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Optimisation of Inertisation Practice

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SUMMARY

This report presents the details and results of work carried out under the Australian Coal Association Research Program (ACARP) project C9006, entitled “Optimisation of Inertisation Practice”. The aim of the research is to develop and demonstrate optimum strategies for goaf inertisation during longwall sealing operations. The project has combined the detailed analysis of the performance of various inertisation field trials together with extensive computational fluid dynamic (CFD) modelling of different inertisation options in order to develop the optimum inertisation strategies. Field demonstration studies of the optimum strategy were conducted at Newlands Colliery in Queensland. A brief summary of the project work is presented in the following sections.

(1) Background

In underground gassy coal mines it is generally recognised that immediately after sealing a longwall panel, the atmosphere behind the seals may enter and pass through the explosive range. The duration of explosive conditions in the sealed longwall goaf ranges from a few hours to 1 or 2 days to a few weeks, which depends largely on the gas emission rate and goaf characteristics. Therefore, any sealed area with methane as the seam gas has the potential to explode depending on the presence of ignition sources. To minimise this risk of explosions, the modern practice in some of the Australian mines is to inject inert gas into the sealed goafs immediately after sealing the panel.

The specific objective of inert gas injection operations is to reduce the goaf oxygen levels below the safe limit of 8% (i.e., with a factor of safety of 1.5 on the explosive nose limit of 12%) before methane concentration reaches the lower explosive limit of 5%. The inertisation schemes usually involved just injecting inert gas through maingate (MG) or tailgate (TG) seals until goaf gas sampling results show that oxygen level was below 8%. In many cases it was found that the goaf oxygen concentration was above 12% even after 2 to 3 days of inert gas injection and in some cases an explosive atmosphere was also present in the goaf during inertisation. There was a need to optimise inertisation operations to reduce the goaf oxygen levels, thus reduce the explosion potential as quickly as possible during longwall sealing off periods.

(2) Project objectives and studies

The main objective was to develop optimum and effective strategies for inertisation during longwall sealing off operations to achieve goaf inertisation within a few hours of sealing the panel. To achieve this objective, the project work involved:

- Comprehensive review and analysis of the effect of various mining, ventilation and inertisation schemes on goaf inertisation.
- Laboratory studies to investigate the effect of various inertisation strategies on temperature changes around the heating area in a coal pile.
- CFD Modelling of airflow and inert gas dispersion patterns in the longwall goafs, including extensive parametric studies with various inertisation options.
- Development of optimum inertisation strategies based on the results of above studies.
- Field studies to demonstrate the effectiveness of the optimum inertisation strategy. This included tracer gas studies and extensive goaf gas monitoring.

(3) Review studies

Longwall goaf inertisation is being carried out in some of the mines in Australia on a regular basis to reduce the potential risk of explosions during the panel sealing-off period. The data review phase of the study involved collection of inertisation data from previous operations and field studies to collect data from the on-going inertisation operations at a number of longwall panels. In total, inertisation data has been collected from 6 different longwall panels. These 6 panels had employed different inertisation schemes and cover 3 different mines with different gas emission rates and panel characteristics. A comprehensive review of the inertisation data has been carried out to analyse the effect of different inertisation designs on goaf inertisation. The effect of mine factors such as goaf layout, ventilation systems and inert gas composition on effectiveness of inertisation was also assessed.

Analysis of data from Mines A and B showed that the initial/trial inertisation schemes implemented were not effective in preventing the formation of explosive gas mixtures near the longwall finish line for up to 2 days after panel sealing. Results from Mine C showed that although the inertisation schemes employed at this mine were relatively more effective when compared with results of other cases, oxygen levels in the goaf were still above 12% for up to two days after panel sealing.

The results from the review studies indicate that just injecting inert gas through MG or TG seals does not achieve the objective of quick inertisation of longwall goafs. Analysis of results indicated that the effect of inert gas injection through the MG/ TG seals on gas composition at inbye locations of the goaf was negligible for up to two days after sealing. It was also noted that development of positive pressure in the goaf alone, even at 500 Pa, does not indicate goaf inertisation.

These review studies indicated that there is a need for optimisation of inertisation strategies to achieve the desired objective of goaf inertisation within a few hours of sealing. Development of optimum strategies requires a detailed understanding of inert gas dispersion patterns in the goaf and their effect on goaf gas distribution. A brief summary of laboratory and modelling studies carried out to improve our understanding of the effect of inertisation is presented in the following sections.

(4) Laboratory investigations

A critical review of the inertisation operations carried out in the field to control heatings shows that in a number of cases, heatings erupted again after stopping the inert gas injection. To improve our understanding of the effect of inertisation on goaf heatings, a number of laboratory studies have been conducted at SIMTARS (Safety In Mines Testing And Research Station) spontaneous combustion testing facility (test rig). The inertisation studies were conducted after completion of spontaneous combustion tests. The objective of these studies was to investigate the effect of different inertisation strategies on temperature changes, goaf flow mechanics and gas concentration levels around the heating area. Inertisation experiments involved injection of inert gas at different flow rates, different inertisation durations and fresh air introduction into the test rig.

Analysis of the results showed that rapid inertisation for short periods of a few hours resulted in only marginal decrease in peak temperatures. Results showed that rapid inertisation resulted in migration of heating zones to adjacent locations in the testing rig. This heat migration has led to development of new self heating zones. Tests indicated that rapid inertisation at higher flow rates for short durations may not be an appropriate strategy to control the major heatings in longwall goafs.

Results showed that introduction of fresh air into the rig immediately after rapid inertisation resulted in revival of heating in the coal pile. Temperatures started to increase steeply at the newly developed self heating zones. Results also indicated that any fresh air introduction, even after a few days of air leakage into the goaf, could result in revival of heatings.

Tests with air leakage into the rig at just 7% oxygen showed that temperatures at the self heating zone did not change significantly during the test period. Temperatures remained constant at above 100 ^{o}C. Test results indicated that heatings in the goaf can survive for long periods even at low oxygen levels of 7%. Therefore, it is very important to prevent air leakages into the sealed area as it can keep the heatings active for longer periods.

Experiments with inert gas injection at lower flow rates for eight days showed that slow inertisation resulted in uniform dispersion of heating zones in the rig. Results showed that temperature decreased uniformly at all the hot spot locations and there was no sign of any new self heating zones development in the rig. Results indicate that inert gas needs to be injected at optimum flow rate depending on the size and location of the heatings in the goaf.

(5) CFD modelling simulations

The focus of the modelling exercise was to obtain a better understanding of the inert gas flow patterns in the goaf and qualitative analysis of the various factors involved in inertisation operations, in order to establish a scientific basis for design of optimum strategies. Computational fluid dynamics (CFD) techniques have been used to develop the goaf models to study the inert gas flow mechanics in sealed longwall panels. Base case models for longwall inertisation were developed using the information obtained from initial field studies on goaf geometry, gas emissions, ventilation system and caving characteristics. Steady state modelling was carried out to simulate goaf conditions before the sealing off period and transient modelling techniques were used to simulate the sealed goaf atmosphere at regular time intervals after panel sealing.

Base case simulation results showed that at airflow rates of 50 m^3/s, ventilation system and gas emission flow rates had a major influence on goaf gas distribution at working seam level when compared with the effects of methane buoyancy pressures. For example, oxygen concentration level at 50 m behind the LW face was around 20% on the intake side and around 16% on return side located at lower elevation. However, when the airflow rate was reduced to 10 m^3/s during panel sealing off periods, methane buoyancy pressure seems to play a major role on goaf gas distribution even at working seam level. In this case oxygen concentration levels and penetration distance were higher on the return side of the goaf.

The base case CFD models were calibrated and validated based on the information obtained from previous inertisation studies and goaf gas monitoring. The validated models were then used for extensive parametric studies involving changes in inert gas injection locations, inert gas flow rates, seam gradients, and different inertisation strategies to investigate their effect on goaf inertisation.

Results showed that inert gas injection through various locations resulted in entirely different inertisation patterns in the goaf. Inert gas injection through the MG seal resulted in the reduction of oxygen concentration only near the point of injection within the first 24 hours. Inert gas injection through 3 c/t, i.e. at 200 m behind the LW face, resulted in oxygen concentration reductions over a wider area in the goaf. Results indicated that the strategy of inert gas injection through the MG seal was not as effective as the alternative strategy of injecting inert gas through the 3 c/t seal under the modelled conditions. Simulations indicated that even during longwall retreat operations injection of inert gas at 50 m to 200 m behind the face on the intake side reduces the spontaneous combustion risk in the goaf.

Computer simulations with different seam geometries showed that seam gradient plays a significant role in goaf gas distribution and needs to be considered during development of goaf inertisation strategies. Analysis of the simulation results also indicated that inert gas flow rate is also one of the important design parameters to be optimised during development of an inertisation strategy. Under the modelled conditions, an inert gas flow rate of 1.0 m^3/s resulted in faster goaf inertisation compared with an inert gas flow rate of 0.5 m^3/s. However, it is to be noted that changes in inertisation strategies could change the optimum flow rates required for any specific conditions. Various simulations with boiler gas and nitrogen inert gases showed that there was no major difference in effectiveness of these gases on goaf inertisation under the modelled conditions.

Analysis of the various simulation results also indicated that longwall panel geometry, goaf characteristics, gateroad conditions in the goaf, goaf gas emission rates and composition, ventilation during panel sealing off period, chock withdrawal and panel sealing sequence would also have a significant influence on goaf gas distribution and inertisation.

CFD modelling simulations with field site geometry and conditions showed that the strategy of inert gas injection through the TG seal only, would not be effective for goaf inertisation. Simulations with inert gas injection through the MG showed that although this inertisation scheme resulted in better goaf inertisation compared with the previous scheme, it did not achieve the objective of goaf inertisation within a few hours of panel sealing. Based on the results of various simulations, an optimum inertisation strategy was developed taking into consideration the positive effects of various inertisation schemes and the field site conditions. Analysis of the modelling results showed that the optimum inertisation strategy developed during the course of investigations had achieved goaf inertisation within a few hours of panel sealing. Simulation results showed that the optimum strategy effectively reduced the oxygen concentration at all locations in the goaf to below 12% levels even before panel sealing.

(6) Field demonstration studies

The optimum inertisation strategy developed during the course of the project for Newlands Colliery site conditions involved:

(i) inert gas injection through tailgate 4 c/t and TG seals for 2 days before sealing
(ii) inert gas flow rate at 0.5 m^3/s (Boiler gas)
(iii) inert gas injection through maingate 4 c/t (i.e. at 200 m behind the face finish line) for 1 day with door on chute road seal still open
(iv) panel sealing and continuation of inert gas injection through maingate 4 c/t until oxygen levels in the goaf reduced below 8%.

Field studies were conducted at N4B panel of Newland Colliery during panel sealing off operations to evaluate and demonstrate the optimum inertisation strategies. Tracer gas studies were also carried out during the field studies to map the inert gas dispersion patterns in the longwall goaf. An extensive underground gas monitoring system was installed around the N4B panel involving 9 moniting tubes installed on both sides of the goaf. Three surface boreholes were also drilled into the goaf specifically for these demonstration studies to monitor the gas concentration levels deep inside the goaf during sealing off and inertisation operations. Newlands Colliery and project collaborator SIMTARS have also been extensively involved in these field studies.

Analysis of the results during inert gas injection though the tailgate side seals confirmed that introduction of inert gas at 100 to 200 m behind the face finish line results in better goaf inertisation compared with inert gas injection through TG or MG seals. Gas distribution in the goaf during inert gas injection through maingate 4 c/t showed that boiler gas dispersion was not just confined to a narrow zone in the collapsed maingate, but extended to a wider area in the goaf and resulted in better and faster goaf inertisation. These results indicate that for N4B longwall geometry and conditions, inert gas injection on maingate side results in goaf inertisation over a wider area compared with inert gas injection on tailgate side.

Results show that within four hours of inert gas injection through maingate 4 c/t seal, oxygen concentration in the goaf was below 12% at all locations around the goaf. Oxygen concentration at the critical 3 c/t and MG seal reduced to 5.9% and 9.1% respectively. Gas distribution in the goaf also indicated that with implementation of the optimum inertisation strategy, inert gas worked in combination with goaf gas emissions and achieved faster goaf inertisation.

Oxygen levels in the goaf reduced to 5% within 24 hours of inert gas injection through 4 c/t seal on the maingate side. Gas distribution in the goaf showed that oxygen levels in the goaf did not rise after stopping the inert gas injection, confirming the success of goaf inertisation. It may be recalled that in some of the review case studies, oxygen levels increased steeply after stopping inert gas injection into the goaf, which indicates ineffective goaf inertisation.

Tracer gas study results indicated a significant difference in tracer gas flow paths under open goaf and sealed goaf conditions. Tracer gas studies also indicated that with the optimum inertisation strategy implemented at the site, inert gas also dispersed towards high oxygen concentration areas inside the goaf and greatly improved the effectiveness of goaf inertisation operation.

(7) Conclusions and Recommendations

The main conclusions and recommendations from the research are:

(1) During longwall retreat operations, the panel ventilation system and goaf gas emission flow rates would have a major influence on goaf gas distribution at working seam level when compared with the effects of goaf gas buoyancy pressures.

(2) During panel sealing off operations, when panel airflows are restricted, goaf gas composition and buoyancy pressure plays a major role on gas distribution in the goaf, even at working seam levels.

(3) Coal seam gradient, panel geometry, caving characteristics, chock withdrawal and panel sealing sequence also play a significant role in goaf gas distribution and needs to be considered during development of inertisation operations.

(4) Development of an inertisation strategy should take into consideration the effect of all the above site parameters on goaf gas distribution. The most important design parameters for goaf inertisation during longwall sealing operations are (in the order of influence):
    a. location of inert gas injection points;
    b. inertisation strategy – leakage paths, timing, etc.;
    c. flow rate of inert gas injection; and
    d. inert gas composition.

(5) In many cases, the standard practice of inert gas injection through MG or TG seals immediately after panel sealing would not be effective for goaf inertisation. In addition, it may increase the inertisation time because it acts against the goaf gas emissions. The optimum inertisation strategy should work in combination with goaf gas emissions to achieve faster goaf inertisation.

(6) Inert gas injection through the 2nd or 3rd cut throughs behind the face, i.e. at 100 to 200 m behind the face finish line, would result in effective goaf inertisation at a faster rate, compared with inert gas injection through TG or MG seals.

(7) Inert gas flow rate of 1.0 m^3/s is recommended under less gassy conditions. Inert gas flow rate of 0.5 m^3/s would be sufficient under moderately gassy conditions, if optimum inertisation strategies are implemented.

(8) The recommended guidelines for optimum inertisation strategy are:
   a. inert gas should be injected into the goaf at around 200 m behind the face finish line, i.e., at an inbye location with respect to explosive fringe in the goaf.
   b. inert gas should be injected on intake side of the goaf OR on both sides of the goaf, if possible.
   c. inert gas injection should start at least 1 or 2 days before panel sealing, with minimum ventilation flow and doors on return seal still open.
   d. inert gas flow rate of 0.5 to 1.0 m^3/s is recommended, subject to implementation of all these optimum strategies.
   e. inert gas injection to be continued after sealing until O_2 levels are below 8%.

