

## REVIEW OF NITROGEN FLUSHING TECHNOLOGY IN COMBATTING MINE FIRES

Nikhil Jain<sup>1</sup>, Adarsha Das<sup>2</sup>, Akash Srivastava<sup>3</sup>, Dr. N.C. Karmakar<sup>4</sup>

<sup>1,2</sup>IDD Student, <sup>3</sup>B. Tech Student, Indian Institute of Technology, (Banaras Hindu University),  
Varanasi, (India)

<sup>4</sup>Professor, Dept. of Mining Engineering, Indian Institute of Technology,  
(Banaras Hindu University), Varanasi, (India)

### ABSTRACT

The elementary aim of the analysis is to probe gas mixing and dilution approaches to provide with an improved apprehension of processing of satisfactory levels of contamination inside a mine ambience, which can be assessed. As an illustration the interaction between gases from inertization systems and the underground mine atmosphere can be judged to serve in design of the mine inertization system. Inertization approaches admit the usage of engine exhausts, nitrogen, carbon dioxide, and diesel fired boiler units. For the important safety approaches inside the many parts of the international industry, inertization systems have been assumed for handling underground fires, spontaneous combustion heating and management of the potential explosibility of newly sealed goafs. For the explanation of designs and applications of inertization systems in stabilizing mine atmosphere is assisted by few given case studies.

**Keywords:** Nitrogen Fluhsing, Mine Fires, Inertization, Underground Mine, Coal, PSA.

### I. INTRODUCTION

It need not be emphasised that coal mining activity contributes to the economic growth of the country. Safety of miners and protection of expensive machineries have always been the major concern for mining industries. Particularly, for underground coal mining, questions on the different safety fronts are also increasing. One such point of concern is that of mine fire. Mine fire or any sudden break out of fire in mine leads to casualties and deaths along with economic losses. There are several cases of mine fire that have left the imprint of being a disaster in the history. Mine fire is one of the major problems to coal mining industry world-wide due to spontaneous heating of coal. India being in the league of high production of coal, since it world's 3<sup>rd</sup> largest coal producing country from opencast and underground mines and thus have their coal mines having extensive fire activity record over 140 years (Raniganj coal field, 1865).[1].[2]

In case of India, a major mine fire accident occurred at Dhori mine in the year 1965 causing 268 fatalities. Similarly, in Chinakuri mines an explosion due to fire dump caused 175 fatalities.[3]

It can be inferred from previous paragraph that selection of appropriate technology is very much crucial to reduce the risk and to deal with any fire outburst accidents. There are several methods available to fight mine fires which include inertization, panel isolation (bord and pillar working) etc. Gases like carbon dioxide, nitrogen and other inert gases are used in the process of inertization. Over years, use of nitrogen has proved the best way to fight mine fires. Nitrogen flushing requires injection of large amount of the gas that can dilute the

**Comment [N1]:** Mitra D.K., Fires in Indian coal mines- An overview, Proc Nat Semin on Mine ventilation, safety and Environment, 29-30 November, 2001, (CMRI, Dhanbad), 135-154.

Singh RVK, Acharya A K, &Dhar B B, Status of mine fire of Indian coal fields- An Overview with suggestions. (CMRI Dhanbad), In-house report, July, 1994.

**Comment [N2]:** Maiti, J., Khanzode, V. V., & Ray, P. K. (2009). Severity analysis of Indian coal mine accidents—a retrospective study for 100 years. Safety science, 47(7), 1033-1042. Chicago

atmosphere at the site of fire which further asks for an efficient nitrogen production technique. There are various adsorption based technology that includes cryogenic gas separation, inert gas generator and pressure swing adsorption. As discussed in later sections, pressure swing adsorption has proved to be most economic and efficient method for production and can deliver nitrogen at purity of more than 99%. [4]

## II. MINE FIRE

The burning of coal seam otherwise known as mine fire adversely affects the economy, society and ecology of a given area. Once initiated, they continue to smoulder underground by spreading through cracks in geological structures etc. Over a long span of time they engulf the whole coal reserve in the area which causes great loss in fossil resources. There are a large number of factors that may cause coal mine fire, but the following three are responsible in most of the cases studied.

