Fighting mine fires using gases with particular reference to nitrogen

by S.K. Ray*, A. Zutshi*, B.C. Bhowmick*, N. Sahay*, and R.P. Singh*

Introduction
The practice of using gases which inhibit combustion for fighting mine fires has been practised for 150 years. However, it is only over the last 40 years that significant progress has been made, largely due to the availability of adequate gas generating systems. Application of suitable gases permits rapid sealing of fire zones and to significantly reduce the hazard of gas explosions. However, this practice is generally less effective and more costly than conventional direct fire fighting methods. Suitable gases can be applied to fighting mine fires in the following ways:

➤ by reducing the oxygen concentration in the air around the seat of the fire to such a degree that combustion is inhibited so that the fire dies down or is extinguished
➤ by preventing gas explosions by modifying the atmosphere where fires are being fought directly or where seals to contain the fire are being built
➤ by reducing the intensity or spread of secondary combustion and to cool the area surrounding the fire zone
➤ by sealing fire zones with pressure chambers.

The main difficulty with gas injection methods has been the limited availability of plant to provide large volumes of gas on site at short notice. Moreover, such methods are costly.

Gas injection systems
There are three types of gases which have proved to be practical for fighting mine fires viz

➤ Carbon dioxide (CO₂)
➤ Combustion gases (GCP)
➤ Nitrogen (N₂).

Carbon dioxide
CO₂ is commercially available in large quantities in gaseous, liquid or solid form. All can easily be stored and transported. The solid form is known as ‘dry ice’. There are some instances where ‘dry ice’ has been transported to the fire scene and placed on the fire (Bacharach et al. 1986). Several advantages are attached to the use of CO₂:

➤ Readily available in commercial quantities as liquid or a solid that can be stored and transported. It can be evaporated on site in commercially available mobile plants.
➤ Density higher than air. Good for fire located in depressions and downgrade workings.

However, the use of CO₂ for fire fighting has not been popular because it possesses the following disadvantages:

➤ CO₂ is absorbed by the strata
➤ Reduction of CO₂ to CO, according to Boudouard principle, may be a source of additional danger when the temperature at the seat of the fire is high. This could contribute to both explosibility and the toxicity of the atmosphere.
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- If CO₂ is pumped into the fire zone before the seals are closed, gas might flow from the return airways in layers along the floor into adjoining inclined roadways. The same difficulty may occur after the seals are opened and the fire zone is ventilated.
- The permissible maximum CO₂ content of 1% by volume might be very quickly reached and exceeded in the manned mine workings on the return side of the fire.
- CO₂ is not available in large quantities
- Difficulty of interpreting atmospheric analysis results.

Combustion gases

Combustion gases generally known as ‘Gaseous Combustion Products’ (GCP), contain a significant proportion of N₂ along with CO₂, CO, water vapour and certain other constituents. GCP are generally low in O₂ (0.74 to 0.40% by volume).

The use of combustion gases for fire fighting has many advantages in terms of cost and efficiency.

Some of the important points are as follows:
- It can be generated on site; independent of commercial suppliers
- It can be generated at high rates of up to 1800 m³/min.
- It carries large water volume as steam into the fire zone which has a cooling effect. However, it could lead to water-gas reaction which vigorously promotes, rather than inhibits combustion and results in very hot fires.

The following disadvantages are attendant with the application of combustion gases (GCP) for fire fighting.
- The gases need to be cooled before pumping into the fire area.
- Monitoring the state of the fire is done by analysis of gas samples from the fire area, so that such monitoring is seriously compromised by the presence of GCP gases used.

Nitrogen

N₂ can be delivered into fire area in liquid form from a tanker or in gaseous form through air separation unit/evaporation unit via piping arrangements.

There are several advantages of using N₂.
- The N₂ is cold and dry and poses no problem with cooling or compression, as is the case with other processes where the gas is produced by chemical reaction or by catalyst.
- It is simple to deliver liquid N₂ on-site and the safety aspects are good.
- It can be gasified in a vaporizer with a rated output of up to 300 m³/min. and this can be increased even further by operating multiple vaporizers in parallel.