In summary, the field demonstration study results showed that the optimum inertisation strategy implemented at the mine was highly successful in converting the goaf environment into an inert atmosphere within a few hours of panel sealing. In fact, during the field demonstration studies, the goaf atmosphere was inert by the time of closing the doors on the final seals, with oxygen concentration below 5% at all locations in the goaf. This represents a major improvement to mine safety compared to typical inertisation practices that were able to achieve goaf inertisation within 2 to 4 days after sealing.

Chief Inspector of Mines, Mr Peter Minahan; Deputy Chief Inspector of Mines (Coal), Mr Brian Lyon and Senior Inspector of Mines, Mr Tim Jackson have visited the mine at the time of sealing to witness the effect of the new inertisation practices.

The project studies have greatly improved the fundamental understanding of the various site parameters and inertisation schemes on goaf inertisation. This new understanding has been used to develop the optimum inertisation strategies for site conditions, which have proved to be highly successful in goaf inertisation.

This project demonstrated that it is feasible to completely inertise the longwall goafs within a few hours of sealing the panel by implementing optimum inertisation strategies. Similar optimum inertisation strategies can be developed for other site conditions. The fundamental understanding of inert gas flow patterns and optimum inertisation guidelines developed during the course of the project greatly enhance the safety of underground coal mines.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

In underground gassy coal mines it is generally recognised that immediately after sealing a longwall panel, the atmosphere behind the seals may enter and pass through the explosive range. The duration of the explosive conditions in the sealed longwall goafs ranges from a few hours to 1 or 2 days days to a few weeks. This depends largely on the gas emission rate and goaf characteristics. Therefore, any sealed area with methane as the seam gas has the potential to explode depending on the presence of ignition sources. Due to this potential risk of explosions, it is a general practice in many Australian mines to withdraw all persons from the mines until the goaf atmosphere behind the seals becomes inert.

In mines with higher goaf gas emissions or CO_2 gas emissions, the sealed area may not pass through the explosive range, or it may pass through very quickly, and the impact of clearing the mine of workers may not be great. However, in mines where there are large voids and the make of methane gas is much lower, the goaf atmosphere may stay in the explosive range for few days and financial/safety impact of withdrawing people from the mine for long durations could be serious.

Although it may be argued that the risk of explosion in particular mines is non-existent due to the absence of a major ignition source, i.e. spontaneous combustion (sponcom) during longwall extraction, it is to be noted that in many cases sponcom indicators were detected only after sealing the panel. In a number of longwall panels, it may be difficult to detect the sponcom at early stages due to the complexity of gas flow movements in the goaf combined with effects of caving characteristics and ventilation system parameters. Even in places where sponcom is non-existent, the second major source of ignition i.e. falling rocks in the goaf causing sparks, has the potential to be present in all the longwall goafs. In fact, in the recent major fires and explosions in the United States, it was identified that roof fall in the goaf was the most likely source of ignition (McKinney et al. 2001). Therefore, one of the best ways to eliminate or minimise the risk of explosions in sealed areas is to ensure that explosive gas mixtures are not developed in the large void spaces of the goaf near the longwall finish line.

To minimise this explosive gas mixture development behind the seals, the trend in Australian mines is to inject inert gas into the sealed goafs immediately after sealing the panel, to hasten the rate of goaf inertisation. The specific objective of these inertisation operations is to reduce the goaf oxygen concentration below the safe limit of 8% (i.e., with a factor of safety of 1.5 on the explosive nose limit of 12%) before methane concentration reaches the lower explosive limit of 5%. The inertisation operations usually involve injecting inert gas through MG or TG seals until goaf gas sampling results show that the oxygen level was below 8%. However, in many cases it was found that goaf oxygen concentration was above 12% even after 2 to 3 days of inert gas injection and in some cases an explosive atmosphere was also present in the goaf during inertisation. There was a need to optimise inertisation operations to reduce the goaf oxygen levels as quickly as possible during longwall sealing off periods.

1.2 OBJECTIVE

The main objective of the project was to develop optimum and effective strategies for inertisation during longwall sealing operations to achieve goaf inertisation within a few hours of sealing the panel.

1.3 SCOPE OF WORK

To achieve the objectives of this research project, a series of field investigations of various inertisation practices have been conducted together with detailed studies of inert gas flow mechanics in the sealed goaf environments using computational fluid dynamics (CFD) models. The project scope included:

- Collection and review of the data from the existing inertisation operations, including data from previous operations.
- Comprehensive review and analysis of the effect of various mining, ventilation and inertisation design parameters on goaf gas composition.
- Laboratory studies to investigate the effect of various inertisation strategies on temperature changes around the heating area in a coal heap.
- Enhance the understanding of the inert gas flow patterns in the goaf through tracer gas studies.
- Development of a longwall gas flow model using computational fluid dynamics (CFD) codes and extensive simulation studies to analyse the inert gas flow mechanics and dispersion patterns in the longwall goafs.
- Application of the calibrated goaf gas model to conduct a number of parametric studies to quantify the effect of various design parameters and to develop optimum inertisation strategies for application during longwall sealing periods.
- Field studies at an underground mine during longwall sealing operations to demonstrate the effectiveness of optimised inertisation strategies. Studies also involve an extensive monitoring arrangement to evaluate the effect of new strategies on gas composition at various locations in and around the longwall goaf.

1.4 PROJECT STUDIES

Total duration of the project was 18 months, which started in June, 2000 and completed in December, 2001. The following studies have been conducted during the course of this research project.

1. Data review

The data review phase of the study initially involved collection of inertisation data from previous operations and field studies to collect data from the on-going inertisation operations at a number of longwall panels. In total, inertisation data has been collected from 6 different longwall panels in 3 underground mines, which includes the participating mine for field demonstration studies. A comprehensive review of the inertisation data has been carried out to analyse the effect of different inertisation designs on goaf gas concentration. The effect of mine factors such as goaf layout, ventilation systems and inert gas composition on effectiveness of inertisation was also assessed. The results of these review studies are presented in Chapter 2, together with detailed discussions.

2. Laboratory studies

A number of laboratory studies have been conducted at SIMTARS (Safety In Mines Testing And Research Station) spontaneous combustion testing facility. The inertisation investigations were conducted after completion of spontaneous combustion tests. The objective of these laboratory tests was to investigate the effect of inert gas injection on temperature changes, gas flow mechanics and on gas concentration levels around the heating area in the sponcom rig. The layout and details of the sponcom testing facility, experimental procedure and results of laboratory trials are reported in Chapter 3. Effects of inert gas flow rate, inertisation duration and fresh air re-introduction on control of heatings in the sealed areas are also discussed in this chapter.

3. CFD modelling

The focus of the modelling exercise was to obtain a better understanding of the inert gas flow patterns in the goaf and qualitative analysis of the various factors involved in inertisation operations, to establish a scientific basis for design of optimum strategies. Computational fluid dynamics (CFD) techniques have been used to develop the goaf models in order to study the inert gas flow mechanics in the sealed longwall panels. Data obtained from the initial field studies and previous inertisation operations was used to validate and calibrate the base-case sealed goaf flow models. The validated models were then used for extensive parametric studies to investigate the effect of various inertisation strategies and designs on goaf gas composition. The effects of goaf layout, geometry and ventilation parameters on inertisation were also investigated in these modelling studies. Results and analysis of the extensive parametric studies were then used to develop an optimum strategy for quick and effective inertisation of the longwall panels during sealing off operations. Modelling details, results and analysis are presented in Chapter 4.

4. Field demonstration studies

The techniques and strategies developed during the course of the project were implemented at Newlands Colliery (the field site) to evaluate and demonstrate the effectiveness of new inertisation strategies. The field studies also involved tracer gas investigations to improve our understanding of the inert gas dispersion patterns in the sealed goaf. An extensive monitoring programme involving 8 monitoring tubes in the underground seals and 3 monitoring tubes in the surface boreholes was implemented during these field demonstration studies to obtain detailed data on performance of the new inertisation strategies. Newlands Colliery and project collaborator SIMTARS have also been heavily involved in these field studies. The mine background, details of inertisation studies, monitoring and analysis of the results are reported in Chapter 5. Results of the tracer gas studies with discussion on gas flow patterns are also reported in this chapter.

Chapter 6 describes the main findings and conclusions of this research project. Recommended inertisation strategies and suggestions for further research are also listed in this chapter.

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CHAPTER 2

REVIEW OF EXISTING INERTISATION PRACTICES

2.1 INTRODUCTION

Inertisation is one of the techniques used in underground coal mines to control active fires and control spontaneous combustion in the goaf. Recently, inertisation is also being used to lower the risk of potential explosions during longwall panel sealing off periods. This research project specifically concentrates on optimisation of this latest application of inertisation technology. Traditionally liquid N_2 and CO_2 were used in most of the fire control inertisation operations. However, it was difficult and expensive to procure large quantities of the inert gases for routine longwall sealing applications, particularly in mines located at remote places of Australia. In 1997, the Tomlinson Boiler low-flow inertisation device and a high capacity GAG 3A jet engine system were demonstrated to the Australian mining industry as new practical tools for inertising underground mine atmospheres. The successful demonstration of these devices has improved the availability of inert gases for routine mine applications.

Over the last 4 years, there have been over 10 applications of inertisation technology in Australia during longwall sealing off operations. At one mine, methane gas from the in-seam pre-drainage system has been utilised to inertise the goaf in an attempt to hasten the rate of sealed goaf inertisation. This chapter reviews the current inertisation practices with detailed analysis of the data collected from 6 longwall panels.

2.2 INERTISATION TECHNIQUES AND PRACTICES

Application of inertisation techniques has increased considerably during the recent years to reduce the potential risk of explosions during or after sealing off longwall panels. Successful field demonstration trials of the Tomlinson Boiler and GAG jet inertisation devices in 1997 (Brady 1997a, b, Bell et al. 1997) has improved the availability of inert gases for routine mine applications. These trials and other inertisation operations carried out over the recent years have increased the confidence of mining staff on inertisation operations. A brief summary of the available inertisation techniques, gases and strategies is presented in this section. Each of the following inertisation techniques has some advantages and disadvantages and selection of any specific technique depends on the purpose and conditions at the application site.

2.2.1 Inertisation Gases and Techniques

(a) Liquid Nitrogen/ Mineshield

The mineshield system vaporises liquid nitrogen carried to the site by bulk tankers before being injected underground. The mineshield system was initially developed in New South Wales and used in a number of occasions to control fires in underground coal mines. The system is currently being maintained by NSW Rescue Station/ Brigade. The major source of liquid nitrogen in Australia is from plants located near Sydney and Newcastle. Each bulk tanker can carry up to 20 tonnes of liquid nitrogen. One tonne of liquid nitrogen is approximately equivalent to 844 m^3 of gas at ambient temperature. The mine shield system can vaporise liquid nitrogen at the rate of 2 to 3 m^3/s, which is equivalent to 7,000 to 11,000 m^3 of inert gas per hour or 8 to 12 tonnes of liquid nitrogen per hour (Bell et al. 1997).

However, the nitrogen pumping rate during any inertisation application depends on the heating conditions at the mine site. Nitrogen is particularly good for inerting large volumes of sealed goafs and where flows are to go to far locations and through difficult paths.

(b) Pressure Swing Absorption (PSA) devices
The pressure swing absorption (PSA) apparatus developed in Germany utilises chromatographic techniques to separate nitrogen in air from oxygen. Typical flow rates of nitrogen are about 0.5 m^3/s at ambient temperature. In some countries, these units are centrally located and maintained by the mining companies to serve a group of coal mines.

(c) Liquid CO_2
Carbon Dioxide (CO_2) may be the better gas where the heating area to be inerted is at a lower elevation than the points of inert gas (CO_2) injection or where coldness of the gas is important. CO_2 is also usually delivered in 20 tonne tankers. One tonne of liquid CO_2 is approximately equivalent to 535 m^3 of gas at ambient temperature. CO_2 changes from a liquid state to gas by heat or by a rapid drop in pressure or by utilising vaporisers.

(d) GAG 3A Jet Inertisation Device
The GAG 3A inert gas generator is based around a small 5 MW aviation jet engine with a single stage afterburner. The GAG 3A inert gas generator was originally developed in Poland in the early 1970's and has been used extensively in Poland, Czech Republic, CIS and South Africa. The device was brought to Australia by the Polish mines rescue service with SIMTARS providing operational support under an ACARP/ industry-funded project. First trials with this device were carried out successfully at Collinsville Colliery in 1997 (Bell et al. 1997).

The output of the device is about 20 m^3/s of inert gas (9 m^3/s gas + 11 m^3/s water vapour) with less than 3% oxygen concentration. Typical specifications of the GAG unit are presented in Table 2.1. Recently, the GAG engine has been utilised in the inertisation of a large area of old underground workings associated with active fires in an opencut mine. Presently, two GAG inertisation units with associated hardware and trained operators are being maintained by the Queensland Mines Rescue Service (QMRS).

(e) Tomlinson Boiler
The Tomlinson boiler system delivers the exhaust gases from a diesel fired boiler unit as inert gas. The output of this inert gas generator is about 0.5 m^3/s. Typical specifications of the Tomlinson unit are presented in Table 2.2. Initial trials with this unit were conducted successfully at Cook Colliery in 1997, under an ACARP project (Brady 1997a, b). The field trials have demonstrated that the Tomlinson inert gas generator has enormous potential for elimination of the explosion hazards that might exist when longwall goafs are sealed.

Over the last 4 years Tomlinson boilers have been utilised over 10 times for spontaneous combustion control or inertisation of sealed goafs. Currently, at least five Tomlinson

Boiler inertisation units are available for mining applications and are being used regularly in some of the Queensland mines during longwall panel sealing operations.

