the oxygen deficiency, ΔO₂ is less than 0.3 per cent.
- The concentration of carbon dioxide may have been influenced by adsorption, its solubility in water, strata emissions of the gas and other chemical reactions.

Willett's Ratio⁸

Carbon dioxide produced divided by sum of blackdamp and combustible gases present is considered as Willett's ratio. This ratio is applicable to the specific situations where there is a higher than usual evolution of carbon monoxide by ongoing low temperature oxidation. This ratio can be used as a criterion of progress towards the extinction of fire behind the seals under circumstances where the Graham's index does not apply. It may be pointed out here that the absolute figures vary from seam to seam and even from district to district, thus it is only the trends that can be universally applied. Some researcher emphasized that the constancy of the Willett's ratio is not an indication that a fire is extinct but only that the fire activity has greatly decreased. He inferred that [CO]/[CO₂] ratio is more relevant in this regard⁸.

CO/CO₂ Ratio^{7,9,10}

This ratio, [CO]/[CO₂] of products of combustion may be considered to attain an equilibrium in a particular combustion situation. Thus attempts have been made to understand the fire situation from this ratio. It indicates the completeness of the combustion or oxidation. If the value of this ratio is more than 2 per cent it indicates active fire in the adjacent zone. If the value of this ratio is equal to or more than 13 it indicates a blazing fire. This ratio has the significant advantage that it is unaffected by inflows of air, methane or injected nitrogen. It is, however, subject to variation in carbon monoxide and carbon dioxide that are not caused by fire. Limitations are chances of appearance of blackdamp and disappearance of CO₂ (dissolution in water, etc.) in mines. Generally

Table 1—Application of C/H ratio in assessment of fire (after Banerjee⁹, 1985)

C/H values, from analytical data of fire areas	Rate of oxygen consumption	Nature of fire
High and very near to that of coal, i.e. nearly 20	Fast	Blazing and extensive burning of coal
	Slow	Blazing but localized burning of coal
Appreciably higher than that of coal, i.e. more than 20	Fast	Blazing and extensive fire associated with burning of props
	Slow	Blazing fire associated with burning of props etc. but a localized one
Appreciably lower than that of coal, i.e. much below 10	Fast	Superficial fire but covering an extensive fire
	Slow	Superficial fire and a localized one

the $[\text{CO}]/[\text{CO}_2]$ ratio is a more sensitive indicator than the $[\text{CO}]/\Delta\text{O}_2$ ratio for determining the state of a coal mine fire, since the former is more sensitive to temperature. However the $[\text{CO}]/\Delta\text{O}_2$ ratio is widely accepted for early detection of coal fire, largely because of the availability of CO field sensor as compare to CO_2 sensor.

Jones and Trickett Ratio¹¹

This ratio $\{[\text{CO}_2] + 0.75[\text{CO}] - 0.25[\text{H}_2]\}/\Delta\text{O}_2$ serves as an indicator of the type of fuel involved in any fire or explosion. Jones and Trickett developed this ratio for determining whether methane or coal dust has been involved in a mine explosion. Its value ranges between 0.4 to 0.5 if methane is involved; 0.5 to 1 for coal, oil or conveyor belt and 0.9 to 1.6 for timber. It is an indication of extinguishment or greatly reduced coal temperatures, if the value is less than 0.5.

C/H Ratio^{12,7,9}

Ghosh and Banerjee introduced C/H ratio to assess the intensity character of the fire, along with rate of oxygen consumption that indicates extensivity character of it.

Considering coal to be a fuel of the type $\text{C}_x\text{H}_y\text{O}_z$ they showed the method of calculation to be as:

$$\frac{3(\text{CO}_2 + \text{CO} + \text{CH}_4 + 2\text{C}_2\text{H}_4)}{(0.2648\text{N}_2 - \text{O}_2 - \text{CO}_2 - 0.5\text{CO} + 0.5\text{H}_2 + \text{CH}_4 + \text{C}_2\text{H}_4)} \dots (1)$$

C/H ratio up to a maximum of 3, indicate only superficial heating, values above 5 of active fire and from around 20 of a blazing fire. Based on C/H ratio and oxygen consumption rate they have given a method to determine the nature of fire in a sealed area (Table 1).

Litton Ratio^{13,14}

This ratio was designed to eliminate the potential for reignition of a mine fire when oxygen was reintroduced into the mine during reopening. Only four gases are required to measure to determine this ratio. They are oxygen, carbon monoxide, methane, and ethane. The atmosphere is divided into three parts: air, methane, ethane, and residual gas. Residual gas (R_g) is the volume per cent of gas within a sealed coal mine after air, methane and ethane have been eliminated from the sample. R_g contains excess nitrogen (not part of air), Products of Combustion (POC) (CO , CO_2 , H_2 and hydrocarbons), along with products formed by chemical processes not related to combustion and is presented as:

$$R_g = 100 - \text{air} - \text{CH}_4 - \text{C}_2\text{H}_6,$$

where $\text{air} = \text{Alfa} \cdot \text{O}_2$ and $\text{Alfa} = 100/20.946 = 4.774$.

The CO concentration in parts per million of air within the residual gas is:

$$(\text{CO})_{R_g} = [(\text{CO})_S / R_g] \times 100,$$

where $(CO)_s$ is the concentration of CO, ppm in the original sample.