However, the system also has some disadvantages.
- It is impractical to store the gas over long periods. Therefore, it is sometimes very difficult to obtain a sufficient quantity of N₂ if large amounts (i.e. more than 300 m³/min. for several days) are needed. This may occur when there are several fires at the same time or if there is a really big fire.
- N₂ can only be introduced into the pit by piping it from the surface which calls for a great deal of preparatory work on surface as well as underground.
- N₂ is less expensive than CO₂ but costlier than GCP.
- Liquid N₂ as the base material is not available in unlimited quantities.

To avoid storage problems of liquid N₂, skid mounted on-site storage vessels are used. They are transportable and can be filled up regularly from tankers. Thus liquid N₂ can be stored and be used directly onto the fire from the vessel through boreholes so as to provide an uninterrupted flow into the area. N₂ flushing is always accompanied by air sample analysis from the fire-affected area. Quantity of N₂ flushing or the rate depends upon O₂ concentration in the area. As O₂ concentration is reduced, CO concentration decreases and the requirement of N₂ becomes less.

However, loss of N₂ flushing may be observed due to following factors (Garg1987).
- Fall in barometer readings resulting in expulsion of goaf gases.
- Roof fall resulting in expulsion of gases.
- Air flow through the goaf due to a difference in ventilation pressure.

Air liquidation plants producing liquid N₂ and liquid O₂ oxygen require large capital investment. The alternative is to have a gas generator available for use in coal seams which carry a high risk of spontaneous combustion. Details of PSA and the membrane based N₂ generator are given below.

PSA-based nitrogen generator

Principle

In the early 1980s, Bergbau-Forschung, Essen of the FRG developed Pressure Swing Absorption (PSA) type N₂ generator to separate N₂ from O₂ by use of carbon molecular sieves. The principle of separating N₂ and O₂ from the air relies on an adsorbent carbon which has the ability to preferentially remove O₂ from air. The characteristics of the carbon molecular sieve is based on the equilibrium load of the smaller O₂ molecules taking place within minutes, while the equilibrium load for the larger N₂ molecules is completed only after a few hours. This gross difference between O₂ and N₂ in the relative load at an early stage is exploited to separate the two gases. It is claimed that such a plant can produce 99.9% pure N₂.

Operation

The operating procedure of the plant is depicted in Figure 1. The plant consists of two identical separation vessels (1 and 2) charged with carbon molecular sieves and a number of pneumatically operated valves. The valves are actuated in the required sequence by an electronic timer which triggers solenoid operated pilot valves. Air is fed from an air compressor at a pressure of 7 to 7.2 kg/cm² to vessel (1). As the air passes through the vessel (1) O₂ and CO₂ are trapped by the carbon molecular sieves while N₂ flows preferentially from the outlet into a surge tank via a non-return valve. The process continues for about 56 seconds, after which the flow of air is stopped and vessel (1) is vented to atmosphere. It results in the release of O₂ and CO₂ from the carbon molecular sieves. The vessel is then flushed with pure N₂ for about 4 seconds and waste products vented off to atmosphere. The process increases the capacity of N₂.
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Figure 1—PSA based nitrogen generator

Membrane based nitrogen gas generator

It has been realized that the extensive and effective use of N₂ for extinguishing mine fires can be provided with N₂ generator of the following characteristics.

➤ Modular construction to facilitate both portability as well as capacity augmentation.
➤ Equipment and system design should be suitable for operating in the typically harsh mining environment.
➤ The system should be compatible with the existing compressed air supply wherever applicable.

Based on these characteristics, membrane based N₂ generators are found to be suitable for fire retardation applications in coal mines. These generators are light-weight and can be started up quickly.

Principle

The membrane of the generator consists of millions of hollow fibres, each about the size of human hair, through which compressed air is passed. The components of air, O₂, CO₂ and moisture diffuse through the semi-permeable membrane surface, leaving behind high purity N₂. Purity of N₂ can be controlled by varying the operating parameters. The system offers a high recovery of N₂ from air up to 99.9% purity.