Table 2.1 Typical specifications of GAG Inertisation unit

1	Principle	Jet engine with a single stage afterburner
2	Inert gas flow rate	20 m^3/s
3	Oxygen content	Less than 3% Oxygen
4	Temperature of exit gas	85 to 90 ^oC
5	Fuel consumption	1,500 l/hr (aviation fuel)
6	Water consumption	66,000 l/hr
7	Weight	2,600 Kg
8	RPM	9,500 to 11,000

Table 2.2 Typical specifications of Tomlinson Boiler Inertisation unit

1	Principle	Exhaust gases from diesel fired boiler unit
2	Inert gas flow rate	0.5 m^3/s
3	Gas delivery pressure	100 kPa
4	Gas composition	O_2 = 2% CO_2 = 13.4% N_2 = 84% CO = 2 to 10 ppm
5	Temperature of exit gas	20 ^oC
6	Fuel consumption	200 l/hr (diesel)
7	Water consumption	2,000 l/hr
8	Electric supply	100 KW – 415 volts/ 3 phase

2.2.2 Typical inertisation practice during longwall panel sealing

Currently inert gas from Tomlinson boiler and drained inseam gas are being used in some mines for routine inertisation operations. The major objective of these inertisation operations is to inertise the goaf as quickly as possible, i.e. to minimise the length of time spent going through the explosive range. Specifically the aim is to reduce goaf oxygen concentration below the safe limit of 8% (i.e. with a factor of safety on explosive nose limit of 12%) before methane concentration reaches the lower explosive limit of 5%. A typical inertisation scheme being employed in Australian mines is shown in Figure 2.1. The inert gas is injected into the goaf generally through MG seal immediately after sealing the panel. Recently, some mines started the practice of injecting inert gas simultaneously into other seals depending on the oxygen levels at various locations around the goaf

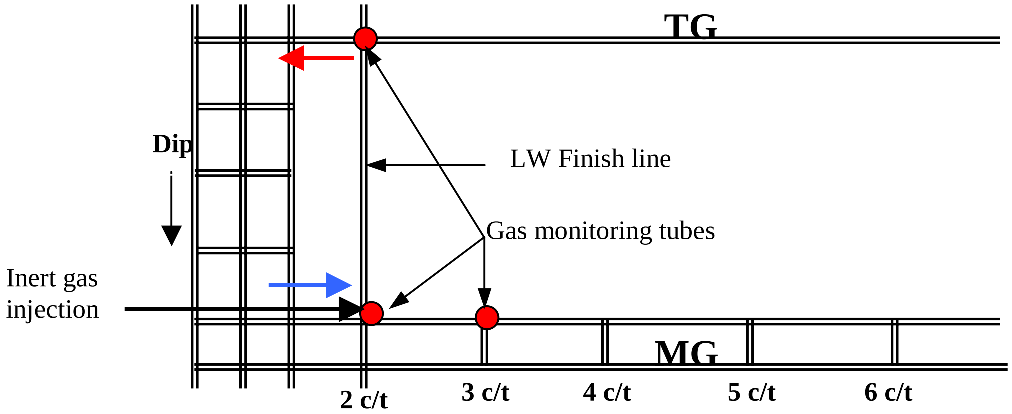

Figure 2.1 Typical inertisation practice in longwall panels

In Australia, normally 2 to 3 tube bundle sampling tubes are installed in a longwall panel for monitoring gas levels around the face, except in some mines where 6 to 8 tubes are used for detailed investigations. During longwall sealing and inertisation operations, these monitoring tubes are installed in TG, MG and one inbye cut-through seals to monitor goaf gas levels.

The inert gas generator is normally set up at a temporary surface site above the longwall panel with a generator for power and a tank for water supply. The generator is manned continuously during inertisation operations. One or two 150 mm diameter boreholes are drilled from the surface into the coal seam near the maingate entries for inert gas delivery.

In some cases, the boiler is commissioned before final sealing and is used to reduce the oxygen concentration near the inbye seals. To estimate the inertisation time, mines initially estimate the goaf void volume near the finish line and then calculate the volume of inert gas required to reduce the oxygen content below 8%. Generally these calculations showed the estimated inertisation time in the range of 48 hours. The following section presents a detailed analysis of data collected from inertisation case studies along with a discussion on effects of various strategies employed at different mines.

2.3 INERTISATION CASE STUDIES

Longwall goaf inertisation is being carried out at some of the mines in Australia on a regular basis to reduce the potential risk of explosions during the panel sealing off period. This section presents a brief review and analysis of inertisation data collected from 6 longwall panels. These 6 panels had employed different inertisation schemes and cover 3 different mines with different gas emission rates and panel characteristics. The first case is from Mine A, second and third cases are from Mine B and the last three cases are from Mine C. The objective of the review study was to analyse the effect of standard inertisation practices on gas distribution and goaf inertisation in different conditions.

2.3.1 Case 1

A schematic diagram of the longwall panel layout along with monitoring tubes locations is shown in Figure 2.2. In this panel, the Maingate (MG) acted as intake and the tailgate as return airway during retreat of the longwall face. Airflow quantity of 40 to 50 m^3/s had been maintained through the face during longwall extraction. The panel orientation was such that the tailgate was at a higher elevation than the maingate. Methane gas emission in the panel was low at the rate of about 300 l/s and there was no need for a goaf gas drainage system in the panel. During face recovery operations, chock withdrawal started from the TG side of the face and continued towards the MG end of the face. After withdrawal of a few chocks, the face line near the tailgate end collapsed, which restricted the airflow through the panel to 5 to10 m^3/s. Therefore, an auxiliary ventilation system was used to supply fresh airflow to the face during chock recovery operations.

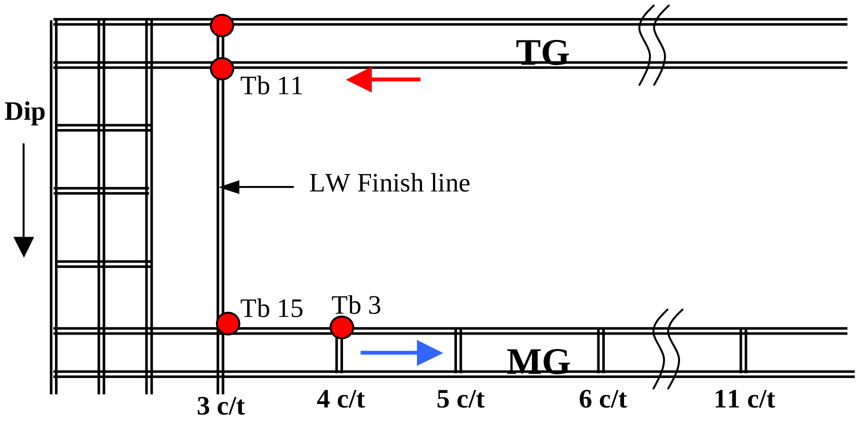

Figure 2.2 Longwall panel layout and gas monitoring locations – Case 1

On completion of the chock recovery operations, the panel was sealed off on 20th Aug at 11:30 am by constructing seals at TG, MG and 3 cut-through (c/t) locations. Boiler inert gas was injected into the goaf immediately after sealing initially through 4 c/t on maingate side for 6 hours and then through both the MG and 4 c/t seals simultaneously for about 3 weeks. In this panel, a Tomlinson Boiler gas was used as the inert gas with a flow rate of about 0.5 m^3/s. Goaf gas concentration was monitored continuously through the tubes 3, 15 and 11 and additional gas bag samples were also collected manually from other seals at regular intervals.

Gas concentration profiles at various monitoring points around the longwall goaf during the inertisation period are shown in Figures 2.3 to 2.7. The gas profile at the MG seal (Figure 2.3) shows that oxygen concentration was above the safe limit of 8% for up to 9 hours after sealing the panel, even when inert gas was being injected through the adjacent 4 c/t seal. At that stage, the inert gas injection strategy had been changed and inert gas was introduced through both the MG and 4 c/t seals simultaneously. From that time onwards gas readings at the MG seal just showed the boiler gas composition. Figure 2.4 shows the gas profile at 11 c/t in the panel, which was almost 800 m behind the face finish line. Results show that even so far deep (800 m behind face) in the goaf oxygen level was above 8% for up to two days after sealing the panel. Results indicate that low goaf gas emissions, ventilation system around the panel and goaf characteristics may have contributed to this unusual gas distribution at this point.

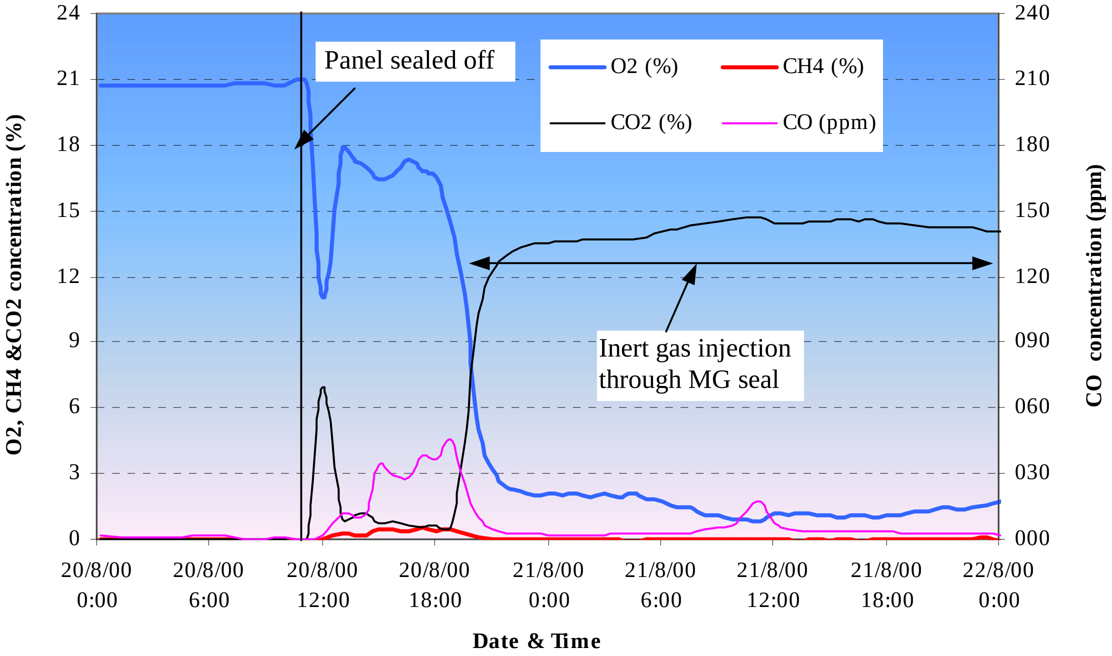

Figure 2.3 Gas concentration profile at MG seal (Tube 15) - during panel seal off and inertisation – Case 1

Figures 2.5 to 2.7 shows the gas profiles at tailgate (TG) seal location in the goaf before sealing, during sealing and after sealing the panel respectively. Results show that methane gas concentration at tailgate was high for a few days before sealing (Figure 2.5) due to lack of ventilation near the tailgate during chock recovery operations. Figure 2.6 shows that introduction of inert gas on MG side of the panel resulted in immediate reduction of CH_4 gas levels at the TG seal with a steep rise in CO levels. Reduction in oxygen levels was slow at that location with O_2 levels above 8% for up to one day after sealing the panel. Gas profiles in Figure 2.7 show that it took almost two weeks for full composition of the boiler inert gas to reach the TG seal.

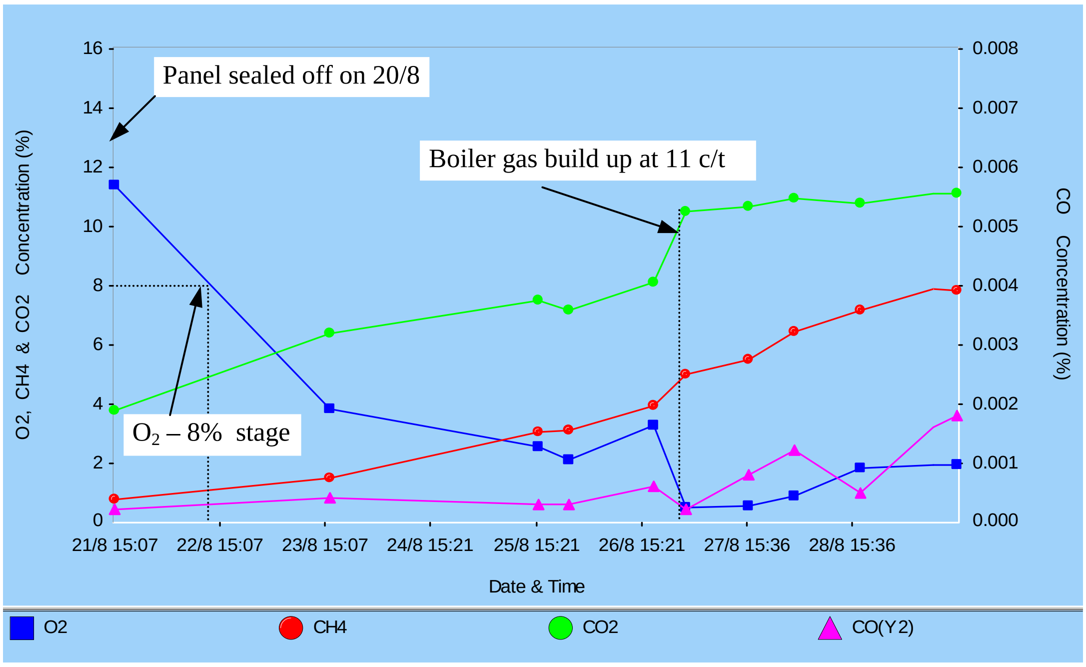

Figure 2.4 Gas concentration profile at maingate 11 c/t seal – after panel seal off – Case 1

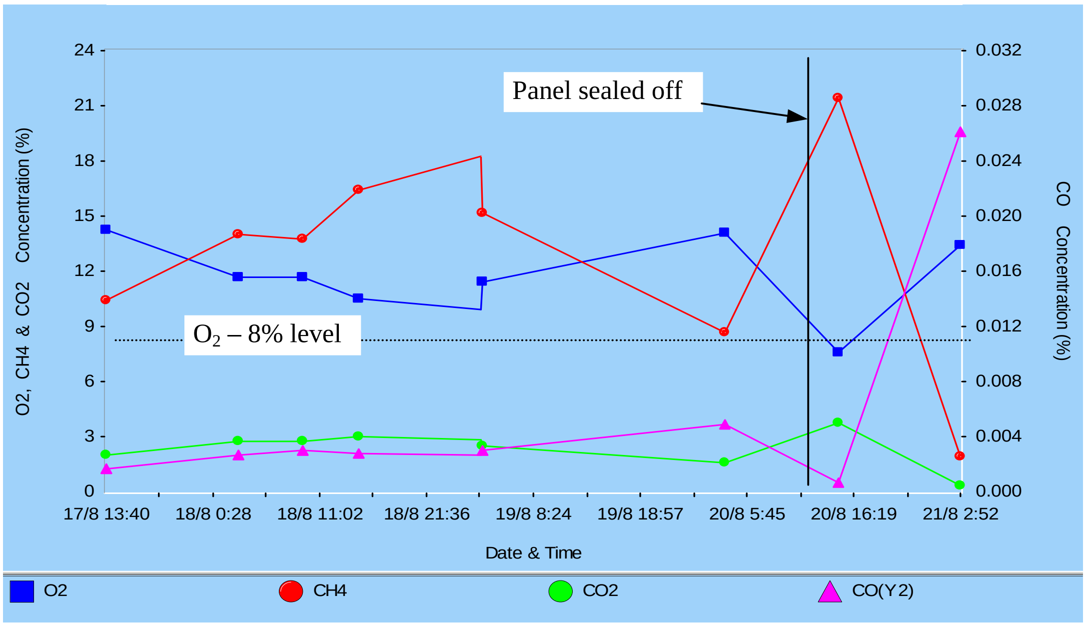

Figure 2.5 Gas concentration profile at TG seal (tube 11) – before panel sealing – Case 1