Utilizing the concentration of CO within the residual gas a new parameter called the R-index (R_1) is derived as:

$$R_1 = \frac{(CO)_{ppm} \times 4.387}{(20.946 - O_2 - 0.20946CH_4 - 0.20946C_2H_6)^2} \quad \dots (2)$$

From mathematical point of view, if CO within a sample remains constant while R_g either increases or decreases the R-index is the absolute value of the rate of change of the CO within the residual gas with respect to change in the residual gas. If R_1 is constant, either sustained low temperature combustion or a low rate of ambient CO production is occurring. When combustion takes place the average R_1 will be greater than if ambient CO production is occurring.

From any sample of gas, R_g can be calculated from the measured O_2 , CH_4 and C_2H_6 . From the measured value of CO (in ppm) and the calculated value of R_g the actual value of R-index can be determined. This value is denoted by $(R_1)_{act}$. Further from the measured O_2 concentration and the calculated R_g value, a maximum equilibrium value for the R-index can be calculated using following equation.

$$(R_1) = 300 \left(\frac{R_g}{O_2} \right)^{-0.5} \quad \dots (3)$$

This equation has been obtained by Litton from the graph plotted R_1 vs the ratio R_g/O_2 . The graph has been plotted after collecting samples from behind stoppings when it was known that no combustion was present.

An equation RATIO determines the state of a sealed area:

$$RATIO = \left(\frac{(R_1)_{act}}{(R_1)_{eq}} \right) \quad \dots (4)$$

If RATIO is equal to one it serves only as a benchmark that divides the region between unsafe and possibly safe conditions. If it is greater than one, temperatures are above ambient and either smoldering combustion or above ambient temperature oxidation is taking place. When RATIO is less than or equal to one it represents that the temperature is ambient and a state of equilibrium exists. However equilibrium continues only if RATIO stabilises at a value less than one and remains there for at least 30 d.

Hydrogen/Methane Ratio¹⁵

This ratio was developed by Mitchell and used as an indicator of flaming combustion. The progression of gas liberation is normally: carbon monoxide, carbon dioxide, hydrogen, ethylene, propylene, and acetylene. Combustion occurs as the temperature rises above the liberation point of hydrogen. Therefore, if gases above hydrogen are detected, an active fire is indicated.

Hydrocarbon Ratio¹⁶

Justin and Kim have suggested a method by which drilling a large number of boreholes in a fire area from surface and drawing out gas samples from within the location of a fire as well as its state of heating could be determined. Methane is the primary hydrocarbon liberated at ambient temperatures. They have shown that the desorption of low molecular weight hydrocarbon coal gases is directly related to temperatures.

The hydrocarbon ratio equation was derived as:

$$R_1 = \frac{[1.01(THC)_{ppm} - (CH_4)_{ppm}]1000}{(THC)_{ppm} + (C)_{ppm}},$$

where THC = total hydrocarbon concentration, ppm; CH_4 = methane concentration, ppm; and C = constant,

0.01 ppm.

RI equals to zero when no hydrocarbons are present in the sample, 10 when methane is the only hydrocarbon measured and about 1010 at the upper limit. The only limiting factor is that methane must be greater than 20 ppm.

Explosibility Triangle

After knowing the status of heating the next question which often comes to a practicing mining engineer is whether the gas mixture in the sealed area is explosive in nature. The gas mixture becomes explosive when there is rising concentration of combustible gases and falling concentration of oxygen. Coward triangle¹⁷ which has been earlier used to assess the explosibility of mine atmosphere suffers from one serious drawback is that it considers the explosibility of methane-air mixture only. Apart from methane mine fire atmosphere also contains combustibles like, hydrogen and carbon monoxide. Further the generation of CO₂ increases the level of incombustible over the level attributable to nitrogen only⁴. The presence of carbon monoxide and or hydrogen may cause significant changes in the Coward diagram. Figure 3 shows the explosive triangles, incorporating more than one combustible gas in the Coward diagram.

These facts were given due consideration while constructing USBM triangle¹⁸ USBM explosibility triangle (Figure 4) was developed, way back in 1959. The explosibility diagram utilises the concept of converting the methane, hydrogen, and carbon monoxide in the atmosphere to an effective combustible content and the carbon dioxide and nitrogen to an effective inert content. Effective inert is equal to per cent of excess nitrogen plus 1.5-times per cent of CO₂. Per cent of excess nitrogen is equal to per cent of nitrogen in the sample minus per cent of normal nitrogen. Per cent of normal nitrogen is equal to 3.8-times per cent of O₂ in the sample. The factor 3.8 is the volume ratio of N₂ to O₂ in normal air. Effective combustible is equal to per cent of CH₄ plus 1.25-times per cent of H₂ plus 0.4-times per cent of CO. The factors 1.25 and 0.4 are the ratios of the lower explosive limits of CH₄ to that of H₂ and CO, respectively. These concentrations then determine the composition point on the explosibility diagram.