### 2.1 Spontaneous Combustion

The coal seam areas are rich in carbonous matters. The oxidation of these carbon content matters at an ambient temperature is the main cause of spontaneous combustion. [5], [6], [7], [8]. Reason as provided by scientists is that at low temperature O<sub>2</sub> is physically adsorbed by coal. However, starting from ambient temperature, physical adsorption changes to chemisorption. [6], [9]. In initial stage, loose coal-water-oxygen is formed which decomposes above 75-800C to yield CO, CO<sub>2</sub>, water vapour etc. Exothermicity and the rate of the reaction changes with rise in temperature and with loss of moisture. It continues until a stable coal-oxygen complex formed and from that point, the real combustion begins. [10]

### 2.2 Methane Explosion

The first documented methane gas explosion occurred in US during 1818 at an operation near Richmond, VA, known as Heath's pit. The main reason as found behind the mine fire caused by methane is due to fire damp formation. Concentration of methane ranging from 4.8-15.8% methane in air produces an explosive mixture. Within this explosive limit, any flash causes the immediate ignition of the damp that causes explosion. The explosion further leads to firing of coal dust present in the seam floor and thus burning the fresh coal surfaces in presence of oxygen in environment.

### 2.3 Coal Dust Explosion

Coal dust explosions are generally initiated by other explosion or fire processes like firedamp and spontaneous combustions. The shock wave that is then propagated causes the settled coal dust to mix into air. Since the fine dust particles together provide a vast surface area exposure, they get vulnerable to immediate burning even on limited heat supply. With oxygen present in air, it acts as a fuel for transmission of flame. The analysis of the sample taken from the Darr mine at Van Meter, Rostraver Township, Westmoreland County, Pennsylvania, near Smithton, proves the explosibility and explosion propagation nature of coal dusts. [12] On testing of various samples it has been found that the methane gas concentration in return air way was within the specified limits. High concentration of methane was only found as local accumulation near the face and along roof to short distance from face. The analysis showed that there would be only local explosions if the fire damp was explosive. Coal dust is the other material that was found in large amount at the site, which may become

**Comment [N3]:** Tomomura, M., Haga, T., Nogita, S., Ichihara, K., & Ishizu, T. (1988). U.S. Patent No. 4,746,332. Washington, DC: U.S. Patent and Trademark Office.

**Comment [N4]:** [5] G<sup>o</sup>uney, 1968; Banerjee, 1985; Goodarzi and Gentzis, 1991

**Comment [N5]:** [2] Münzner and Peters, 1965; Banerjee, 1985; Postrzednik et al., 1988

**Comment [N6]:** [11] EXPLOSION HAZARDS FROM METHANE EMISSIONS RELATED TO GEOLOGIC FEATURES IN COAL MINES By James P. Ulery.

**Comment [N7]:** [12] Mohalik, N. K., et al. "Application of nitrogen as preventive and controlling subsurface fire—Indian context." J Sci Ind Res India 64 (2005): 273-280.

explosive upon suitable environment. This coal dust was the cause for the propagation of flames throughout the mine as demonstrated by dust analysis.

### III. INERTIZATION

Inertization is the process of diluting the mine environment to reduce the concentration of the oxygen or other explosive or flammable gases like methane, hydrogen etc. It is done by variety of inert or non-reactive gases like argon, carbon dioxide, nitrogen etc. These are generally discharged at relatively low temperature into the sealed mine which helps in bringing the temperature of mine atmosphere below flash point and hence suppress the fire.

#### 3.1 Co<sub>2</sub> Inertization

It is done by flushing carbon dioxide in the fire area. Since it has density higher than air, it is good for fire located in depressions and downgrade workings. However, carbon dioxide inertization is not popular because the strata readily absorb it. Some times at high temperature there are chances of reduction of carbon dioxide to carbon monoxide according to Boudouard principle which further adds the danger of toxic mine atmosphere[13]. Further, carbon dioxide is not an abundantly available constituting only 0.03% of earth's atmosphere.

#### 3.2 N<sub>2</sub> INERTIZATION

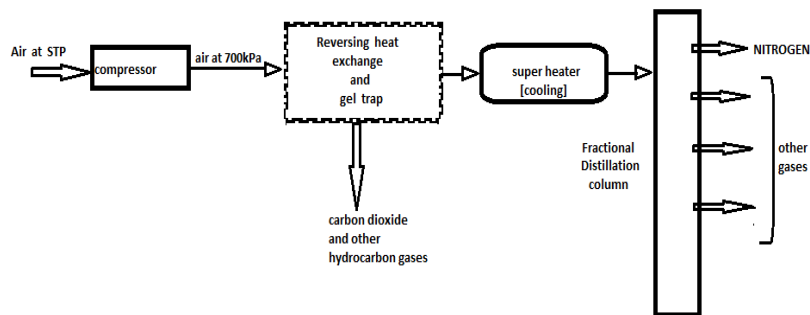
Nitrogen has been used as inertization process for more than 50 years. Out of all other gases used for inertization, nitrogen has been proved to be best choice. There are many advantages of this method over others as discussed below:

- Lighter than air and fill the whole space near the goaf area.
- The temperature of the discharge is very low hence readily absorbs the heat emission from the strata (preventing spontaneous heating) and from the fire seats (reduces the surrounding temperature below flash point).
- Non-toxic, un-reactive, readily available and economically feasible gas.
- Dilutes the explosive mixture and hence reduces the possibility of explosion.
- Transportation is easy through pipe lines as unlike carbon dioxide it can be liquefied.
- 1m<sup>3</sup> of liquid nitrogen converts to 691m<sup>3</sup> of gaseous nitrogen at 1.013 bar and 15°C which is sufficient to create an inertization umbrella in the goaf area.
- Latent heat of vaporization is very high, hence acts as a very efficient coolant.
- It reduces the concentration of oxygen from the sealed-off area.
- It reduces the intensity and propagation of fire by secondary combustion.
- In case of negative pressure difference, its seals off the fire zone with pressure chamber.

**Comment [N8]:** THE REACTION OF CO<sub>2</sub> WITH COKE ON SPENT CATALYSTS  
W. P. Hettinger, Jr., J. F. Hoffman and S. M. Kovach  
Ashland Petroleum Company  
Research and Development Department  
Ashland, Kentucky 41114

**Comment [N9]:** [5]Caption taken from website.  
<http://www.niir.org/g/c/ni-89/16.jpg>. ; dated.5<sup>th</sup> Jan 2014

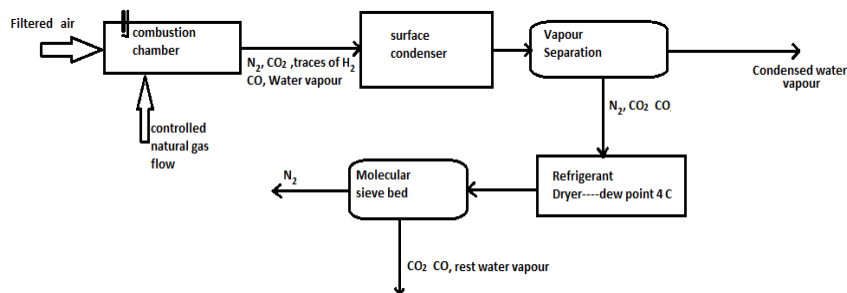
#### 4.1 Cryogenic Air Separation



**Figure 1: Flowchart of Cryogenic Air Separator**

The dust free air is compressed to 700 kPa and water is condensed out at the interstage coolers. Then the gas mixture is passed through the gel trap or through molecular sieves to remove carbon dioxide and hydrocarbons. Moisture, carbon dioxide and hydrocarbons are removed prior to other processes because they have low melting (sublimation in case of carbon dioxide) as compared to rest of the gases which may freeze and block the equipments in later cooling stages. The air then is passed to the heat exchanger and super heater where the gas is cooled against the waste product of cryogenic gas. Then the liquefied gas mixture containing mostly nitrogen and oxygen (rest gasses <1ppm) is transferred to distillation column where nitrogen is separated out.

#### 4.2 Inert Gas Generator



**Figure 2: Flowchart of Inert Gas Generator**

(Source: The Linde Group; Documentation: "Nitrogen Generation by Pressure Swing Adsorption"; dated: 5<sup>th</sup> Jan)

In this process, filtered air is used for combustion of the natural gas which causes consumption of all oxygen from the intake air. The flow of natural gas is controlled so that carbon monoxide generation due to lack of oxygen is minimum. It causes the air to be left with nitrogen, carbon dioxide, water vapour and traces of hydrogen, carbon monoxide. The mixture then passes through the surface condenser which condenses the water

vapours to liquid which is subsequently separated from the gas mixture. Then temperature is further reduced to 4°C, the carbon dioxide and rest water vapour are removed using carbon molecular sieve. The gas coming out of it is left with nitrogen.