Operation

The unit is designed to generate N₂ from ambient air by membrane diffusion. The operating procedure is depicted in Figure 2. Ambient air is compressed to a pressure of 11.5 kg/cm². After passing through an air cooler and moisture separator, it enters an air receiver. In this way, the compressed air is first cleared of dust particles. The heated compressed air is then separated by the membrane modules into a N₂ flow and a permeate flow, consisting mainly of O₂, CO₂ moisture and some N₂. Several sets of membrane modules and valves are placed in parallel so as to have maximum air flow through the system and hence yield maximum amount of N₂ within minimum time. Subsequently, the permeate flow from each module may be vented to atmosphere or can be used in a combustion process to enhance combustion efficiency. The N₂ flow thus generated is continuously checked by an O₂ analyser to determine the oxygen content (Veecon-ipa Gastechnik Ltd, 1997).

Advantages

➤ The membrane system operates at a constant pressure with no change-over cycles which results in consistent gas purity at the outlet of the module. The chances of sudden failure is absent.
➤ The operating pressure of the system is 11 kg/cm². It thereby eliminates the need for a gas booster which results in a saving on capital, spares inventory, maintenance.
➤ O₂ enriched air of 40% purity is available as a by-product from the outlet of the membrane module. The enriched oxygen can be used for assisted combustion or waste water treatment.
➤ This system is much more compact, leading to space saving and lower expenditure on civil construction.
➤ This system is not affected by changes in the ambient temperature and the operation is noise free.

Some of the disadvantages experienced with the PSA type N₂ generator are:

➤ Initial capital cost is high.
➤ The replacement of carbon molecular sieves (CMS) is an expensive exercise.
➤ The purity of N₂ deteriorates progressively with the passage of time, as the life cycle of carbon molecular sieve is nearing its end. It may fall as low as 85% and the other constituent is mainly O₂ which is detrimental to the fire control operation.
➤ The breakdown of compressors is frequent and, thus, idle time is experienced. The running cost in terms of manning and replacement parts is high. Frequent change-over cycle (2 min.) makes the PSA plant susceptible to breakdown. This may be due to solenoid coil burn out, valve failure and attrition of the molecular sieves.
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**Disadvantage**

Initial capital cost is very high, at least three times that of PSA type N₂ generator. It is the main reason why the nitrogen generator is not generally favoured.

**Pumped gas requirements**

Pumped gas requirements are determined by the rate at which air leaks into the fire area. As far as possible, air leakage should be prevented to ensure minimum gas requirements. Air leakage rate depends upon several factors such as:

- the difference in pressure inside and outside the sealed area which is caused by pressure losses in the adjoining ventilated mine workings.
- the buoyancy pressure developed by density differences between sealed and unsealed mine atmosphere.
- Absolute air pressure changes caused by barometric pressure variations at the surface of the mine.

In the first two instances, pressure differences can be reduced by equalizing the pressures in the adjoining mine workings, adjusted for possible buoyancy pressures. Barometric pressure variations cannot be reduced by equalizing ventilating pressures in adjoining mine workings, but by equalizing pressures across the seals. It calls for a pressure balancing chamber. The chamber is formed by building a thin brick stopping 2 m outside of the isolation stopping. Two pipes are laid to connect the pressure chamber to the main intake as well as return airways. Differential pressure across the seal is adjusted by airflow through these pipes.

To calculate the concentration of N₂ required to control the fire in a sealed area, consider a sealed panel which is subjected to a sustained unidirectional leakage and a substantial inflow of external gases (such as methane) from the surrounding strata. After a time, the concentration of N₂ inside the sealed panel (Fauconnier and Meyer1986) can be given as below:

\[
N(t) = \left( \frac{C_2}{C_4} \right) \left[ 1 - \exp \left( -C_2 t \right) \right] + N_0 \cdot \exp \left( -C_4 t \right) \quad [1]
\]

Where \( C_5 = \frac{(Q_L + Q_N + Q_G)}{V} \) and \( C_4 = \frac{(N_0 Q_L + Q_N)}{V} \)