The ratio R of methane (CH₄) to total combustibles (CH₄ + H₂ + CO) determines the explosibility curve to be used in Figure 4. These curves are labeled 1.0, 0.8, 0.6, 0.4, 0.2 and 0. Curve 1.0 applies to a mine atmosphere that contains only methane as combustible gas and the explosive mixtures are those with composition points lying in area A₁. Curve 0.8 applies to a mine atmosphere that contains four-times as much methane as hydrogen plus carbon monoxide, and the explosive mixtures are those with composition points lying in the areas A₁ and

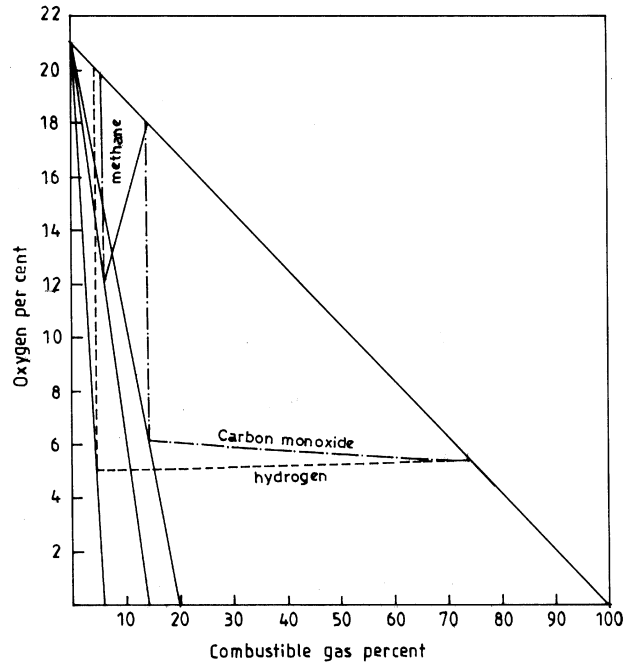


Fig. 3 — Coward diagrams for methane, carbon monoxide and hydrogen

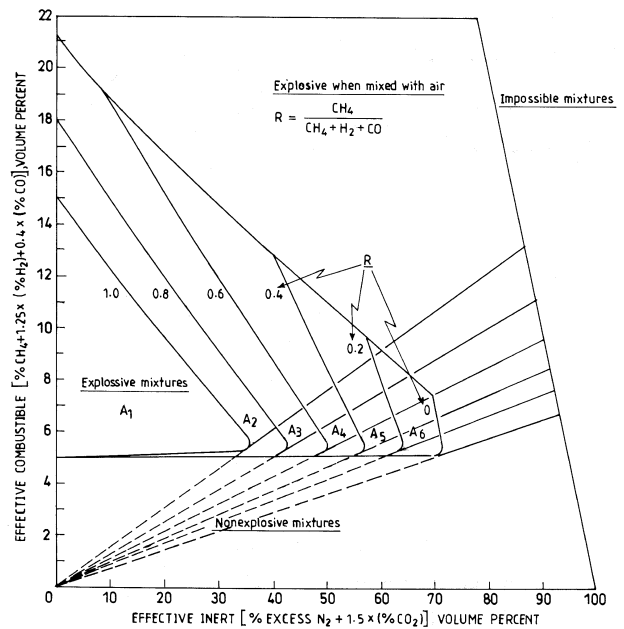


Fig. 4 — USBM explosibility diagrams

A₂. In the case of curve 0.6 the mine atmosphere contains 1.5-times as much methane as hydrogen plus carbon monoxide and the explosive mixtures are those with composition points lying in areas A₁ and A₂ and A₃, etc. Curve 0 applies to mine atmosphere that does not contain methane. It contains only hydrogen and carbon monoxide in addition to air and inert gases. Likewise intermediate curves may be constructed.

Let us take one example to understand the methodology to calculate whether the gas mixture is explosive or not. A sample taken from a sealed area yields the following analysis.

Oxygen	8.7 per cent
Carbon monoxide	0.94 per cent
Methane	1.8 per cent
Carbon dioxide	11.2 per cent
Hydrogen	3.3 per cent
Nitrogen	74.06 per cent

Per cent excess nitrogen = per cent N₂ in the sample – per cent normal N₂

= 74.06 per cent – 3.8 X per cent O₂ in the sample

= 74.06 per cent – (3.8 X 8.7) per cent = 41 per cent

Effective inert = per cent excess nitrogen + 1.5 X per cent CO₂

= 41 per cent + (1.5 X 11.2) per cent = 57.8 per cent

Effective combustibles = per cent CH₄ + 1.25 X per cent H₂ + 0.4 X per cent CO

= 1.8 per cent + (1.25 X 3.3) per cent + (0.4 X 0.94) per cent = 6.301 per cent

Total combustibles = 0.94 per cent + 1.8 per cent + 3.3 per cent = 6.04 per cent

R = (1.8 / 6.04) = 0.298

In Figure 5, effective inert is plotted on the horizontal axis and effective combustible on the vertical axis to arrive at the composition point shown in the above example. As this point lies, just within the explosive region for the 0.298 methane-to-total combustible flammability curve, the mine atmosphere should be considered explosive.

Both the above methods require the plotting of diagrams. They become cumbersome if a large number of samples are to be analyzed in emergency. To overcome these difficulties and for rapid assessment, Ellicott¹⁹ has further developed the Coward triangle method which does not require the drawing of diagrams to assess the explosibility of gas mixtures.