#### 4.3 Pressure Swing Adsorption Method

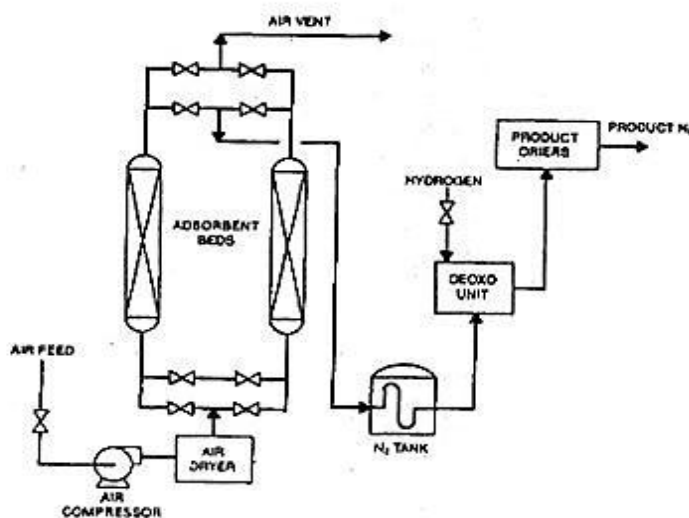


Figure 3: Flowchart of PSA (Pressure Swing Adsorption) System.

(Source: The Linde Group; Documentation: "Nitrogen Generation by Pressure Swing Adsorption"; dated: 5th Jan)

#### 4.3 PRESSURE SWING ADSORPTION FOR NITROGEN PRODUCTION:

The compressed air alternatively pressurises the two identical adsorbent bed containing carbon molecular sieves. Separation of oxygen and nitrogen is based on the fact that, faster kinetic diffusion of the oxygen molecules into the pore structure of carbon molecular sieve than for nitrogen molecule.

The PSA cycle works on two-step process [15]:

- Pressurisation
- Depressurisation

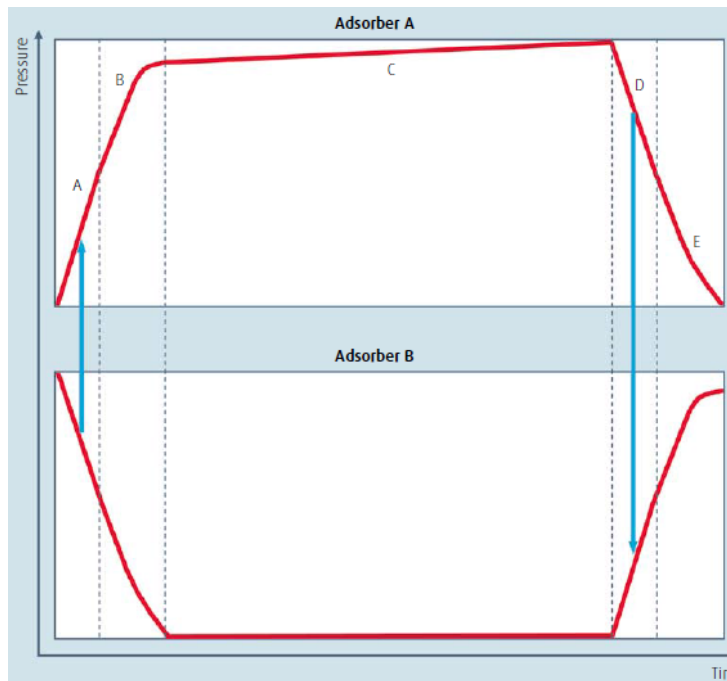
Moisture, oxygen, and carbon dioxide are adsorbed as the compressed air flows into adsorbent bed A. On achieving operating pressure, nitrogen product flows from adsorbent bed A into a nitrogen product receiver. Simultaneously, adsorbent bed B is depressurized to atmospheric pressure. On completion of nitrogen removal from bed A, the valve connecting bed A and B is released. It causes the gas remaining in adsorbent bed A under pressurized situation to flow into bed B which acquires an intermediate pressure. During this step there is no intake of air, hence the nitrogen receiver is applied to prevent pulsating gas output and provide a consistent flow, purity and pressure of the nitrogen product throughout the PSA cycle (as shown in figure 5). Bed A then undergoes depressurization and the oxygen enriched waste gas is vented to the atmosphere. Depressurization

**Comment [N10]:** [6]The Linde Group ; Documentation: "Nitrogen Generation by Pressure Swing Adsorption" ; dated: 5<sup>th</sup> Jan

**Comment [N11]:** [7]Ray, S.Ketal, "Fighting mine fires using gases with particular reference to nitrogen", JOURNAL-SOUTH AFRICAN INSTITUTE OF MINING AND METALLURGY 100.4 (2000): 265-272.

releases oxygen, carbon dioxide, and water vapor previously adsorbed during nitrogen production from adsorbent bed A. At the same time, adsorbent bed B is brought to operating pressure, and begins its nitrogen production portion of the cycle.

Following nitrogen production, adsorbent bed B undergoes equalization and subsequent depressurization. The cycle continues at the point where adsorbent bed A undergoes pressurization and adsorbent bed B is depressurized.