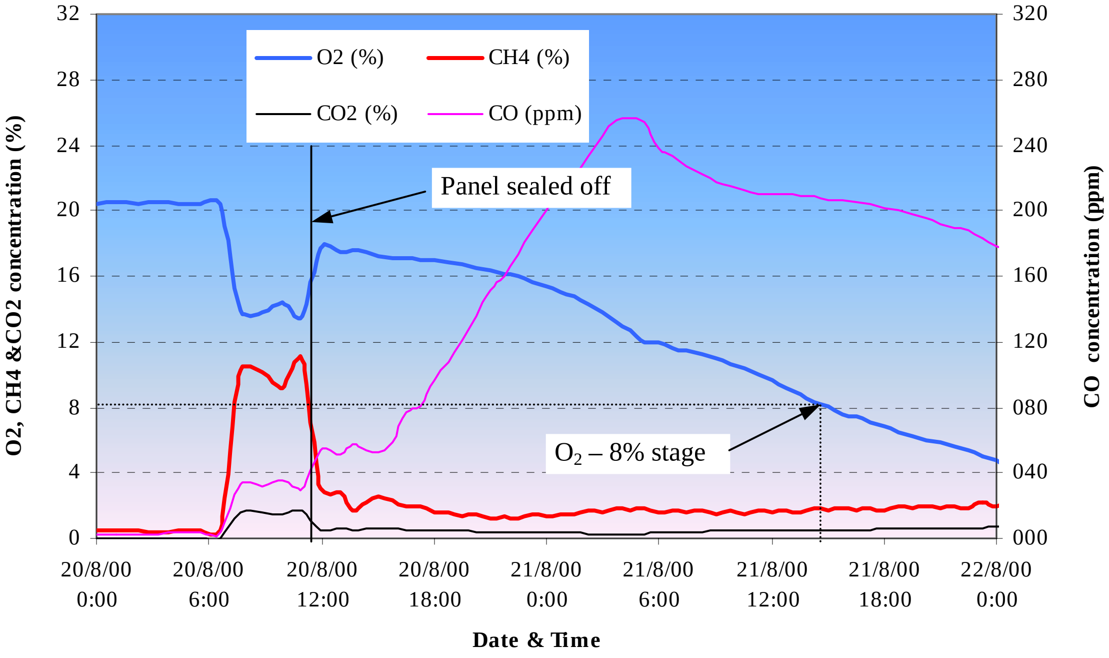

Figure 2.6 Gas concentration profile at TG seal (tube 11) – during panel seal off and inertisation – Case 1

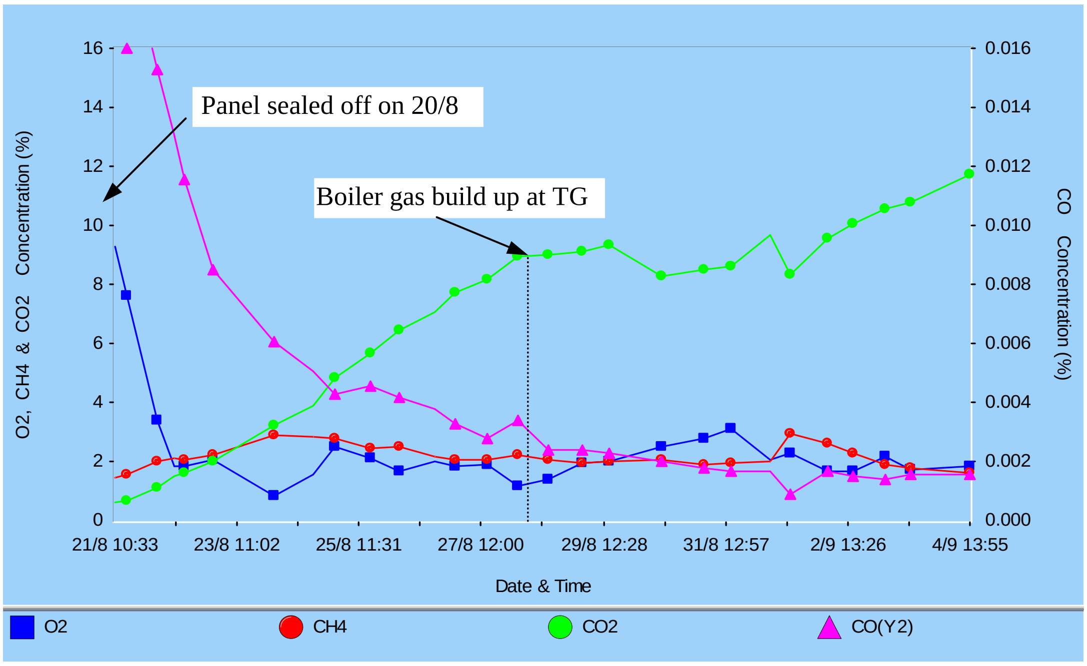

Figure 2.7 Gas concentration profile at TG seal (tube 11) – after panel seal off – Case 1

Goaf gas distribution at various locations around the goaf in plan view is shown in Figures 2.8 and 2.9. Gas distribution in the goaf just before sealing (Figure 2.8) shows that oxygen level on maingate side was above 12% over a wide area in the goaf. During inertisation process, gas levels in the goaf (Figure 2.9) show that dispersion of inert gas into the goaf was slow even after 6 hours of inert gas injection. Comparison of figures 2.8 and 2.9 indicates that inert gas introduction on MG side has resulted in migration of CH_4 gas towards the upper zones of the caved roof. Results show that oxygen concentration reduced to 8% by 23rd August, i.e. 3 days after sealing the panel.

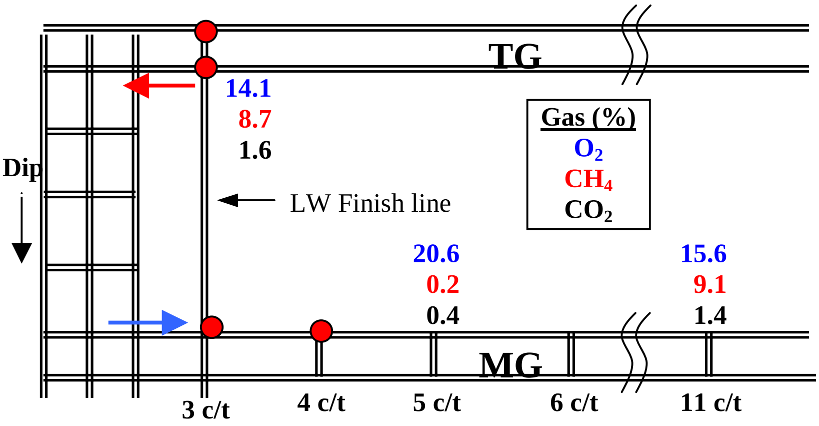

Figure 2.8 Gas distribution in the goaf – just before panel sealing – Case 1

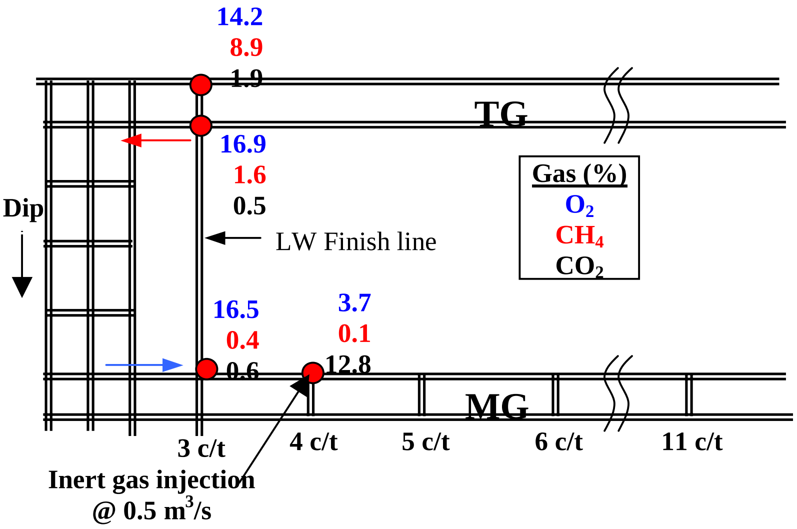

Figure 2.9 Gas distribution in the goaf – 6 hours after sealing – Case 1

In summary, analysis of the results indicated that the traditional inertisation scheme implemented at this panel was too slow in reducing the oxygen levels below the safe limit of 8%.

2.3.2 Case 2

The longwall panel layout was similar to the previous case, with maingate (at lower elevation) as the intake roadway and tailgate as return airway. Two monitoring tubes were installed in this panel at maingate (MG) and tailgate (TG) seals. Goaf gas emission in the panel was high at the rate of about 2,500 l/s of pure methane. Goaf gas drainage system was used extensively in the panel with a number of goaf holes drilled from the surface into the panel. Chock withdrawal in the panel started from TG end of the face towards MG side. The longwall panel was sealed on 29th October and in-seam drained methane gas was introduced into the goaf through MG seal to fasten the rate of goaf inertisation. In this first trial of inertisation at this mine, methane gas injection/ inertisation into the goaf was carried out only for few hours on a trial basis.

Gas concentration changes at the MG and TG seals during longwall sealing-off process are shown in Figures 2.10 and 2.11. Methane gas concentration at the tailgate quickly rose above 25% within a few minutes of sealing the panel (Figure 2.10). However, oxygen concentration was still above 8% for up to three days after longwall panel sealing. Figure 2.11 shows that at the MG seal, the rise in methane gas and reduction in oxygen levels was gradual and led to formation of explosive gas mixtures near the finish line. Five days after sealing the panel, oxygen level in the goaf reduced to the safe level of 8%. The results represent more of a natural inertisation process in the longwall goafs at this mine, as methane gas was injected into the goaf for only a few hours on a trial basis.

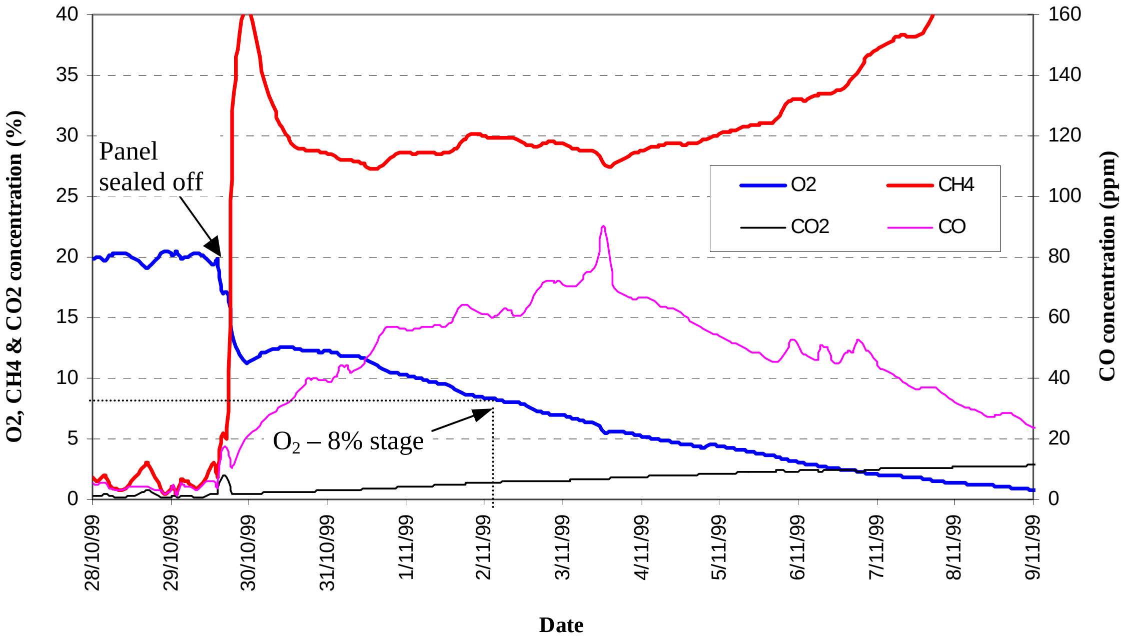

Figure 2.10 Gas concentration profiles at TG seal for two weeks after sealing – Case 2

Gas distribution in the goaf near the longwall finish line is shown in Figures 2.12 and 2.13. Goaf gas distribution just before sealing the panel (Figure 2.12) indicates that good airflow was maintained through the face during chock recovery operations. Figure 2.13

shows that gas mixture in the goaf was in the explosive range even one day after panel sealing. Both the figures also show the effect of buoyancy on gas distribution at MG and TG seals. Analysis of the results for this panel indicate that the trial inertisation scheme, involving injection of methane gas through MG seal for only a few hours, was not effective in preventing the formation of explosive gas mixtures near the longwall finish line for up to two days after sealing the panel.

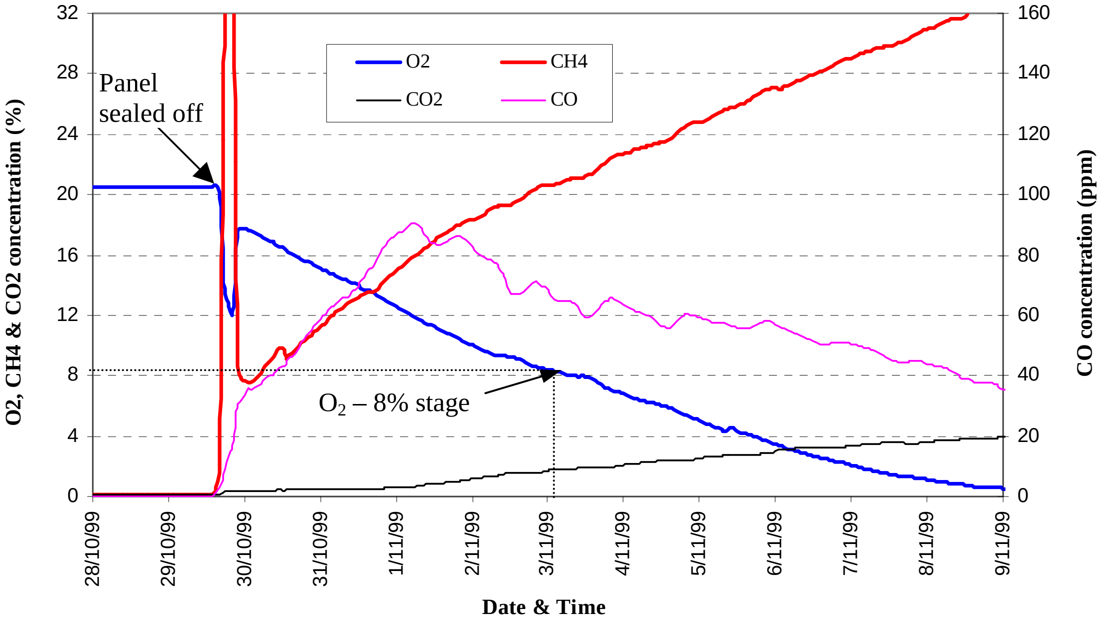

Figure 2.11 Gas concentration profiles at MG seal for two weeks after sealing – Case 2