Ellicott has transformed the Coward's diagram that can be coded into computer. The program can convey the explosive state of analyzed gas mixture quickly and easily in interpretable form. The coordinates of the analyzed gas sample are modified to [Xm, Ym] in cartesian coordinates. All the characteristics of Coward's diagram are retained in the Ellicott's extension. Effect of air or inert gas dilution or increased combustible contents in general air dilution cause shift of the sample point towards top-left (Non-explosive), inert dilution towards bottom-left (Non-explosive) and increase in combustible content towards bottom-right (Potentially explosive). Conversion from Coward's diagram to Ellicott's extension for a mixture of multiple combustible gases are achieved by first calculating the coordinates of lower and upper limit of explosibility and coordinates of nose point using standard mathematical technique. Shifting the origin of the system to the nose point then modifies these coordinates. Central Mining

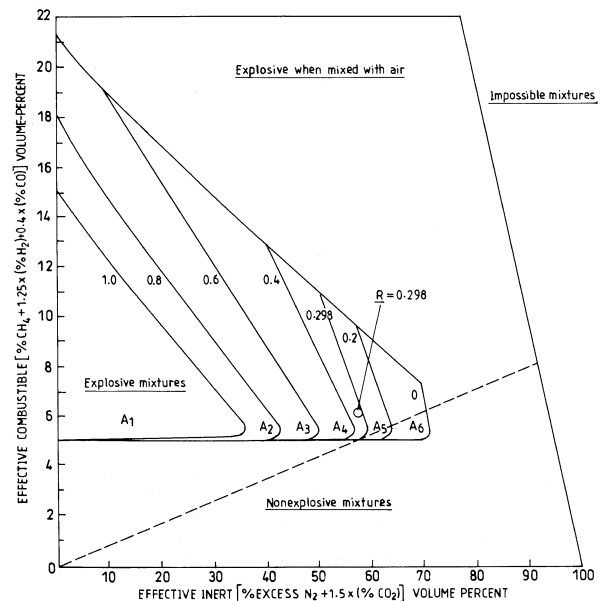


Fig. 5 — Gas analysis results plotted on USBM explosibility triangle

Table 2 — Fire-ratios and state of explosiveness for gas samples obtained from isolation stopping A

Day	O ₂	CO	CH ₄	CO ₂	H ₂	N ₂	Graham's ratio	Young's ratio	CO/CO ₂ ratio	Jones & Trickett ratio	Willett's ratio	Explosiveness
12-Sep	4.7	1.25	3.5	14.2	0	76.35	8.047513	91.41974	8.802817	0.974554	0.183368	NE
13-Sep	5.6	1.16	2.4	13.7	0	77.14	7.815606	92.305	8.467153	0.981667	0.187363	NE
14-Sep	6.3	1.19	3	12.9	0	76.61	8.498998	92.132	9.224806	0.985062	0.18492	NE
15-Sep	6.2	1.15	2.3	13.4	0	76.95	8.103299	94.42105	8.58209	1.004985	0.190774	NE
16-Sep	2.1	1.4	3.8	16.6	0	76.1	7.749149	91.88277	8.433735	0.976946	0.184609	NE
17-Sep	1.6	1.47	2.3	17	0	77.63	7.748281	89.60597	8.647059	0.954172	0.184142	NE
18-Sep	2.1	1.42	3.2	17.1	0	76.18	7.850639	94.53938	8.304094	1.004274	0.190169	NE
23-Sep	1.6	1.58	3.6	18	0	75.22	8.618197	98.182	8.777778	1.046456	0.194974	NE
24-Sep	6.4	1.02	3.2	12.2	4.3	72.88	7.898894	94.47697	8.360656	0.920763	0.176097	PE
27-Sep	2.6	1.32	4.4	17	5.7	68.98	8.418528	108.4204	7.764706	1.056462	0.194241	PE
01-Oct	5.2	1.56	4.4	16.4	7.2	65.24	12.90472	135.665	9.512195	1.304535	0.21855	PE
09-Oct	3.9	1.16	4.2	17	5.9	67.84	8.240041	120.7592	6.823529	1.164616	0.209154	PE
22-Oct	2.3	1.32	4.4	17.7	5.6	68.68	8.301782	111.3194	7.457627	1.087408	0.198966	PE
31-Oct	3.4	1.08	3.8	15.5	4.8	71.42	6.955939	99.83061	6.967742	0.973187	0.185229	PE
08-Nov	6.2	0.98	3.2	13	3.8	72.82	7.482458	99.2571	7.538462	0.976155	0.18508	PE
14-Nov	4.5	0.68	3.6	14.2	3.9	73.12	4.570875	95.45063	4.788732	0.92325	0.181122	PE
26-Nov	1.9	1.28	3.8	16.5	4.8	71.72	7.482842	96.45851	7.757576	0.950555	0.181558	PE
06-Dec	2	1.3	3	26	1.2	66.5	8.321331	166.4266	5	1.707473	0.287611	NE
13-Dec	8.8	0.98	2	11.2	2.9	74.12	9.039089	103.3039	8.75	1.033961	0.193906	NE
18-Dec	2.4	1.04	4	15.1	3.7	73.76	6.065413	88.06513	6.887417	0.872195	0.17066	NE
23-Dec	5.5	1.32	2.8	11.9	5.1	73.38	9.465283	85.33096	11.09244	0.832873	0.161685	PE
26-Dec	4.5	1.62	3.4	16.1	6.5	67.88	12.0105	119.3636	10.06211	1.163239	0.205357	PE
03-Jan	8.7	0.94	1.8	11.2	3.3	74.06	8.60341	102.5087	8.392857	1.014104	0.192308	E
31-Jan	1.9	1.42	3.2	16.75	5.6	71.13	8.377853	98.82327	8.477612	0.968468	0.184309	PE
12-Feb	2.4	1.28	2.6	11.6	5.3	76.82	7.12802	64.59768	11.03448	0.625651	0.131103	PE
13-Feb	2.4	1.42	3.2	15.7	5.5	71.78	8.543049	94.45484	9.044586	0.925898	0.177441	PE

NE – Non-explosive, PE – Potential explosive, E - Explosive

Research Institute, Dhanbad has developed a computer program “EXPLO”²⁰ in this regard.