**Figure 4: Pressure Variation Demonstrating A: Pressure Equalization; B: Back Purge Step; C: Nitrogen Production; D: Pressure Equalization; E: Depressurization with Respect to Time in Adsorbent Vessel A (Absorber A) and Adsorbent Vessel B (Absorber B) (Source: Ray, S.Ketal (2000))**

## V. NITROGEN CONCENTRATION VARIATION IN SEALED OFF AREAS

Further, the amount of gas to be pumped inside the fire site depends on the rate of air leakage into the fire zone. For minimum gas requirement air leakage has to be minimized. The air leakage basically depends on the air pressure difference in sealed and rest part of the mine. The pressure difference can be caused due to the following [16]:

1. Pressure loss in ventilated mine working adjoining to the sealed area.
2. Buoyancy pressures that develop due to differential density of air in sealed and rest mine.
3. Barometric pressure variations.

**Comment [N12]:** [7] Ray, S.Ketal, "Fighting mine fires using gases with particular reference to nitrogen", JOURNAL-SOUTH AFRICAN INSTITUTE OF MINING AND METALLURGY 100.4 (2000): 265-272.

**Comment [N13]:** [16] FAUCONNIER, C.J. and MEYER, M.J.R. Conceptual Mathematical Models for the Injection of Nitrogen into Sealed Colliery Fires. *J. S. Afr. Inst. Min. Metall.* vol. 86, no. 3, March 1986. pp. 81-88.

Concentration of nitrogen to suppress fire in sealed-off area can be calculated when the target panel is subjected to continuous unidirectional leakage and inflow of an external gas which may be methane due to strata emission. The concentration of nitrogen after a time 't' in the sealed panel subjected to above conditions can be given by [17]:

$$N(t) = \frac{C_4}{C_3} [1 - e^{-C_3 t}] + N_0 e^{-C_3 t} \quad 1$$

$$\text{Where } C_3 = (Q_L + Q_N + Q_G)/V \text{ \& } C_4 = (N_a Q_L + Q_N)/V \quad 2$$

'T' is average temperature inside the panel. All the values are at temperature 'T'.

QL : air leakage rate (m3/s).

QN : rate of nitrogen injection (m3/s).

QG : inflow rate of external (m3/s).

N0 : initial nitrogen percentage in panel.

Na : nitrogen percentage in ambient air.

V : volume of sealed panel.

The above equation is valid only when:

1. The leakage rate as well as gas inflow rate is assumed to be constant.
2. QL and QG are reasonably accurate.

## VI. CASE STUDIES

### 6.1 Tisco, Sujia Colliery, India

Large scale application of liquid N2 for controlling fires in various regions like Sujia Colliery, TISCO has firmly established the usefulness of cryogenic N2 technology in controlling mine fires.

The following case study (adopted) demarcates successful implementation of previously described technique.

Sujia Colliery, TISCO is an underground coal mine in Dhanbad district of Jharkhand. Fires started in No. 13 and 14 seams due to contribution of multiple negative contributing factors including spontaneous combustion of coal. As the first step of damage control, the fire in Nos. 13 and 14 seams of the mine were sealed off and after continuing for several years, was brought under control by Pressure Balancing. Later on, 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 also made several changes in the ventilation network of the mine. The change proved to be detrimental as it resulted in deterioration of condition of fire. This was because the changes had resulted in pressure imbalance across the two affected areas. Central Mining Research Institute (CMRI), Dhanbad, India was designated to look into this grave problem which was affecting the overall production of the mine apart from raising safety issues. After detailed assessment, dynamic balancing of pressures across various regions and installation of a 500 m<sup>3</sup>/hr capacity N<sub>2</sub> gas generator (PSA type) for fire control was recommended. At most of the places, former recommendation incurred largely positive results. However, some regions were still not mitigated but that was due to leakage of O<sub>2</sub> in these regions. Taking into account these results, nitrogen flushing was called upon and a 500 m<sup>3</sup>/hr PSA N<sub>2</sub> generator was installed. To maintain an uninterrupted supply of N<sub>2</sub> for further operations, an additional plant with similar technical characteristics, but of larger capacity of 1000 m<sup>3</sup>/hr was suggested to be installed. The first plant is showing

**Comment [N14]: [17]** ADAMUS, ALOIS, HAJEK, LUBOMIR and POSTA, VACLAV. A review of experiences on the use of nitrogen in Czech coal mines. *Proceeding of the 7th US Mine Ventilation Symposium*, 1995. pp. 237-241.