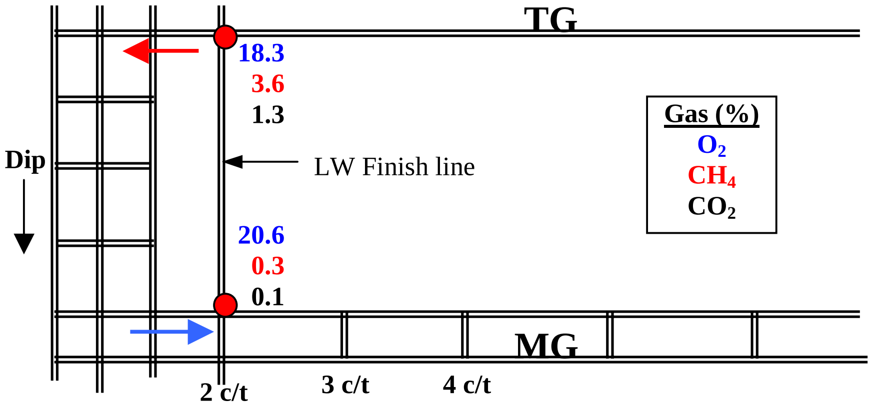

Figure 2.12 Gas distribution in the goaf – Just before panel sealing – Case 2

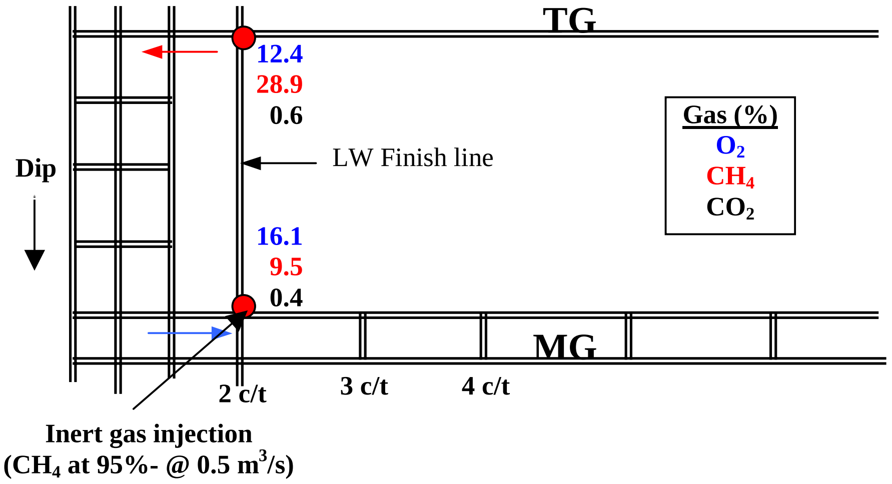

Figure 2.13 Gas distribution in the goaf – 1 day after panel sealing – Case 2

2.3.3 Case 3

The longwall panel layout in this case was similar to case 2 layout, with maingate as intake and tailgate as return airway. However in this case, the orientation of the panel was such that the maingate corner near the finish line was at slightly lower elevation compared with maingate corner at mid-panel position. Two sampling tubes at MG and TG seals were available for goaf gas monitoring during inertisation. Goaf gas emissions in this panel were also high at around 3,000 l/s of pure methane and surface goaf holes were used for draining a larger proportion of the goaf gas. The longwall panel was sealed on 25th August and in-seam drained methane gas was introduced into the goaf through MG seal immediately after sealing. In this second trial of inertisation at this mine, methane gas was initially introduced for 8 hours and after a gap of 1 day, methane gas injection started again and the inertisation process continued for one week. During the methane gas injection process attempts were made to draw goaf gas from the nearest goaf hole in order to improve inert (methane) gas dispersion into the goaf. Flame arrestors were installed at both the methane gas injection and gas drainage points to prevent any untoward incidents during the inertisation process.

Figures 2.14 and 2.15 shows the gas concentration levels at TG and MG seals during and after inertisation process. Figure 2.14 shows that methane gas concentration at the TG seal crossed 40% immediately after sealing the panel and continues to rise thereafter. Oxygen level at this location reduced to 4% within three days of sealing and to 1% after 10 days. Figure 2.15 shows that there were a lot of fluctuations in gas concentration levels at the MG seal. Results show that injection of methane gas for 8 hours changed the oxygen and methane gas levels at the MG seal to 11% and 35% respectively. However, stoppage of methane gas injection resulted in rapid changes in goaf gas composition, with oxygen level increasing to 16% and methane level reducing to 6% within a few hours of stopping the inertisation process. Consequently, the inertisation process had started again and continued for almost a week. Analysis of the results indicated that the trial inertisation scheme implemented in this panel was also not effective in reducing the oxygen levels down to 8% within few hours of sealing.

However, it was noted that goaf inertisation in the subsequent panels was achieved within 4 hours of sealing by implementing new optimum inertisation strategies. The new strategies include injection of inert gas through both MG and 3 c/t seals, changing the pressure balance around injection points and creating a pressure differential near high oxygen concentration areas in the goaf.

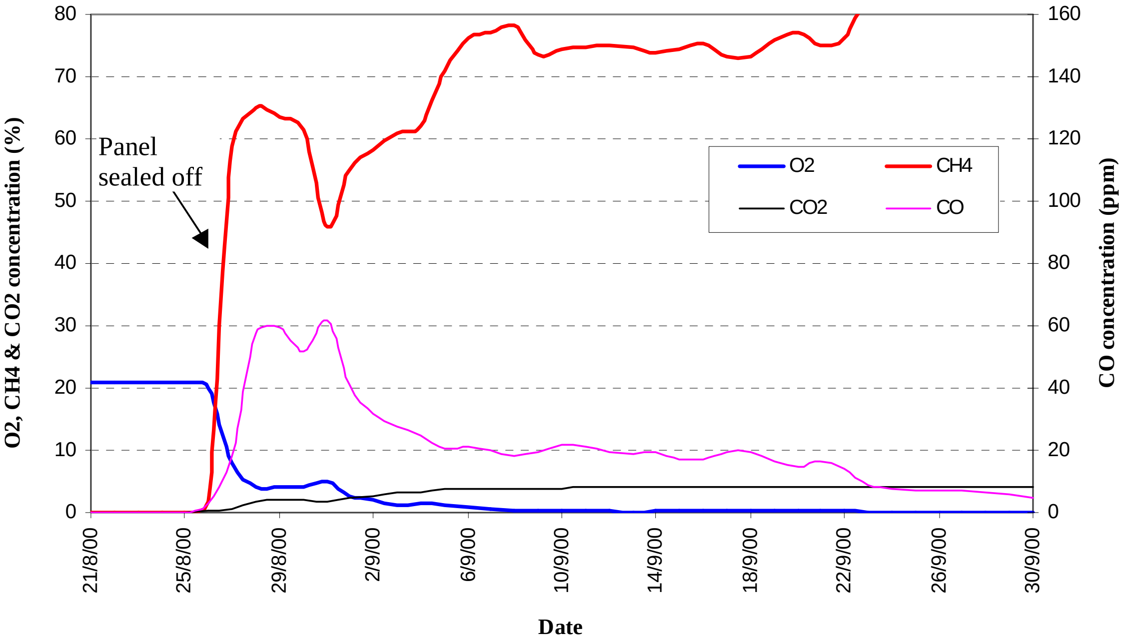

Figure 2.14 Gas concentration profiles at TG seal – Case 3

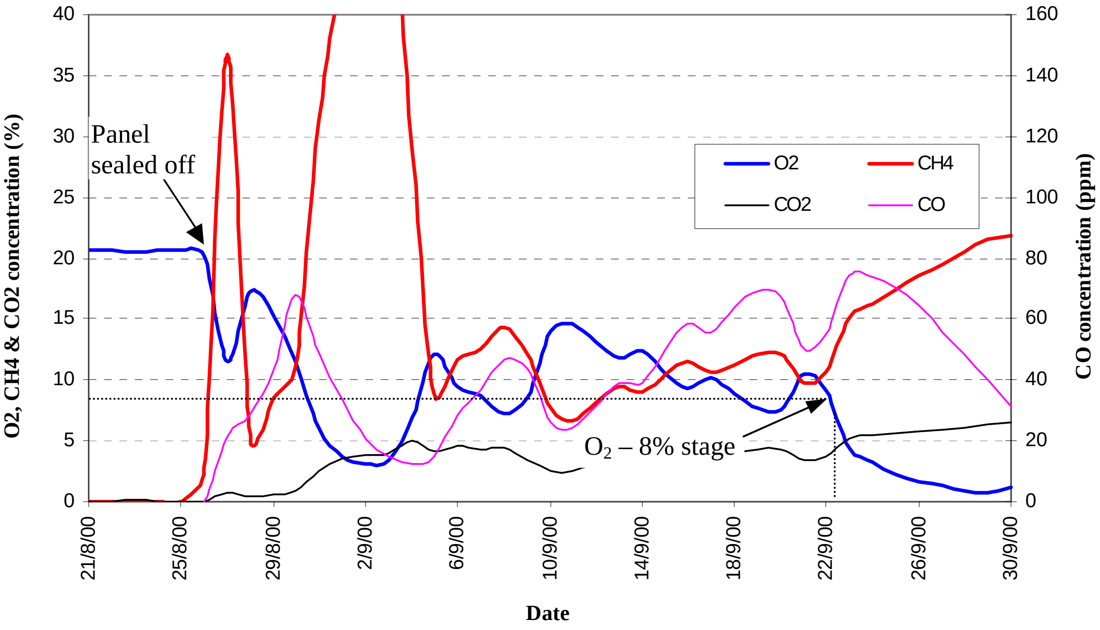

Figure 2.15 Gas concentration profiles at MG seal for one month after sealing – Case 3

2.3.4 Case 4

Longwall panel layout for case 4 along with monitoring tubes location is shown in Figure 2.16. Six sampling tubes were installed in the goaf for detailed monitoring during inertisation. During face retreat operations, the maingate was used as an intake airway and the tailgate as return airway. Airflow quantity of 40 to 50 m^3/s had been maintained along the face during longwall extraction. In this case, the panel orientation was such that the maingate intake was at a higher elevation compared with the tailgate roadway and the outbye tailgate corner was the point of lowest elevation. Methane gas emission in the panel was low at the rate of about 300 l/s and a goaf gas drainage system was not used in the panel.

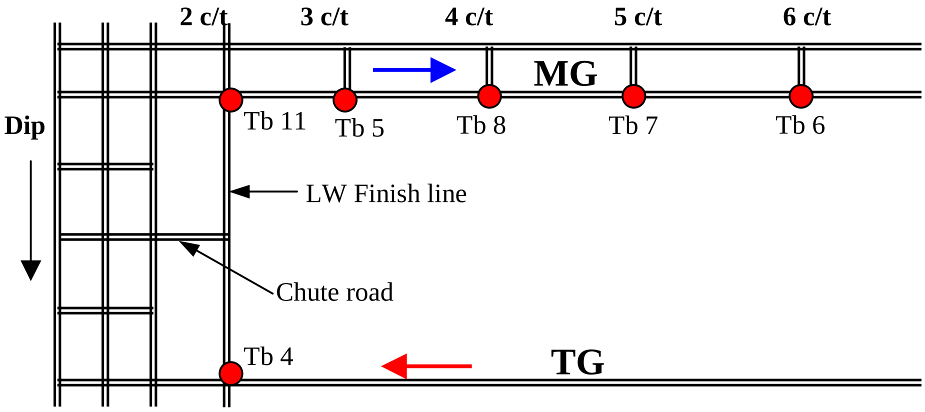

Figure 2.16 Longwall panel layout and gas monitoring locations – Case 4

The longwall panel sealing sequence was as follows:

- Longwall recovery operations start at TG side of the face. Ventilation at that stage was from maingate to tailgate.
- After recovery of chocks up to chute road, ventilation airflow was allowed to return through chute roadway and the TG was sealed off.
- Complete recovery of the face and then MG and chute roads were sealed-off completely. Panel sealing completed.

After sealing off the panel on 16th August, boiler inert gas was injected initially through the MG seal and then through both the MG and 3 c/t seals for 3 days.

Gas concentration profiles at various monitoring points around the longwall goaf during the inertisation period are shown in Figures 2.17 to 2.20. Gas levels recorded at the MG seal (Figure 2.17) just showed the composition of boiler gas, as inert gas was injected from the same seal. Figure 2.18 presents the gas levels as recorded at the TG seal and shows that oxygen concentration was above the designed safe limit of 8% for up to 1 day after sealing the panel. Gas levels recorded at the 3 c/t seal on maingate side (Figure 2.19) also shows that O_2 concentration was above 8% for up to 1 day after sealing. Although the rate of increase in methane was below the dangerous level, CO levels increased steeply at the seal location and exceeded the mine safety trigger levels, leading to mine evacuation. At that stage inert gas was also injected through 3 c/t seal. From then onwards gas levels recorded at 3 c/t location also just showed the boiler gas composition.

Figure 2.20 presents the gas levels recorded at the 4 c/t seal on maingate side, which shows that although the goaf gas composition had not gone through the explosive range, it was very close to explosive composition for up to10 hours after sealing the panel.