Utilizing the above program the above data have been analyzed and it has found that the gas mixture lies in the explosive zone.

Case Study

Table 2 and 3 indicates the data obtained from two isolation stoppings viz., A and B of a mine of Bharat Coking Coal Limited (BCCL). To assess the status of fire of the sealed area, these stoppings were used for drawing gas samples. Gas analysis results gave the concentration of O₂, CO, CH₄, CO₂ and H₂ (per cent), and N₂ was calculated by difference. Graham's ratio, Young's ratio, CO/CO₂ ratio, Jones and Trickett's ratio, Willett's ratio and explosibility of gas mixtures (explosiveness) are determined by relevant formula and computer program “EXPLO”, respectively. They have been given in Table 2 and 3.

Gas analysis results have been shown for stopping No. A collected from 12 September 2002 to 13 February 2003 and for stopping No. B collected from 24 September 2002 to 12 February 2003. Results have been interpreted in the light of fire-ratios and explosiveness. Ratios have been plotted along with CO concentration for the entire period to find / establish any relationship. Figure 6 and 7 indicate comparison of different fire-ratios like Graham's ratio, CO/CO₂ ratio, and Jones and Trickett's ratio with CO for stoppings A and B. The figures reveal that as CO concentration increases, Graham's ratio increases, CO/CO₂ ratio increases and Jones and Trickett's

Table 3 — Fire-ratios and state of explosiveness for gas samples obtained from isolation stopping B

Day	O ₂	CO	CH ₄	CO ₂	H ₂	N ₂	Graham's ratio	Young's ratio	CO/CO ₂ ratio	Jones & Trickett ratio	Willett's ratio	Explosiveness
24-Sep	5	0.86	4.4	15.9	4.2	69.64	6.391866	118.1752	5.408805	1.151651	0.209211	PE
27-Sep	3.8	0.84	4.8	17.15	4.1	69.31	5.766399	117.7306	4.897959	1.150191	0.20976	PE
1-Oct	5.8	0.96	5.2	16.7	5.3	66.04	8.204707	142.7277	5.748503	1.37557	0.23143	PE
9-Oct	4.7	0.68	4.8	15.2	4.2	70.42	4.870607	108.8724	4.473684	1.050045	0.196281	PE
22-Oct	4.2	0.72	4.6	16.8	3.2	70.48	4.973337	116.0445	4.285714	1.142486	0.210421	NE
31-Oct	6.5	0.52	3.8	13.75	2.7	72.73	4.070944	107.6452	3.781818	1.05414	0.199855	NE
8-Nov	4.9	0.72	4.2	16.25	3.2	70.73	5.201016	117.384	4.430769	1.155059	0.212474	NE
14-Nov	3.4	0.38	4.2	10	3.6	78.42	2.186258	57.5331	3.8	0.539948	0.119503	NE
26-Nov	3.1	0.76	4.2	17.2	3	71.74	4.77654	108.1006	4.418605	1.069693	0.202068	NE
6-Dec	2.5	0.96	4	17	2.8	72.74	5.722427	101.3346	5.647059	1.014539	0.193182	NE
13-Dec	1.8	1	3.8	16.8	3	73.6	5.648441	94.89381	5.952381	0.948938	0.183888	NE
18-Dec	3.9	1.44	3	13.7	5.1	72.86	9.345855	88.91543	10.51095	0.876498	0.168553	PE
23-Dec	2.8	0.96	4	13.95	4.1	74.19	5.693832	82.7385	6.88172	0.809295	0.16116	PE
26-Dec	5.1	0.88	3.6	15.4	5.6	69.42	6.618383	115.8217	5.714286	1.102562	0.203919	PE
1-Jan	3	0.9	3.6	14.7	3.5	74.3	5.392612	88.07933	6.122449	0.86881	0.171729	NE
3-Jan	2.3	1	3.8	18.5	3.3	71.1	6.045401	111.8399	5.405405	1.113865	0.207959	NE
4-Jan	1.6	1.04	4.2	20.1	3.2	69.86	6.149152	118.8442	5.174129	1.187259	0.217721	NE
5-Jan	1.8	0.64	3.8	17.9	3	72.86	3.655493	102.2396	3.575419	1.006974	0.195928	NE
13-Jan	1.6	0.44	3.8	19.1	3.6	71.46	2.537939	110.1696	2.303665	1.068819	0.206889	NE
12-Feb	3.2	0.84	3.6	11.4	4.1	76.86	4.892852	66.403	7.368421	0.641022	0.134688	PE

NE – Non-explosive, PE – Potential explosive, E - Explosive

ratio also increases and when CO concentration decreases these ratios also decrease. For stopping A, in most of the days Graham's ratio is more than 7, indicating blazing fire, whereas for stopping B, the value is less than 6, indicating active fire.

Figure 8 and 9 indicate Young's ratio with CO. From these figures, it can be said that with the increase in CO concentration, Young's ratio also increases. This relationship was very much predominant in Figure 9. For both the stoppings, it has been found that mostly the value of Young's ratio was more than 80, indicating intensive heating or high intensity fire.

Graphs were plotted between Young's ratio and Willett's ratio to establish any relationship among them (Figures 10 and 11). It has been found that they maintain a good relationship. As Young's ratio increases Willett's ratio also increases.