encouraging results yielding 99.3% purity of N<sub>2</sub>. In a total void area of 8 million m<sup>3</sup>, 7million m<sup>3</sup> of N<sub>2</sub> has been injected to date.[18]

Following figure gives the quantity used and rate of injection of gas in fighting figures in some important mines in various countries[19]-

**Table 1: Quantity and Rate of Gas Injection Used in Various Mines (Fauconnier and Meyer1986)**

Sl. No.	Name of Colliery	Inert Gas used	Quantity of Inert gas used (m <sup>3</sup> )	Rate of Injection (m <sup>3</sup> /hr)
1	Kottadih, ECL	Liquid N <sub>2</sub>	106400	680
2	Sijua Colliery, TISCO	Liquid N <sub>2</sub>	7000000*	500
3	GDK-9 Incline	Liquid N <sub>2</sub>	323645	1470
4	Lodhna Colliery	Liquid N <sub>2</sub>	94000	500
5	LadakhDeeo colliery	N <sub>2</sub> (Gas)	1000000	500
6	Fernhill Colliery (South Wales)	N <sub>2</sub> (Gas)	85000	708 to 1132
7	Schlangel and EisenColliery (Germany)	N <sub>2</sub> (Gas)	126000	1200 to 3000
8	Osterfield Colliery (Germany)	N <sub>2</sub> (Gas)	194000	1800 to 3600
9	Springfield Colliery (South America)	Liquid N <sub>2</sub>	52144	828
10	Doubrava Mine, (Czech Republic)	N <sub>2</sub> (Gas)	506000	708
11	Bituner Mine, USA	Liquid	18406	190
12	Colliery No.1, Tchegan,	CO <sub>2</sub> and N <sub>2</sub>	99109	515

\*Plant is in operational stage. Wuatity represents total quantity rejected so far.

### 6.3 India

As suggested by Garg, French nitrogen flushing equipment entails prevention of heating for mining of the Salma seam present in the Eastern Coalfield of India. [20] The foremost test in March, 1981 at Laikdih colliery, employed an inert gas generator of 500 m<sup>3</sup> h<sup>-1</sup> capacity established on combustion technology. In the direction of late 1984, liquid nitrogen technology grew among interests of the Indian Oxygen Company. In 1985-86 Indian Oxygen has set up an evaporation plant at Londa colliery and gave in a production of a total quantity of 94 000 m<sup>3</sup> of nitrogen disseminated over a period of round about eight months, a mean of less than 400 m<sup>3</sup>/day.[21] Established on pressure swing adsorption technology, carbon molecular sieves were set up at

**Comment [N15]:** [18]BANERJEE, S.P. Nitrogen Flushing in Coal Mines as a measure against Mine Fires. *Transactions, The Mining Geological and Metallurgical Institute of India*, vol. 84, no. 2, Oct. 1987. pp. 1-9

**Comment [N16]:** FAUCONNIER, C.J. and MEYER, M.J.R. Conceptual Mathematical Models for the Injection of Nitrogen into Sealed Colliery Fires. *J. S. Afr. Inst. Min. Metall.* vol. 86, no. 3, March 1986. pp. 81-88.



the same mine in July, 1986; this implementation of molecular sieves was their foremost application in the circumstances of mine safety context.[22]

Mass use of liquid nitrogen was caused in 1986 at the Godavarikhani No. 9 incline of Singareni Collieries Company, Ltd., to fight a blazing underground waste fire. 36 Close to 462 m<sup>3</sup> of liquid nitrogen was expended throughout from 11 April to 4 July, 1986. The liquid nitrogen was channelized to the colliery through a mobile tanker of 8.4-m<sup>3</sup> capacity and then directly shot in underground via seven boreholes to the level 330 m below surface. The sealed off mine was unfolded within 55 days of closure, total ventilation was launched in 93 days and production was rejuvenated in 109 days. The methods of liquid nitrogen flushing, foaming nitrogen flushing and equipment like portable nitrogen generator (pressure swing adsorption nitrogen generator) was employed during the Jhanjra project—curtailment of self-generated heating in a goaf of longwall face AW1 in the R-VIIA seam of Jharia mine, Eastern Coalfields, Ltd., West Bengal<sup>37</sup> (Fig. 9). The foaming chemical compound and nitrogen foam generator machine were acquired from M/S Technovent, Czech Republic. To render the foam 3–5% of foaming compound (detergent/protein based) was fused with 95–97% water in the tank. The mixture was made to go through the foam generator, where gaseous nitrogen was also made to go through at a pressure of 4–5 bars. The liquid mixture was altered into foam and channeled to the caved goaf through a pipe established in the boreholes from the surface (to depth of the AW1 goaf, 103 m below surface).