\( Q_L \) is leakage into the panel at temp. \( T_3 \) (m³/sec), \( Q_N \) is rate of N₂ injection at temp. \( T_3 \) (m³/sec), \( V \) is volume of sealed panel (m³), \( N_0 \) is initial concentration of N₂ in the panel (fraction), \( N_0 \) is concentration of N₂ in the ambient air outside the panel (fraction), \( Q_G \) is inflow of external gas at temperature \( T_3 \) (m³/sec), \( T_3 \) is average temperature inside the panel (°K)

Equation [1] can be used to derive the concentration of N₂ at any given time after the start of N₂ injection provided reasonable estimates of \( Q_L \) and \( Q_G \) can be made. The maximum concentration of N₂ gas for a given set of conditions can be determined from the Equation [1] if \( t \to \infty \)

\[
N_{\text{max}} = \left( N_0 Q_L + Q_N \right) / \left( Q_G + Q_N + Q_L \right) \quad [2]
\]

However, the above Equations are only valid for the following conditions:

- Rate of leakage and gas inflow is considered to be steady and constant
- Reasonably accurate estimates of \( Q_L \) and \( Q_G \) are possible.

The time for a given N₂ concentration to be attained within the panel can be determined from the following Equations [3] and [4]

\[
t = \ln \left( \frac{(N_{\text{max}} - N_0) / (N_{\text{max}} - N(t))}{(Q_G + Q_N + Q_L) / V} \right) \quad [3]
\]

However, determination of the time(\( t \)) is theoretically not possible because \( N(t) \) approaches the maximum value asymptotically i.e. \( N_{\text{max}} \) is achieved when \( t \to \infty \). In practice \( N(t) \) will soon approach \( N_{\text{max}} \) and ‘\( t \)’ can be determined as
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The time required to reach a value near $N_{\text{max}}$ (say 0.99999 $N_{\text{max}}$). Therefore, the time ($t_m$) required to reach the maximum concentration of $N_2$ inside the sealed panel can be determined by

$$t_m = \frac{\ln [(N_{\text{max}} - N_o)/N_{\text{max}} - 0.99999N_{\text{max}}]}{(Q_L + Q_G + Q_o)/V}.$$

Therefore

$$t_m = \frac{\ln [(N_{\text{max}} - N_o)/0.00001N_{\text{max}}]}{(Q_L + Q_G + Q_o)/V}.$$

The above Equations can be illustrated with a small example.

Consider

$$Q_L = 0.01 \text{ m}^3/\text{sec}, \quad Q_o = 0.14 \text{m}^3/\text{sec}, \quad V = 1,000,000 \text{m}^3, \quad N_o = 80\%, \quad Q_G = 0\%.$$


$$N_{\text{max}} = 0.986 \text{ i.e. } 98.6\% \text{ and } t_m = 1823 \text{ hrs.}.$$

This indicates that in a void area of 0.1 million m$^3$ having 0.01 m$^3/\text{sec}$, leakage rate, if $N_2$ injection is 500 m$^3$/hr, it takes two-and-a-half months to reach 98.6% $N_2$. So, leakage rate must be minimized to reduce the duration of $N_2$ injection. It is possible to achieve this by proper reinforcing of all stoppings and, finally, by adopting dynamic balancing of pressure.

**Application of nitrogen in Indian coal mines**

An attempt was made to control an old fire, which started in the 50s, in Laikdih deep colliery, Bharat Coking Coal Ltd. (BCCL) with $N_2$ plant in March 1981. Only partial success was achieved because of heavy leakage into the fire section of the mine. However, on the grounds of this experience, a breakthrough was achieved in extinguishing a blazing underground mine fire with $N_2$ technology in Godavari Khani No. 9, incline of Singareni Collieries Company Ltd. (SCCL) in 1986 (Acharaya1996). Large scale application of liquid $N_2$ for controlling fires in Kottadih Colliery, Easten Coalfields Ltd. (ECL); Sijua Colliery, Tata Iron and Steel Company (TISCO); Lodna Colliery (BCCL) in quick succession has since firmly established the usefulness of the cryogenic $N_2$ technology.