Table 2 and 3 reveal that the value of Jones & Trickett ratio lies between 0.8 and 1, and it has got no relationship with the explosibility of gas mixture (explosiveness).

From the above discussion it is evident that there was high intensity fire in the mine. The CO/CO₂ ratio mostly lies between 4 and 11, which is also indicative of active fire, approaching near to blazing stage^{7,9}.

Conclusions

While dealing with fire in Indian coal mines it has been experienced that in many cases it is difficult to calculate fire ratios involving higher hydrocarbons

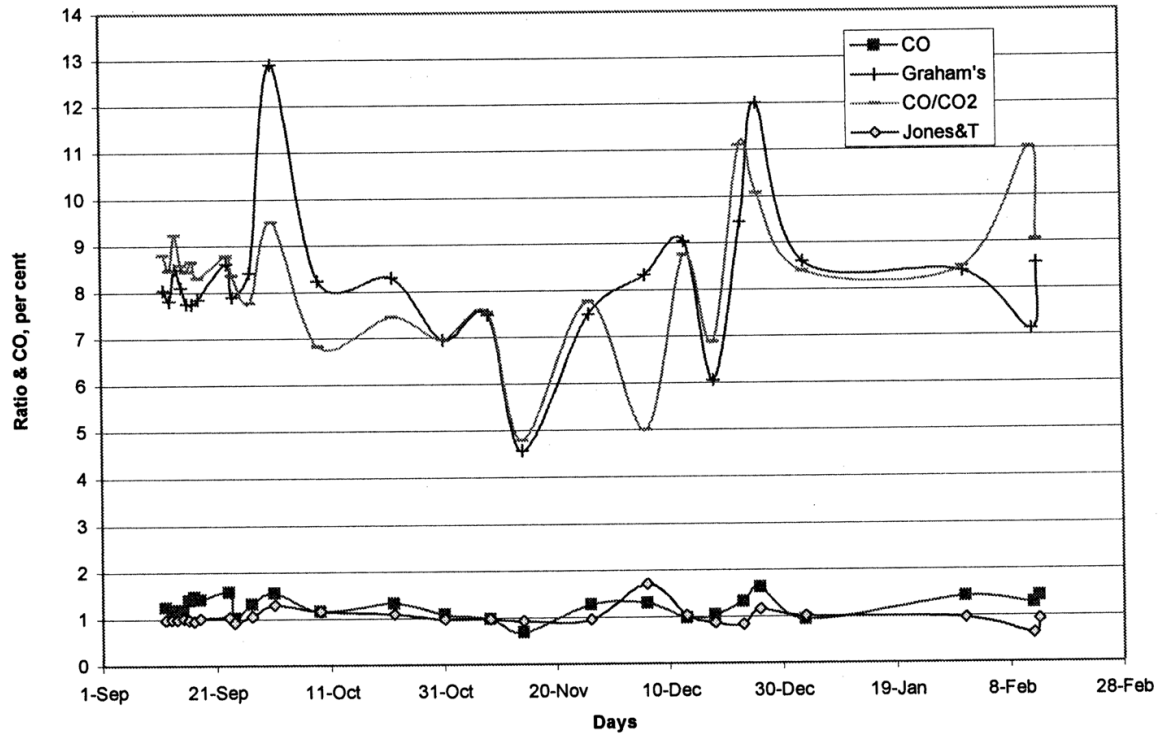