**Figure 6: Liquid Nitrogen Flushing, Foaming Nitrogen Flushing and Portable PSA Nitrogen Generator at Jhanjra Project, West Bengal, India. (Photograph by Voráček)**

#### 6.4 Great Britain

Nitrogen smothering has been used at Fern hill colliery. [23] On 24 July, 1962, a shot firing event ignited methane and set coal on fire in the north main heading. The following day it was decided by the mine management decided to seal off the area and the mine was closed for normal working. In a series of events

**Comment [N17]:** 20. Garg P. C. and Bhowmick P. C. Use of nitrogen flushing to spontaneous heating—proposals for a trial in an Indian mine. *J. Minerals, Metals and Fuels*, September 1978, 315–22.  
21. Garg P. C. Development of nitrogen infusion technology for fighting and inhibition of fires. *J. Minerals, Metals and Fuels*, August 1987, 368–77, 394.  
22. Adamus A. Experience of the use of nitrogen and foam technology in the Czech coal mines. In *Proc. First International mine environment and ventilation symposium, Dhanbad, 11–12 December 2000*, Appendix 68, 1–4.

**Comment [N18]:** [23] Vaughan-Thomas T. The use of nitrogen in controlling an underground fire at Fernhill colliery. *Trans. Instn Min. Engrs*, **123**, March 1964, 311–27.

which followed and the futile attempts of balancing the pressures, nitrogen injection was finally called to control the fire. Gaseous nitrogen at a rate of 50 000 ft<sup>3</sup>/h (1415 m<sup>3</sup>/h), at a purity of 99.5% was supplied. Nitrogen injection started on 10 August, when the oxygen percentage in the fire area was 15.38%. After 24 hr of injection, after 16 700 m<sup>3</sup> nitrogen had been pumped in, the oxygen level had dropped to 10%. After a further 36 hr, with a total of 53 000 m<sup>3</sup> of gaseous nitrogen injected, the oxygen level had fallen to 7.37%. From the concentration changes of gases within the fire area it was calculated that the volume of sealed-off roadway inside the stopping was 11,300 m<sup>3</sup>, disregarding leakage. The rate of nitrogen flow varied from 550 to 12500 m<sup>3</sup>/hr throughout the operation period. To sum up, 2,400,000 m<sup>3</sup> of gaseous nitrogen was supplied to Fern hill colliery. [24] Following this effective utilization of Nitrogen inertization technique to control the atmosphere of the sealed off areas, work had been resumed in areas near the region of fire seat, while doing away with an explosion hazard.

## VII. CONCLUSION

The use of nitrogen for inhibition, control and extinguishing underground fires, exclusively from 1960 was universal due to its physical and chemical properties. For the last two decades, momentous progress, made largely due to availability and cost effectiveness of nitrogen as compared to other options available in India, like inert gases. It helps in protection of rescuers from fire and explosions, creating the opportunity to open sealed off fire area, controlling spontaneous combustion in goaf of working panels. The following factor considered before its use in underground fires:

- a. Leakage factor should be taken into account for applications of nitrogen in sealed off fire areas in order to also keep the N<sub>2</sub> requirements minimum;
- b. Dissipation of accumulated heat should take place in goaf areas of working panels to avoid spontaneous heating; and
- c. Regular thermo compositional monitoring should be carried out during after application of nitrogen in goaf area to know the explosive behavior of gas mixture.
- d. We also have arrived to few conclusive points:
- e. Face ventilation can influence the effectiveness of nitrogen inertization;
- f. Nitrogen inertization is generally found to be most effective injected on head gate side while on the tail gate side, if injected, nitrogen travel mostly to the return airway and thus not an effective measure.

During the years 1980-90 the use of nitrogen to inertise the sealed off fire areas was at peak, thus being called as 'Golden Age'. Extensive experiences of the use of nitrogen in mines for the last two decade in India have shown that it is useful to combine this technology with other measures in the prevention and control of subsurface fires.

## REFERENCES

- [1] Mitra D.K., Fires in Indian coal mines- An overview, Proc Nat Semin on Mine ventilation, safety and Environment, 29-30 November, 2001, (CMRI, Dhanbad), 135-154.
- [2] Singh, R. V. K., Acharya, A. K., &Dhar, B. B. (1994). Status of mine fire of Indian coal fields–An Overview with suggestions. CMRI, Dhanbad, Inhouse report.

**Comment [N19]: [24]**Harris L. The use of nitrogen to control spontaneous combustion heatings. *The Mining Engineer*, June 1981, 883–92.