**Table I**

<table>
<thead>
<tr>
<th>Name of colliery</th>
<th>Inert gas used</th>
<th>Quantity of inert gas used (m$^3$)</th>
<th>Rate of injection (m$^3$/hr.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Kottadih, ECL</td>
<td>Liquid $N_2$</td>
<td>1,06,400</td>
<td>680</td>
</tr>
<tr>
<td>2. Sijua Colliery, TISCO</td>
<td>Liquid $N_2$</td>
<td>70,00,000 *</td>
<td>500</td>
</tr>
<tr>
<td>3. GDK-9 incline, SCCL</td>
<td>Liquid $N_2$</td>
<td>3,23,645</td>
<td>1,470</td>
</tr>
<tr>
<td>4. Lodhna Colliery</td>
<td>Liquid $N_2$</td>
<td>94,000</td>
<td>500</td>
</tr>
<tr>
<td>5. Laikdih Deep Colliery</td>
<td>$N_2$ (Gas)</td>
<td>10,00,000</td>
<td>500</td>
</tr>
<tr>
<td>6. Fernhill Colliery (South Wales)</td>
<td>$N_2$ (Gas)</td>
<td>85,000</td>
<td>708 to 1,132</td>
</tr>
<tr>
<td>7. Schlagel and Eisen Colliery (Germany)</td>
<td>$N_2$ (Gas)</td>
<td>1,26,000</td>
<td>1,200 to 3,000</td>
</tr>
<tr>
<td>8. Osterfied Colliery (Germany)</td>
<td>$N_2$ (Gas)</td>
<td>1,94,000</td>
<td>1,800 to 3,600</td>
</tr>
<tr>
<td>9. Springfield Colliery (South Africa)</td>
<td>Liquid $N_2$</td>
<td>52,144</td>
<td>828</td>
</tr>
<tr>
<td>10. Doubraiva Mine (Czech Republic)</td>
<td>$N_2$ (Gas)</td>
<td>5,06,000</td>
<td>708</td>
</tr>
<tr>
<td>11. Bituner Mine, USA</td>
<td>Liquid $CO_2$</td>
<td>18,406</td>
<td>190</td>
</tr>
<tr>
<td>12. Colliery No.1, Tchegan div. China</td>
<td>$CO_2$ and $N_2$</td>
<td>99,109</td>
<td>515</td>
</tr>
</tbody>
</table>

*Plant is in operational stage. Quantity represents total quantity injected so far.

Recently, in April 1997, powered support and other equipment costing more than $ 23.2 million was trapped in the P-3 longwall face of Kottadih project in the Ranigunj Coal Fields due to sudden strata collapse caused by dynamic loading and spontaneous heating thereafter in the gob of the panel.

Nine boreholes were drilled after the collapse of P3 longwall face to assess the condition of strata. Liquid $N_2$ was pumped into the goaf of the panel through borehole No.7. For this purpose, liquid $N_2$ tankers were brought close to the borehole. Infusion of liquid $N_2$ through borehole No. 7 was frequently interrupted due to blockage of the borehole. It took quite some time to clear the borehole by re-drilling. The disruption was considered detrimental to controlling the fire.

To overcome the problem and to inject liquid $N_2$ close to the face and probable seat of heating, borehole No. 6B was selected. The liquid $N_2$ was first evaporated into gaseous form and then passed through the borehole. To avoid damaging the casing of the borehole due to low temperature and freezing water at the bottom of the borehole, a set of four evaporators, having a total capacity of about 500 litre per hour of liquid $N_2$ was deployed. A reservoir having the capacity of three tankers was arranged near the borehole, to overcome the problem of delay in arrival of liquid $N_2$ tankers. The reservoir was then connected to the evaporator coils which, in turn, was connected to the bore-hole No. 6B.