Fig. 6 — Comparison of different fire ratios with CO for stopping A

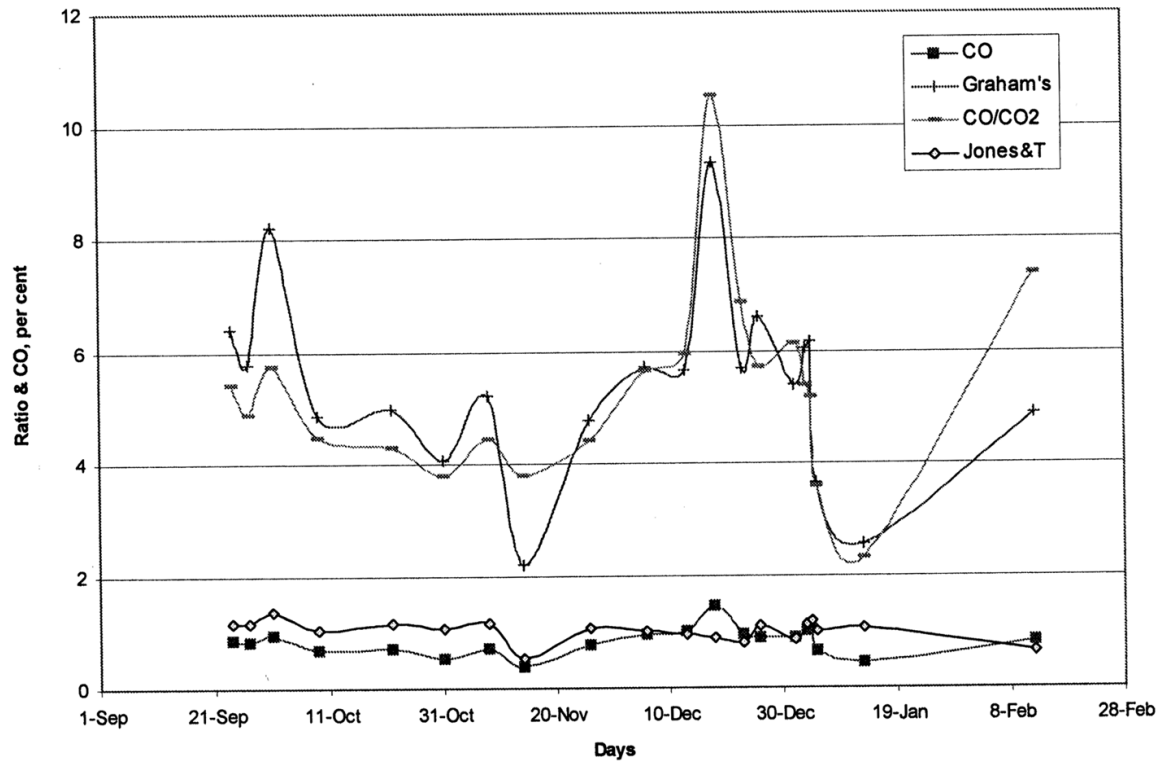


Fig. 7 — Comparison of different fire ratios with CO for stopping B

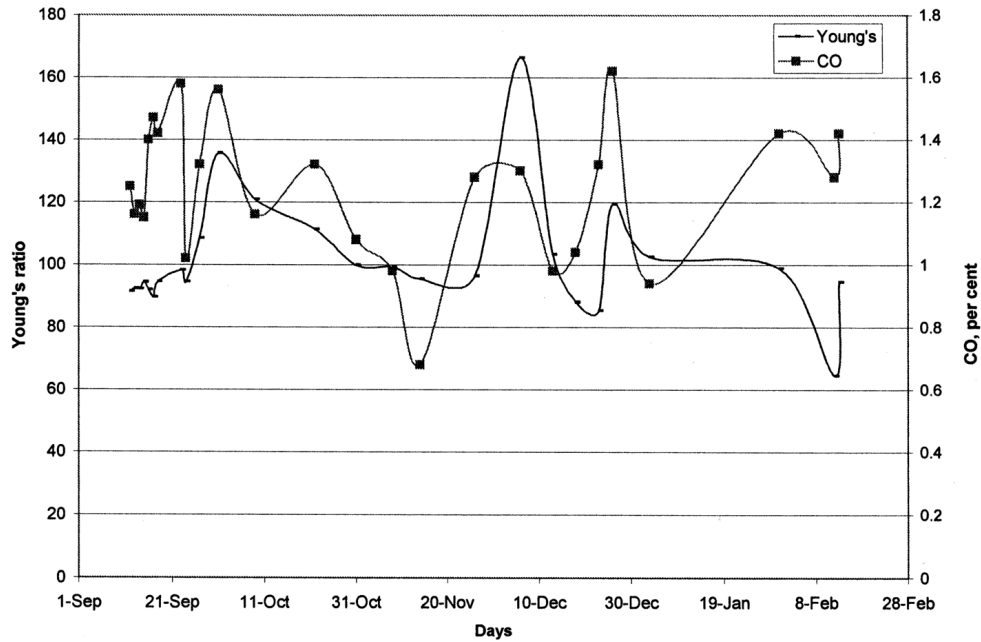


Fig. 8 — Young's ratio with CO for stopping A

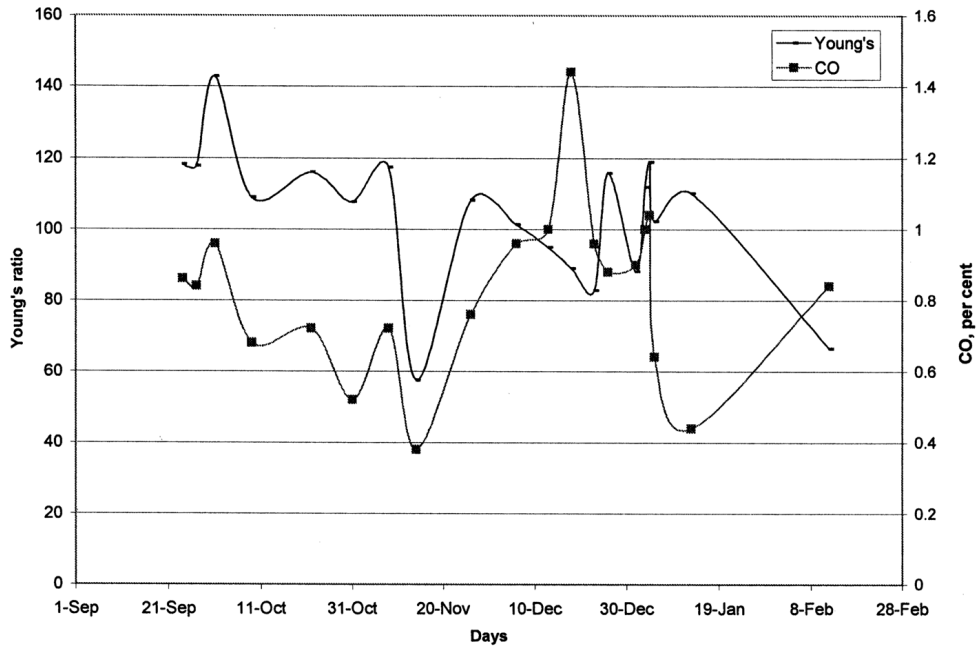


Fig. 9 — Young's ratio with CO for stopping B

(like C/H Ratio, Litton Ratio, and hydrocarbon Ratio) because of unavailability of instruments. However, with the available instruments, rest of the above mentioned fire ratios discussed earlier have been calculated to assess the status of fire.