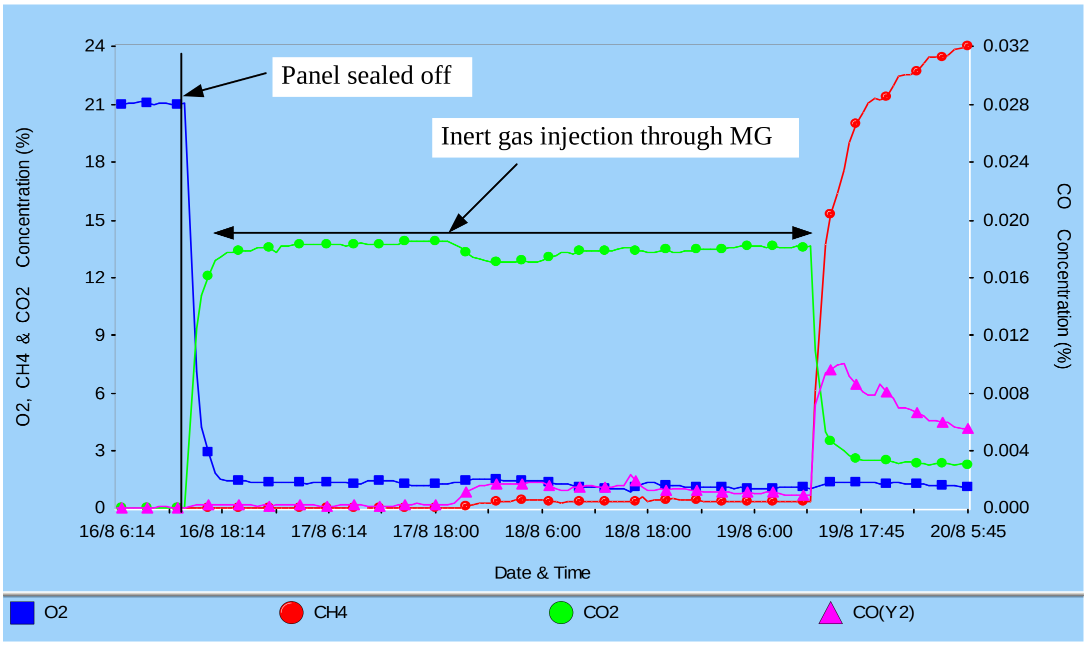

Figure 2.17 Gas concentration profiles at MG seal (Tube 11) – Case 4

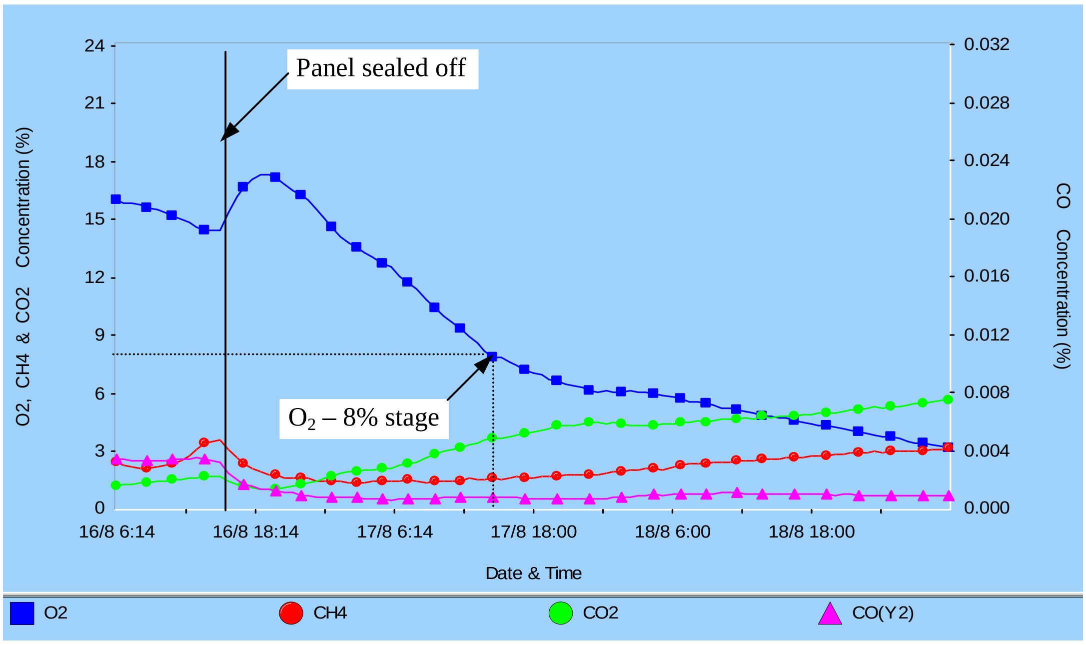

Figure 2.18 Gas concentration profiles at TG seal (Tube 4) – Case 4

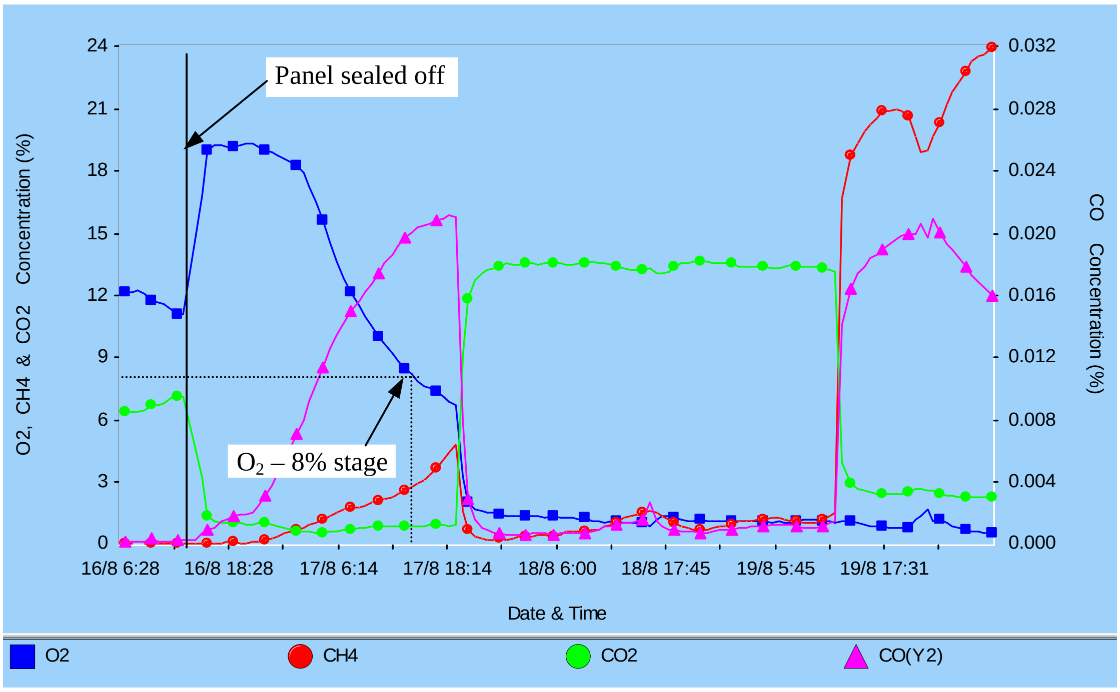

Figure 2.19 Gas concentration profiles at maingate 3 c/t seal (Tube 5) – Case 4

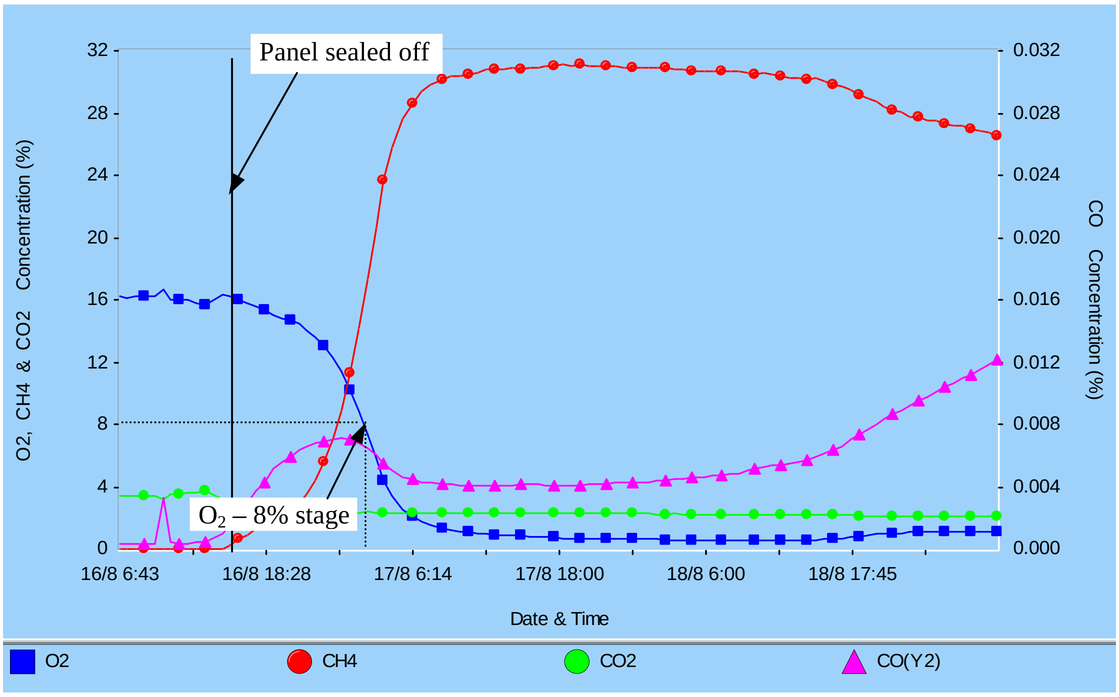

Figure 2.20 Gas concentration profiles at maingate 4 c/t seal (Tube 8) – Case 4

Goaf gas distribution at various locations around the longwall panel in plan view is shown in Figures 2.21 to 2.23. Figure 2.21 presents the goaf gas composition immediately before sealing off the panel and shows that the oxygen level was above the explosive nose limit of 12% even at 6 c/t, i.e. at 400 m behind the finish line on maingate side. Gas distribution in the goaf 6 hours after sealing the panel is shown in Figure 2.22. Comparison of figures 2.21 and 2.22 shows that fresh air/oxygen from face finish line area was pushed towards 3 c/t and TG areas after introduction of inert gas through MG seal. Figure 2.23 shows that the goaf O_2 level was above the safe limit of 12% even at 12 hours after panel sealing. Gas monitoring results showed that the goaf became completely inert 2 days after panel sealing.

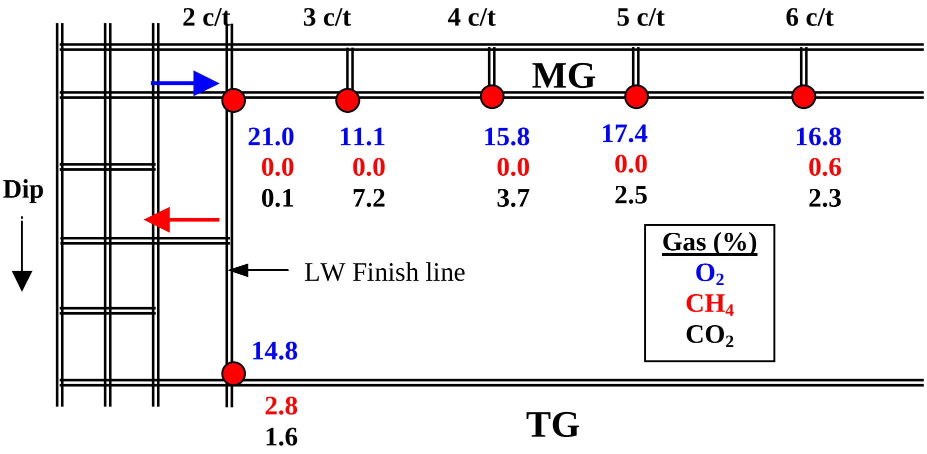

Figure 2.21 Gas distribution in the goaf – Just before panel sealing – Case 4

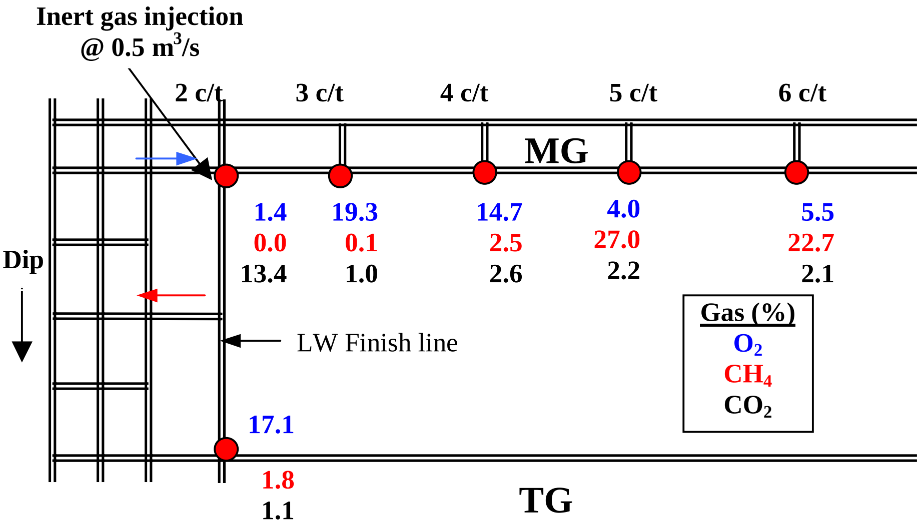

Figure 2.22 Gas distribution in the goaf – 6 hours after panel sealing – Case 4

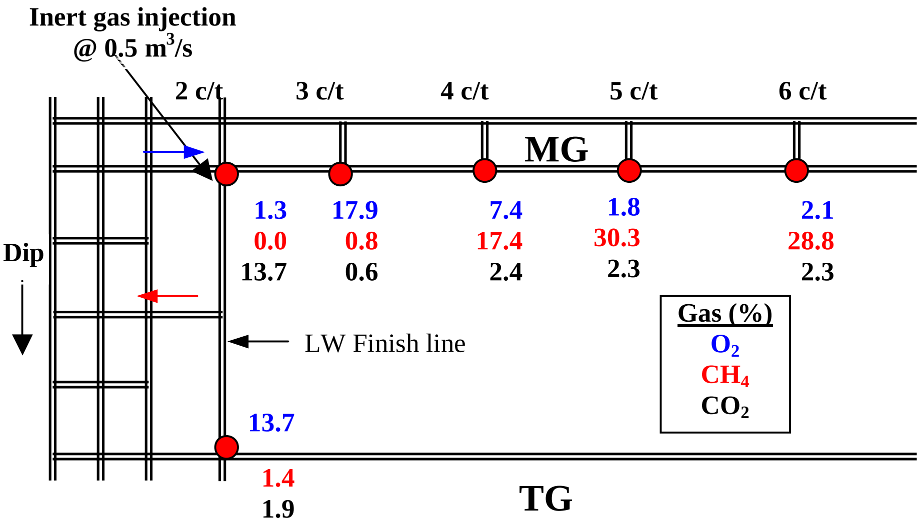

Figure 2.23 Gas distribution in the goaf – 12 hours after panel sealing – Case 4

In summary, analysis of the results indicates that although the inertisation scheme implemented in the case 4 panel was able to achieve better results compared with cases 1 to 3, goaf gas composition at 4 c/t was very close to explosive composition for up to one day after longwall panel sealing.

2.3.5 Case 5

The longwall panel layout in this case was similar to case 4 layout, with the maingate as intake and the tailgate as return airway. Orientation of the panel was also similar to case 4, with the maingate at a higher elevation than the tailgate position and outbye tailgate corner was the point of lowest elevation in the panel. Goaf gas emission in the panel was around 200 to 250 l/s, which was slightly less than previous case gas emissions. Chock withdrawal and sealing sequence in this panel was also similar to the system described in the previous case.

A Tomlinson Boiler inert gas generator was used for longwall inertisation operations. There was a slight change in the inertisation scheme, compared with case 4 inertisation. Inert gas was injected into the goaf immediately after completion of the seal construction at the TG. Injection of inert gas into the TG seal continued for 2 to 3 days until completion of the face recovery and panel sealing-off operations. After sealing-off the panel on 21st February, most of the inert gas was injected through the MG seal with around 20 to 30% flow through the TG seal. One day after panel sealing, inert gas was injected through TG, MG and 3 c/t seals simultaneously for another 2 to 3 days.

Oxygen and other gases concentration in the longwall goaf during inertisation process are shown in Figures 2.24 to 2.27. Gas levels recorded at the TG seal were not presented here because readings just showed the boiler gas composition as inert gas was injected through that seal all the time before and after sealing. Oxygen concentration behind the MG seal (Figure 2.24) reduced gradually from 21% to 8% within 10 hours of sealing, in line with gradual increase in inert gas flow rate through that seal. Figure 2.25, which presents the gas levels behind the 3 c/t seal, shows that O_2 level was above 15% even after 36 hours of sealing and continuous inert gas injection through both the MG and TG seals.