By considering the volume of the void in the sealed off area from face line to compact zone, average concentration of $O_2$ in the goaf and time limit for opening the panel, it was estimated that the $N_2$ pumping rate of about 800 m$^3$/hour would be sufficient to bring $O_2$ concentration in the panel below 2% needed to control the fire quickly.

Accordingly, gaseous $N_2$ was pumped from a PSA type plant, installed close to the colliery pithead. The quality of gaseous $N_2$ produced by the PSA generator was monitored. The plant was run at about 400 m$^3$/hour capacity, producing...
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gaseous N\textsubscript{2} at a concentration of 98\%. However, the plant was stopped as soon as the O\textsubscript{2} concentration in the gas reached 4\%. About 400 litres/hour of liquid N\textsubscript{2} was injected through borehole 6B. Altogether 0.152 million litres of liquid N\textsubscript{2} was pumped into the mine until reopening of the panel on 08/08/97. It was soon realized that the rate of N\textsubscript{2} injection was insufficient. Close examination of the stoppings of P-3, P-2 and P-1 panels revealed that pressure difference across most of them were high causing heavy air leakage. It was also noted that all the boreholes were highly negative. It was clear that the rate of air leakage was quite high. This automatically promoted consideration of ways and means to reduce air leakage rate to a minimum. It called for pressure balancing around all three interconnected longwall panels viz. P-3, P-2 and P-1. Thus, an integrated approach i.e. pressure balancing along with N\textsubscript{2} injection could help in controlling the fire and salvaging equipment in the longwall.

**Sijua Colliery (TISCO)**

The fire in Nos. 13 and 14 seams of Sijua colliery, TISCO was sealed off and after continuing for several years, was brought under control by Pressure Balancing. In order to meet production target and provide adequate ventilation at various working faces, mine management installed a higher capacity fan (VF-3000) at pit No. 8 and made several changes in the ventilation network of the mine. These changes resulted in pressure imbalance across the fire-affected zones in Nos. 13 and 14 seams, leading to deterioration of condition of the fire. Central Mining Research Institute (CMRI), Dhanbad, India was commissioned to investigate the recurring problem of fighting mine fires which had adversely affected the production of mine for many years and to find suitable practical solutions. CMRI, after detailed investigation and computerized planning, advised the management of mines to opt for Dynamic Balancing of Pressure for some portions of the mine and recommended procurement, installation and commissioning of a 500 m\textsuperscript{3}/hr. capacity N\textsubscript{2} gas generator (PSA type) for fire control purposes.

Measures to implement and adopt Dynamic Balancing of Pressure yielded encouraging results. The fire was brought under control in most parts of the mine. However, at a few places in the sealed-off area, O\textsubscript{2} concentration did not fall to the desired level. This was attributed to existence of an air leakage path extending beyond the pressure balancing zones. In view of the results, it was recommended that a N\textsubscript{2} generator be installed to inject gas into the sealed off area. Based on the existing conditions, the capacity of the plant and injection rate was calculated and a 500 m\textsuperscript{3}/hr. PSA N\textsubscript{2} gas generator was procured and installed in April 1997. The injection of N\textsubscript{2} gas at 6 points at a time resulted in a dramatic reduction of O\textsubscript{2} concentration which had in most places reached a level exceeding 98%.

For further improvement in the condition of the mine, it was suggested that a second identical N\textsubscript{2} flow to 1000 m\textsuperscript{3}/hr. in the mine, but will assist in maintaining an uninterrupted supply of N\textsubscript{2} during any breakdown or maintenance of one of the units. However, dynamic balancing of pressure should be practiced throughout the life of the mine.

The first plant is showing encouraging results yielding 99.3\% purity of N\textsubscript{2}. In a total void area of 8 million m\textsuperscript{3}, 7 million m\textsuperscript{3} of N\textsubscript{2} has been injected to date.