- [3] Maiti, J., Khanzode, V. V., & Ray, P. K. (2009). Severity analysis of Indian coal mine accidents—a retrospective study for 100 years. *Safety science*, 47(7), 1033-1042.
- [4] Tomomura, M., Haga, T., Nogita, S., Ichihara, K., & Ishizu, T. (1988). U.S. Patent No. 4,746,332. Washington, DC: U.S. Patent and Trademark Office.
- [5] Banerjee, S.C., "A Theoretical Design to the Determination of Risk Index of Spontaneous Fires in Coal Mines", *Journal of Mines, Metals and Fuels*, 399-406, 1982.
- [6] Banerjee, S.C., "Spontaneous Combustion of Coal and Mine Fires", Oxford and IBH Publishing Company, India, 1985.
- [7] Goodarzi, F. and Gentzis, T., "Geological Controls on the Self Burning of Coal Seams", D.C. Peters, Ed., *Geology in Coal Resource Utilization*, TechBooks, Fairfax, Virginia, 1991.
- [8] G'uney, M., "Oxidation and Spontaneous Combustion of Coal – Review of Individual Factors", *Colliery Guardian*, 216, 105-110 and 137-143, 1968
- [9] M'onzner, H. und Peters, W., "Zur Kinetik der Kohlenoxidation im Temperaturbereich 30-100°C", *Brennstoff-Chemie*, 12, 399-406, 1965.
- [10] Postrzednik, S., Bialecki, R., Novak, A., Scholz, R. und Specht, E., "Zur Problematik der Selbsterwärmung fester Brennstoffe (1)", *Erd'ol-Erdgas-Kohle*, Heft 2, 79-85, 1988.
- [11] Ulery, J. P. (James P.); Explosion hazards from methane emissions related to geologic features in coal mines; DHHS publication; no. (NIOSH) 2008-123; Information circular (National Institute for Occupational Safety and Health); IC 9503
- [12] Mohalik, N. K., et al. "Application of nitrogen as preventive and controlling subsurface fire—Indian context." *J Sci Ind Res India* 64 (2005): 273-280.
- [13] W. P. Hettinger et al. Jr., J. F. Hoffman and S. M. Kovach, the reaction of CO<sub>2</sub> with coke on spent catalysts; Ashland Petroleum Company Research and Development Department Ashland, Kentucky 41114.
- [14] <http://www.niir.org/g/c/ni-89/16.jpg>; dated: 5th Jan 2014.
- [15] Ray, S. K. et al., "Fighting mine fires using gases with particular reference to nitrogen", *Journal-South African Institute of Mining and Metallurgy* 100.4 (2000): 265-272.
- [16] Fauconnier, C.J. and Meyer, M.J.R. Conceptual Mathematical Models for the Injection of Nitrogen into Sealed Colliery Fires. *J. S. Afr. Inst. Min. Metall.* vol. 86, no. 3, March 1986. pp. 81–88.
- [17] Adamus, Alois, Hajek, Lubomir And Posta, Vaclav; "A review of experiences on the use of nitrogen in Czech coal mines"; *Proceeding of the 7th US Mine Ventilation Symposium*, 1995. pp. 237–241.
- [18] Banerjee, S. P. (1987). Nitrogen flushing in coal mines as a measure against mine fires. *Transactions, Mining Geological and Metallurgical Institute of India*, 84(supplement no. 2), 1-9.
- [19] Fauconnier, C. J., & Meyer, M. J. R. (1986). Conceptual mathematical models for the injection of nitrogen into sealed colliery fires. *JS Afr Inst Min Metall*, 86(supplement no. 3), 81-88.
- [20] Garg P. C. and Bhowmick P. C. Use of nitrogen flushing to spontaneous heating—proposals for a trial in an Indian mine. *J. Minerals, Metals and Fuels*, September 1978, 315–22.
- [21] Garg P. C. Development of nitrogen infusion technology for fighting and inhibition of fires. *J. Minerals, Metals and Fuels*, August 1987, 368–77, 394.

- [22] Adamus A. Experience of the use of nitrogen and foam technology in the Czech coal mines. In Proc. First International mine environment and ventilation symposium, Dhanbad, 11–12 December 2000, Appendix 68, 1–4.
- [23] Vaughan-Thomas T. The use of nitrogen in controlling an underground fire at Fernhill colliery. Trans. Instn Min. Engrs, 123, March 1964, 311–27.
- [24] Harris L. The use of nitrogen to control spontaneous combustion heatings. The Mining Engineer, June 1981, 883–92.