This approach has its own limitations. Extension of fire affected areas cannot be measured only from the values of these indices. This demands monitoring from different places of the fire affected area as well as examination of other mining conditions of the sealed zone.

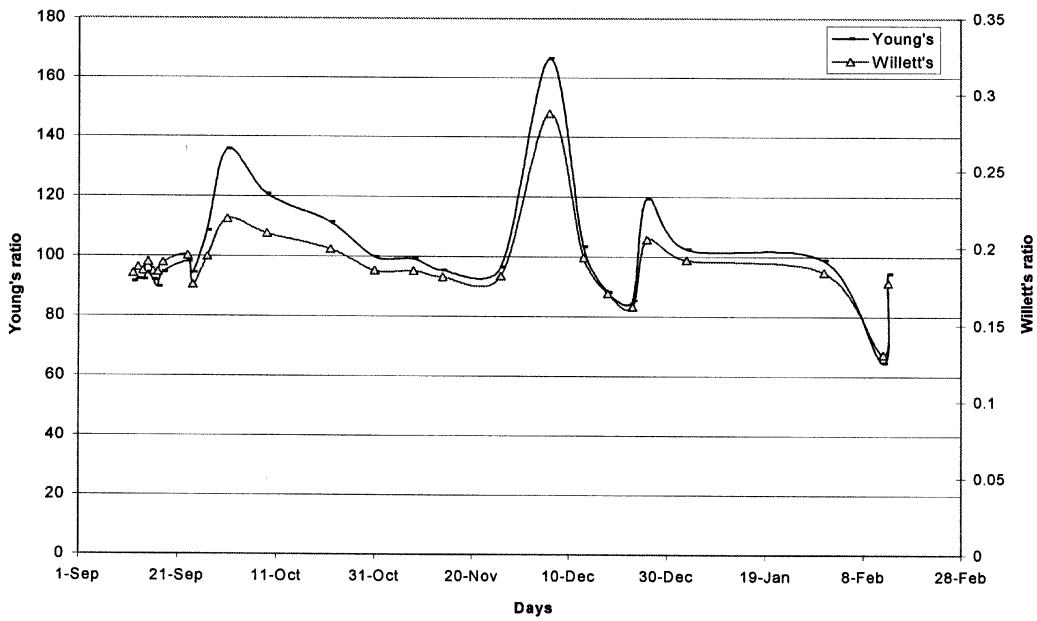


Fig. 10 — Comparison of Young's and Willett's ratio for stopping A

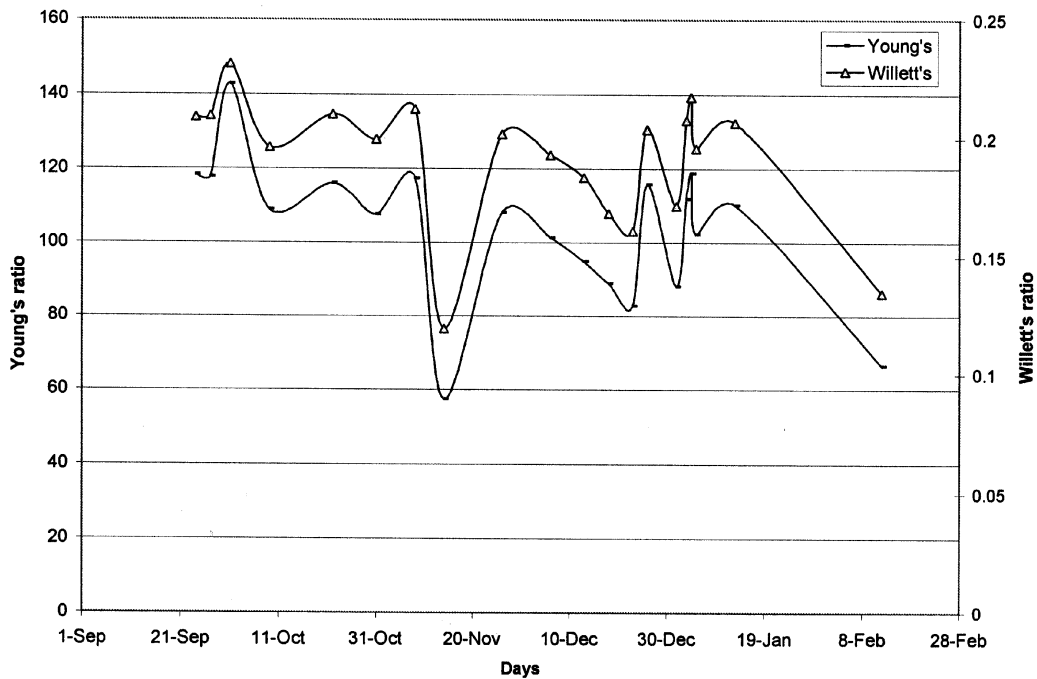


Fig. 11— Comparison of Young's and Willett's ratio for stopping B

Trends of oxygen sorption value may give an idea about the amount of coal involved in fire but uncertain air leakage lead to erroneous oxygen deficiency values.

Practically, none of the fire ratios taken singly, can interpret the status of fire rather trends of a group of fire ratios are able to speak regarding the status of heating. Further, no definite relationship has been found out with any of the fire-ratios and state of gas mixture (explosiveness).

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