**GDK - 9 incline, Singareni Collieries**

GDK 9 incline is one of the highly mechanized and highly productive collieries in the Ramagundam area. Large scale use of liquid N\textsubscript{2} was made in 1986 at Godavarikhani No.9. Incline of Singareni Collieries Company Ltd to combat a blazing underground fire. The intensity of the fire was so severe that the mine management staff was compelled to seal the mine from the surface. Liquid N\textsubscript{2} helped in extinguishing of the fire, cooling the atmosphere and conditioning it so as to be non-explosive. It took 125 days to reopen the mine and restore it for normal production (Ramaswamy and Katiyar1988). The whole mine had been sealed off due to fire affected panel Nos. 8 and 8A. These panels were at a depth ranging from 30 m to 40 m. Stoppings of the panels as well as few stoppings at panel No. 7, were damaged and subsequently an explosion occurred. Mine management was faced with the problem of recovering equipment worth $ 4.18 million. The plan of operations for combating fire was as follows (Ramaswamy and Katiyar1988):

- Building concrete plugs around fire-affected area in No. 3 seam from surface
- N\textsubscript{2} injection
- Blanketing of subsided areas from surface
- Sampling and monitoring the atmosphere in sealed areas
- Establishing chemical analytical laboratories at the mine.

A total of 89 boreholes was drilled for placing concrete plugs, N\textsubscript{2} injection and environmental monitoring.

A total of 4.6 million litres of liquid N\textsubscript{2} was used during the period from 11.4.86 to 4.7.86 and cost of N\textsubscript{2}, including the hire charge of the tanker came to about $ 85,581.

**Lodna Colliery**

In Lodna colliery, an underground fire was advancing to beneath an office building, washer, coke oven plant and railway line. A trench was dug to stop the fire and protect the office complex. The fire was initially fought with liquid N\textsubscript{2} transported to the mine. It was fed through a bank of vapourizers and into the mine through boreholes. Subsequently, a PSA type N\textsubscript{2} generator, was installed at the mine.

In 1985–86, Indian Oxygen Limited installed an evaporation plant at this colliery and fed a total quantity of 94,000 m\textsuperscript{3} of N\textsubscript{2} into the mine, spread over a period of about 8 months. This N\textsubscript{2} injection had a positive effect on the fire (Garg1987). Capacity of the plant was 500 m\textsuperscript{3}/hr.

**Laikdih deep colliery (BCCL)**

At Laikdih deep colliery 25 m thick coal seam is extracted by bord-and-pillar method. There are three sections of coal, each of 4–6 m thick, with a parting of inferior coal between them. The selective method of mining and friable nature of coal have resulted in numerous fires occurring. A fire, which originated in the 1950s was advancing towards access shafts, requiring regular shifting of a row of...
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stoppings, thus sterilizing more and more coal. In 1981, the row of stoppings was again threatened, but no further retreat was possible. The sealing of fires had been ineffective due to multi-section working and weak parting of coal which allows inflow of fresh air. Superimposition of stoppings in different sections and cement injection around stoppings has also not helped. Frequently the fire jumped over stoppings.

Due to the fact that the fire had not been properly isolated, the decision was taken to install an \( N_2 \) generating plant at the colliery. The plant, with a capacity of 500 m\(^3\)/hr, was commissioned in March 1981. The gas was fed through stoppings via the mine pump delivery system. The oxygen concentration was reduced 5% to 0.5% over a two-month period (Garg1987). Temperature of stoppings also came down to normal. CO content in the samples at most of the stoppings was no more than a trace. One million m\(^3\) of \( N_2 \) gas was pumped in over the period, with average running time of the plant being 2 hrs per day. With continued injection of \( N_2 \) gas, the fire remained dormant, the only requirement being the injection of water through sprays to lower the temperature. This whole exercise was only partially successful because of heavy air leakage in this section of the mine.

**Application of nitrogen injection in other collieries**

Spontaneous heating started in 1983 in S4 panel of Jambud seam J K unit of Madhujore Colliery. Liquid \( N_2 \) tankers of 4000 litres capacity were used. The operation continued for two months. O\(_2\) concentration in the fire affected, sealed off area was reduced from 13.75% to 0.51%. CO concentration, within the same period reduced from 190 to 15 ppm and CH\(_4\) from 0.14% to zero. Continuous \( N_2 \) infusion decreased the temperature of the sealed off area by 6°C. Production of mine started within three months from the time the fire started.