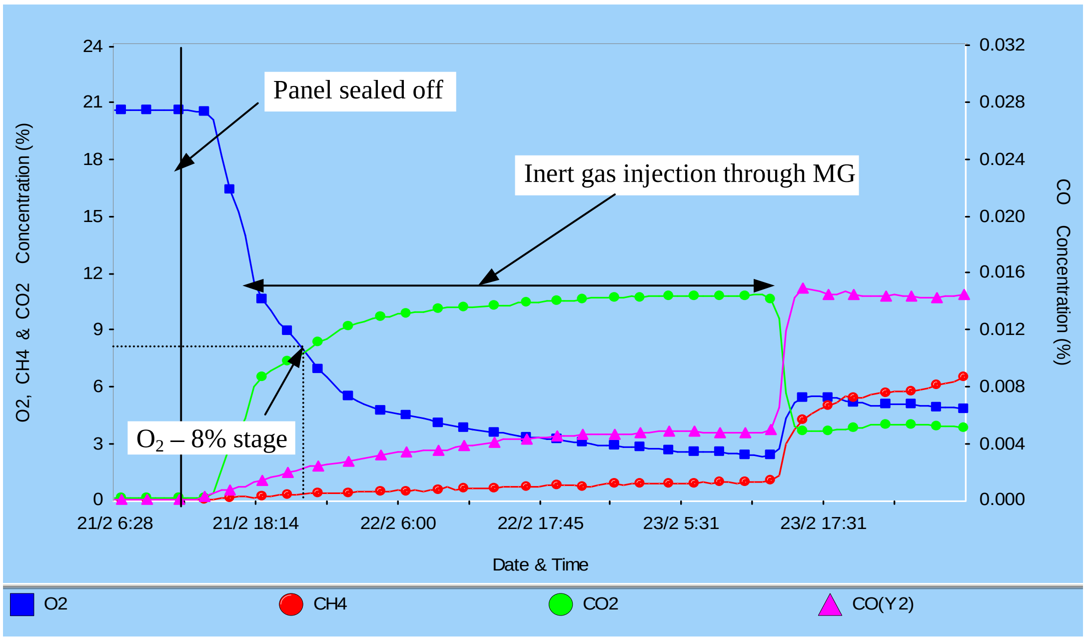

Figure 2.24 Gas concentration profiles at MG seal (Tube 2) – Case 5

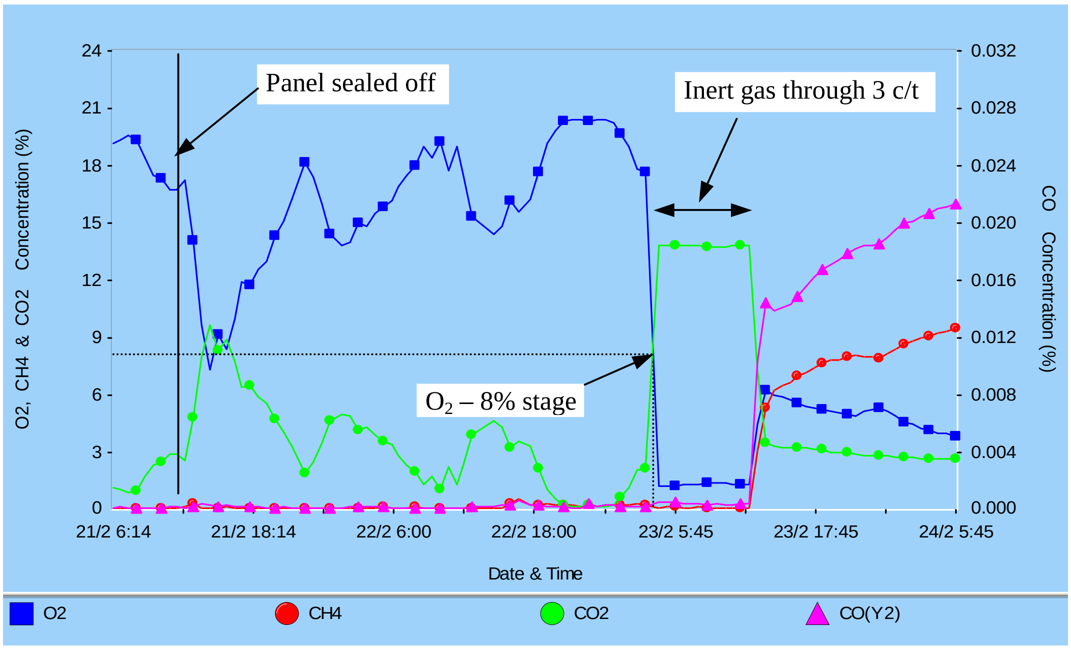

Figure 2.25 Gas concentration profiles at maingate 3 c/t seal (Tube 8) – Case 5

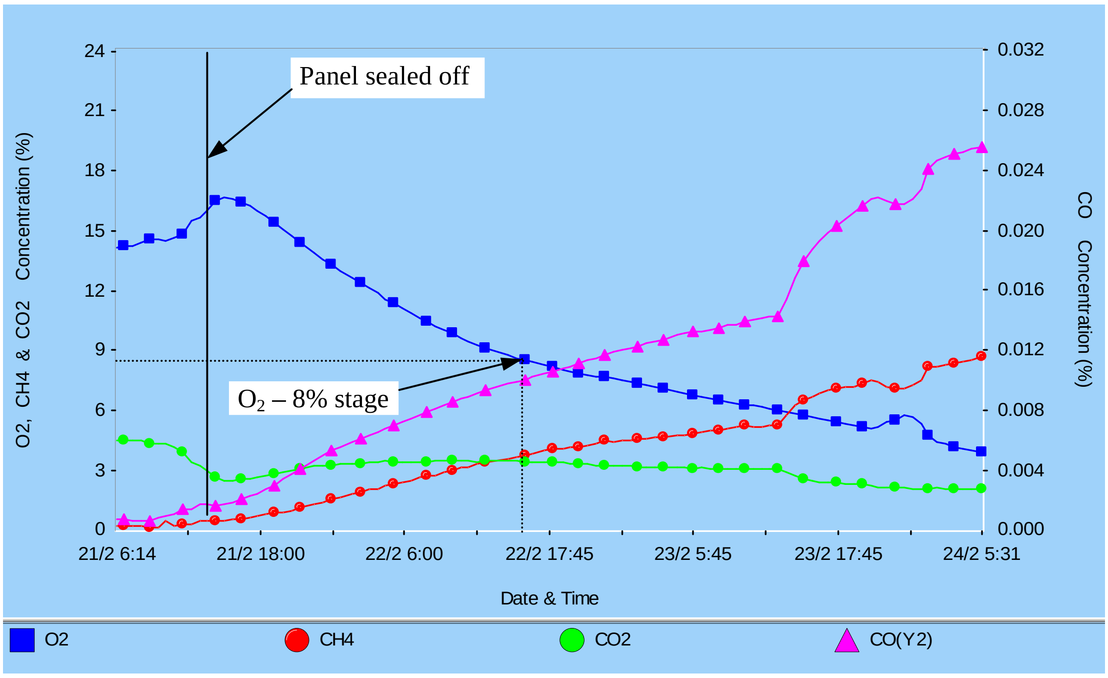

Figure 2.26 Gas concentration profiles at maingate 4 c/t seal (Tube 7) – Case 5

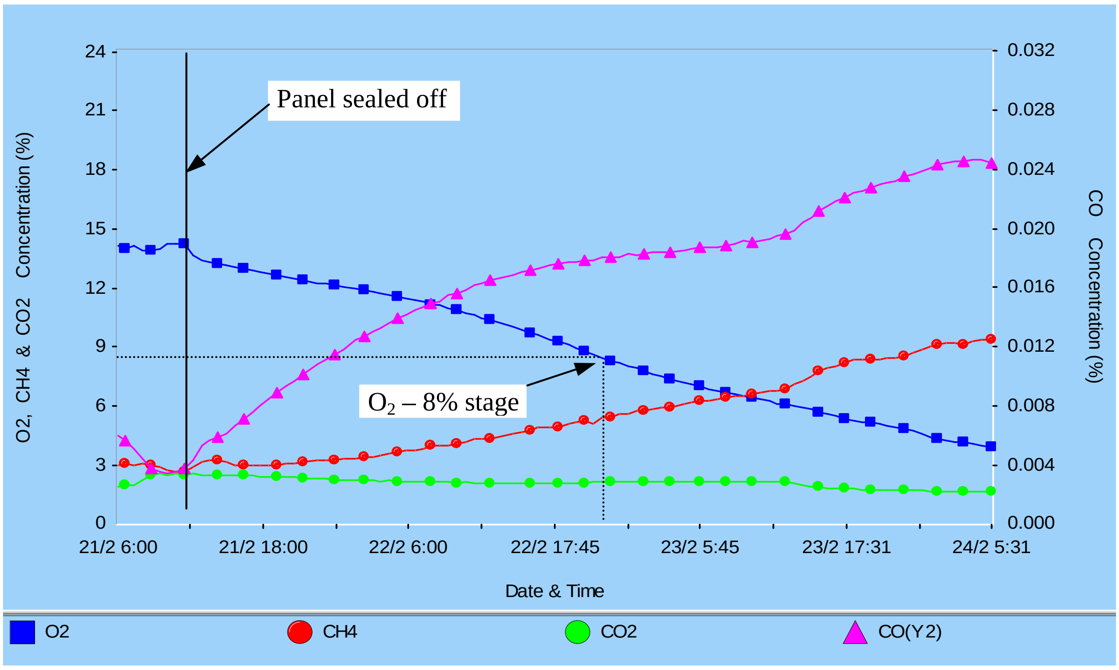

Figure 2.27 Gas concentration profiles at maingate 5 c/t seal (Tube 6) – Case 5

At that point inert gas was injected through the 3 c/t seal also, which had resulted in O_2 zone shifting deeper into the goaf. By that stage all the three important monitoring points in the goaf at TG, MG and 3 c/t seals had lost contact with the actual goaf gas concentration, as inert gas was being injected from all the three seals. Gas levels at the 4 c/t seal are presented in Figure 2.26. Oxygen level at 4 c/t was reduced to the designed safety level of 8%, one day after panel sealing. Even at 5 c/t, which was about 300 m behind the finish line, O_2 level was above the safety level for up to 36 hours after sealing (Figure 2.27).

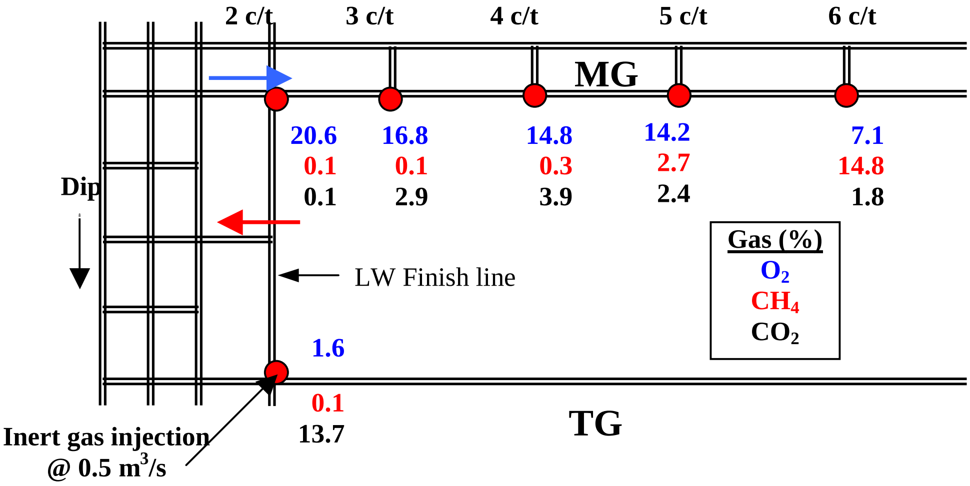

Figure 2.28 Gas distribution in the goaf – Just before panel sealing – Case 5

Gas composition in the longwall goaf at various locations during inertisation is shown in Figures 2.28 to 2.30. Goaf gas distribution just before panel sealing, presented in Figure 2.28, shows that oxygen concentration was above 12% even at 5 c/t, which was 300 m behind the face finish line.

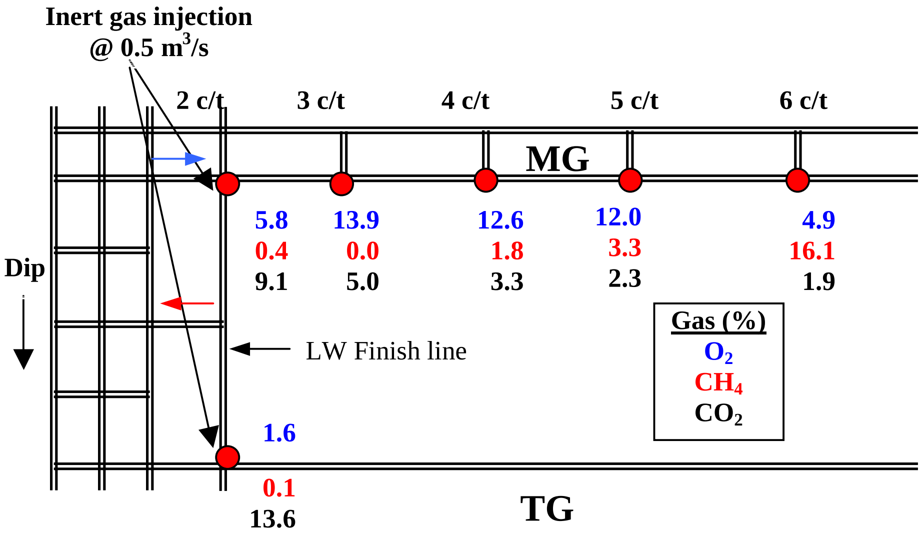

Figure 2.29 Gas distribution in the goaf – 12 hours after panel sealing – Case 5

Figure 2.29 shows that oxygen distribution in the goaf was above 12% over a wide area even after 12 hours of sealing and inertisation. A high methane concentration zone in the goaf was located at more than 400 m from the finish line (i.e. at 6 c/t) due to low goaf gas emissions in the panel. Figure 2.30 shows an increase in oxygen level to 15% at 3 c/t seal, which indicates that high O_2 concentration pockets were still present in the goaf even one day after panel sealing. In summary, results indicate that with this type of inertisation scheme, all the important monitoring tubes near the face finish line were masked by inert gas injection and there was no opportunity to monitor the actual goaf gas concentration levels for ensuring safety of the people in the mine.

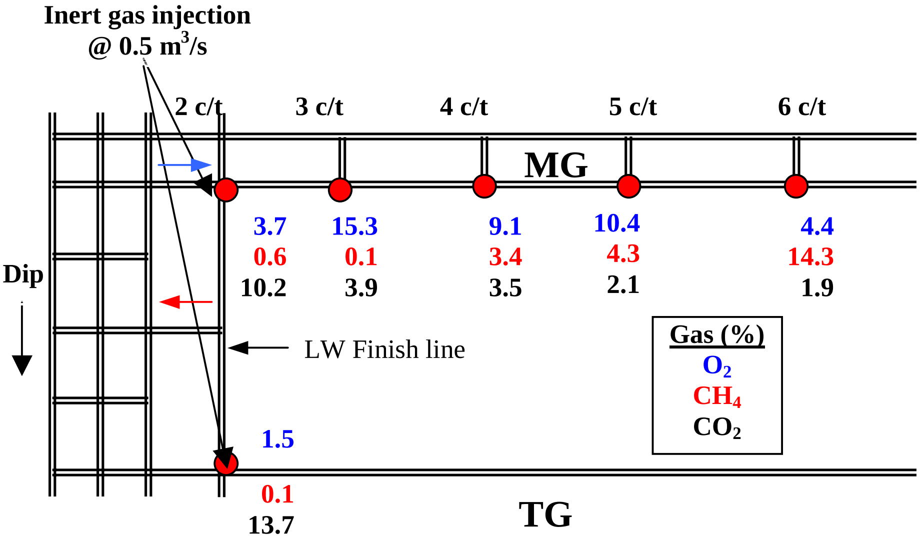

Figure 2.30 Gas distribution in the goaf – 1 day after panel sealing – Case 5

2.3.6 Case 6

The panel layout and monitoring tube locations for case 6 longwall are shown in Figure 2.31. Goaf gas emission in the panel was very low at only 100 l/s of methane. The longwall orientation in this case was also similar to cases 4 & 5 with outbye tailgate corner as the point of lowest elevation in the panel. The panel sealing procedure was also the same as in cases 4 & 5. During sealing of this panel, further changes were implemented in inertisation procedure. Tomlinson boiler inert gas was injected into the goaf through the TG seal immediately after completion of the seal construction at that location. After one day of inertisation through the TG seal, inert gas was also injected through the 4 c/t seal on the maingate side. Inert gas injection through these two seals continued until completion of seals at the MG and chute roads. After panel sealing on 3rd September, most of the inert gas was injected through the maingate 4 c/t seal, with 20-30% of inert gas still flowing through the TG seal. One day after panel sealing and inertisation through the TG and 4 c/t seals, inert gas injection points were changed to maingate 4 c/t and 6 c/t seals and inertisation was continued for another 2 to 3 days. Positive pressures up to 300 Pa were recorded within a few hours of inert gas injection into the goaf.