Spontaneous heating in F1 longwall caving panel of XVI combined seam was detected in August 1993 in Moonidih Colliery (BCCL), a degree III gassy mine. The ratio of goaf-volume and quantity of \( N_2 \) pumped was 1:1.65. \( N_2 \) injection helped in salvaging the longwall equipment (Acharyya1996).

A fire occurred in Oct 1993 at 51 level junction of travelling and conveyor roadway in No. 5 seam Churcha Colliery (SECL). The ratio of void volume of developed workings and the quantity of \( N_2 \) injection was 1:1.76 (Acharyya1996).

In New Kenda Colliery (ECL), a fire occurred in the main intake in Dobrana seam near two pits in Jan 1994. Liquid \( N_2 \) as well as gaseous \( N_2 \) was pumped into the affected mine workings through boreholes. After the sealing operation was completed, a foam mixture of Mariflex Resin and Mariflex catalyst was applied over some of the stoppings to prevent air leakage. The \( N_2 \) pumped after treatment of the stoppings was thus contained in the limited area which was sealed (Acharyya1996).

In West Bokaro Collieries (TISCO) a fire occurred in March 1995 in No. 10 seam abandoned workings of quarry A. The ratio of void volume and the \( N_2 \) pumped in 1995 was about 1:10.6 (Acharyya1996).

**Economics of inert gas injection**

\( N_2 \) injection is considered an excellent method for controlling mine fires. It has been used for fighting mine fires in prominent mining countries, but it has been found that large volumes of \( N_2 \) are used in the process. Also, the cost of liquid \( N_2 \) is high. In 1982, during the fire fighting operations at Laikdih deep colliery, the cost of \( N_2 \) gas was estimated at \$ 11,628 per million m\(^3\) and this cost rose to \$ 18,605 per million m\(^3\) in 1986. In 1986 at Lodna Colliery, the cost of producing \( N_2 \) of 99% purity from a PSA plant was found to be \$ 18,140 per million m\(^3\) (Garg1987). The cost of liquid \( N_2 \) at GDK-9 incline mine was about \$ 0.15 per litre (Ramawasy and Katiyar1988). The cost of the generation of \( N_2 \) by PSA type generator at Sijua Colliery (TISCO) was estimated to be \$ 46,512 per million m\(^3\).

The cost of mine atmosphere conditioning with gas depends on several factors viz:

- Leakage
- Road conditions
- Location of mines
- Capacity of \( N_2 \) generating plant.

The \( N_2 \) generating plant should be established as near to the fiery mine as possible to ensure maximum effectiveness and efficiency. In Europe, excellent road networks exist and commercial liquid \( N_2 \) plants are generally located at reasonable distances from coal mines making it possible to deliver liquid \( N_2 \) in quick time (Banerjee1987). In this respect, India is still in the developmental stage. Although, \( N_2 \) generating plants (PSA type) have been installed at some of the mines in India, (Singareni Collieries, Sijua Colliery, Lodna colliery) extension of the principle is highly desirable.

**Conclusions**

Underground mine fire control by conditioning the atmosphere is proven technology that has been applied world-wide.

The following factors should be borne in mind by mine managers before taking the decision to use \( N_2 \) to control underground fires.

- Purpose of \( N_2 \) injection should be well defined. \( N_2 \) may be used either to push the mixture of gases in the sealed area beyond the explosive range or to extinguish the fire. Needless to say, the latter objective will require much greater quantities of \( N_2 \) than the former.
- The fire area to be neutralized should be tightly sealed in order to keep the \( N_2 \) requirements to the minimum.
- Leakage factor should be taken into account while calculating \( N_2 \) requirements.
- While injecting \( N_2 \), the atmosphere behind the seals must be continuously monitored to ensure that the gas mixture is not explosive. If this possibility exists, everyone should be withdrawn from the mine before injection commences.

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Fighting mine fires using gases with particular reference to nitrogen

References