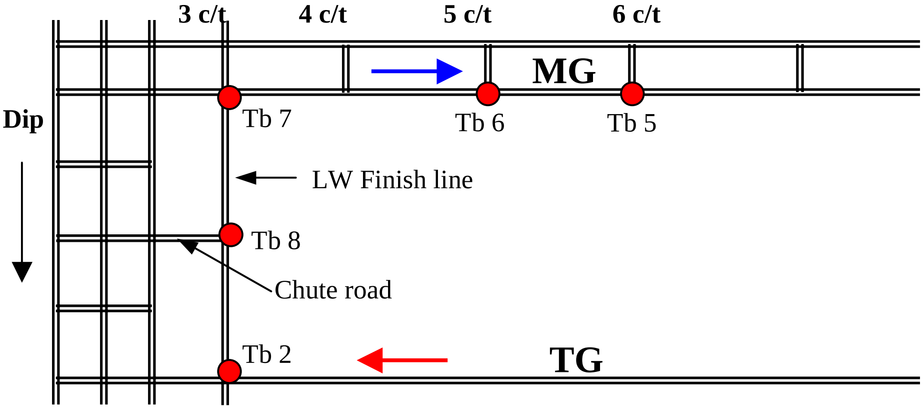

Figure 2.31 Longwall panel layout and gas monitoring locations – Case 6

Gas concentration profiles at various seals around the longwall goaf are shown in Figures 2.32 to 2.35. Gas composition behind the MG seal gradually changed to inert gas composition (as shown in Figure 2.32) as inert gas was injected through the adjacent 4 c/t seal. Figure 2.33 shows that O_2 concentration at the chute road was well above 8% for up to one day after sealing the panel. Figures 2.34 and 2.35 show that during inert gas injection through TG and 4 c/t seals, there was no significant change in oxygen levels at 5 c/t and 6 c/t locations even after one day of inertisation process. Gas readings at 5 c/t and 6 c/t locations show that the oxygen level was almost constant at around 12% and the methane level was building up towards the lower explosive limit. At that stage inert gas was introduced through 6 c/t seal, which ultimately lowered the O_2 levels at 5 c/t and 6 c/t locations.

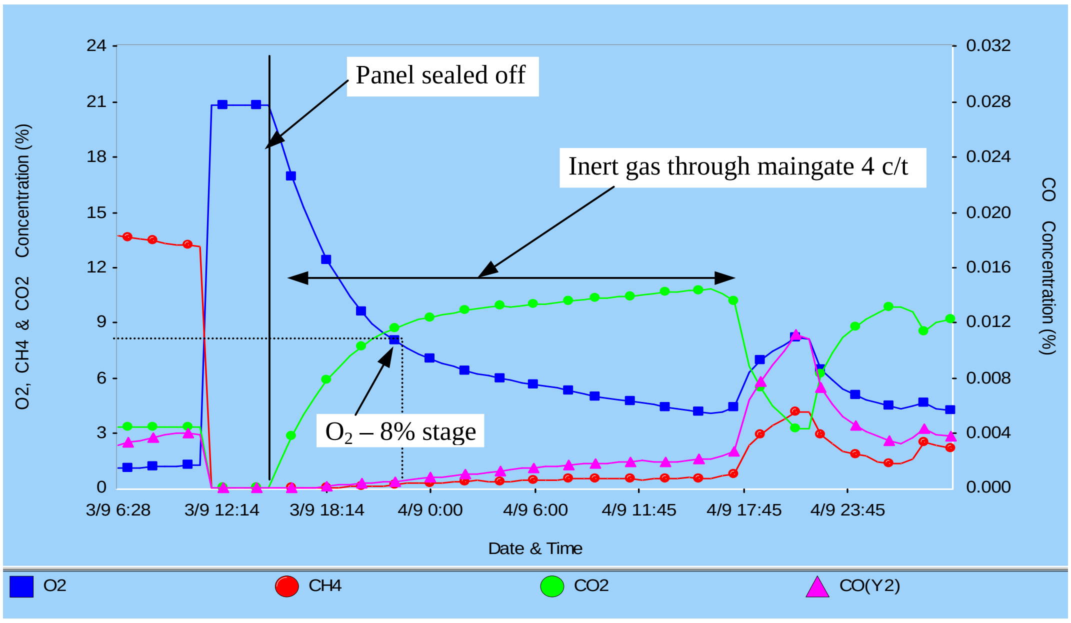

Figure 2.32 Gas concentration profiles at MG seal (Tube 7) – Case 6

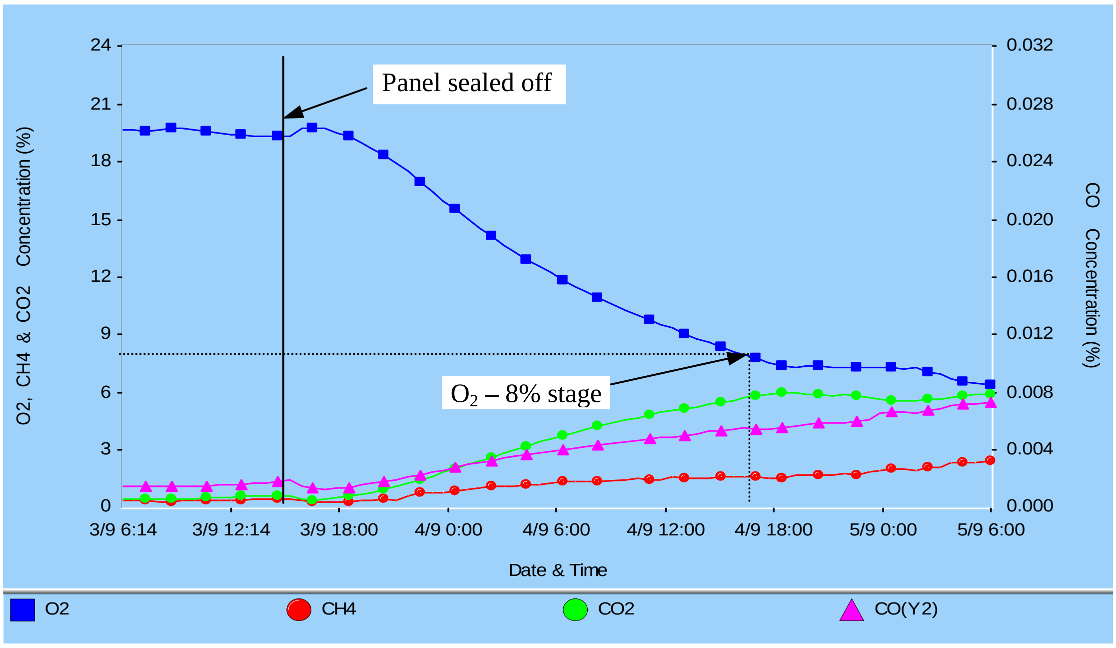

Figure 2.33 Gas concentration profiles at chute road seal (Tube 8) – Case 6

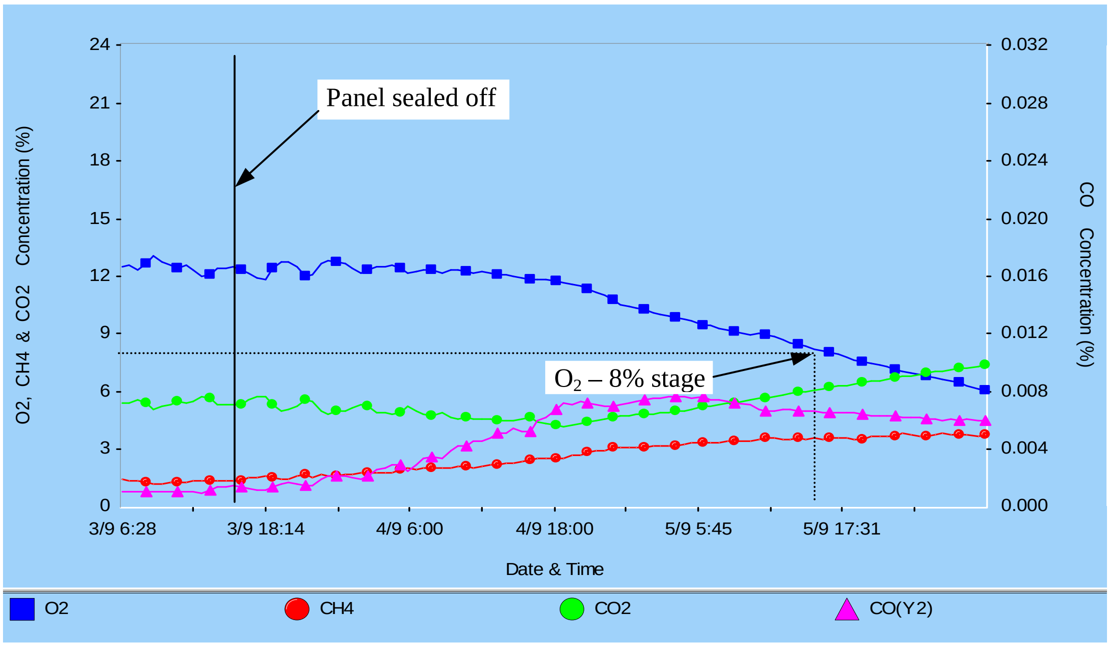

Figure 2.34 Gas concentration profiles at maingate 5 c/t seal (Tube 6) – Case 6

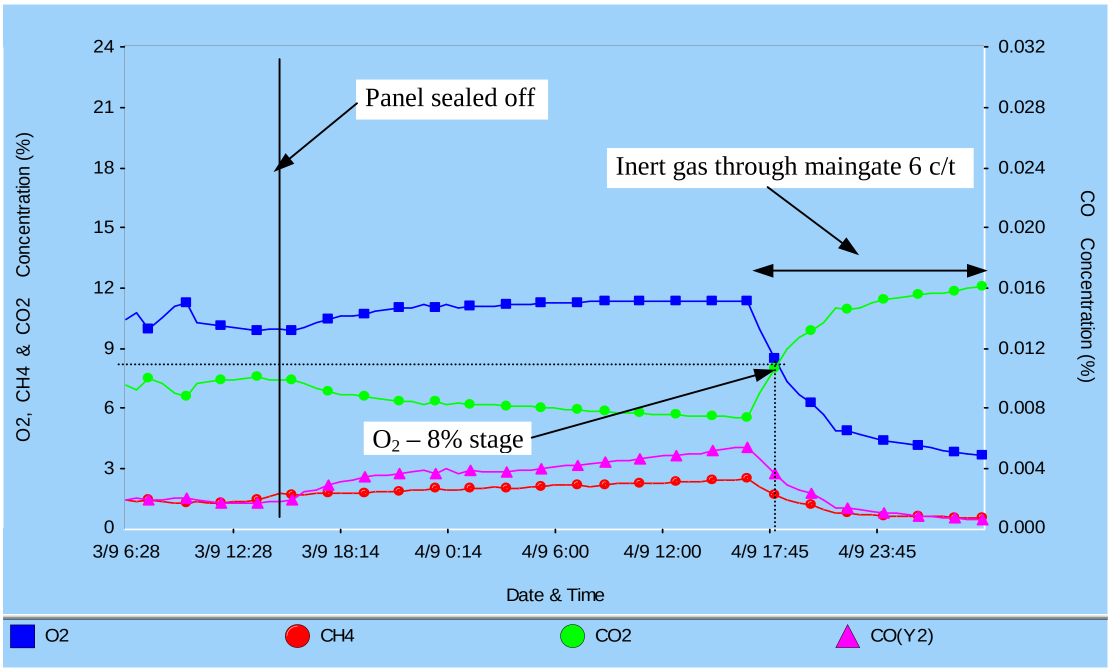

Figure 2.35 Gas concentration profiles at maingate 6 c/t seal (Tube 5) – Case 6

Distribution of various gases in the longwall goaf during the inertisation process is shown in Figures 2.36 to 2.38. Comparison of figures 2.36 and 2.37 show that even 6 hours after sealing, there was only marginal change in gas composition near the chute road and almost no change at 5 c/t and 6 c/t seals. Even one day after sealing there was no change in gas levels at those inbye locations and ultimately inert gas was injected through 6 c/t seal to reduce oxygen levels in that area, as shown in Figure 2.38.

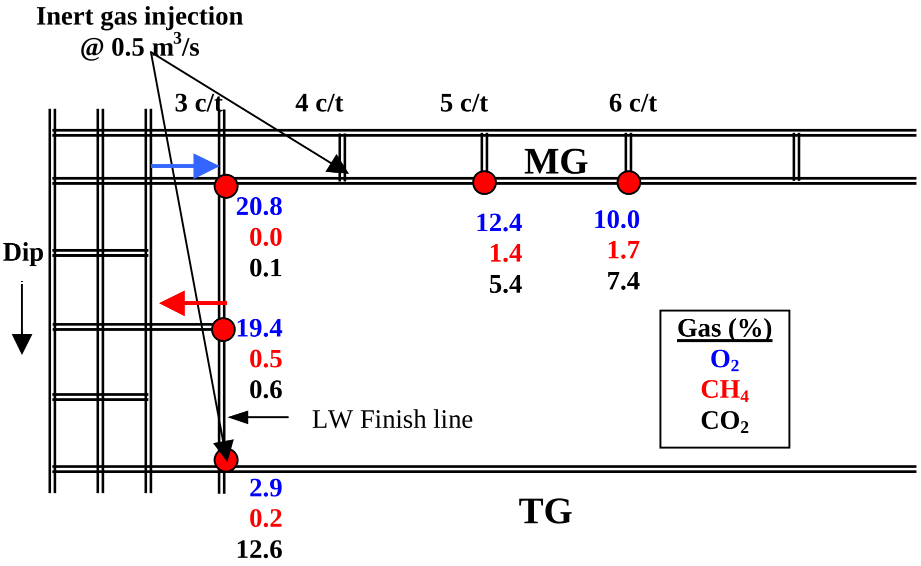

Figure 2.36 Gas distribution in the goaf – Just before panel sealing – Case 6

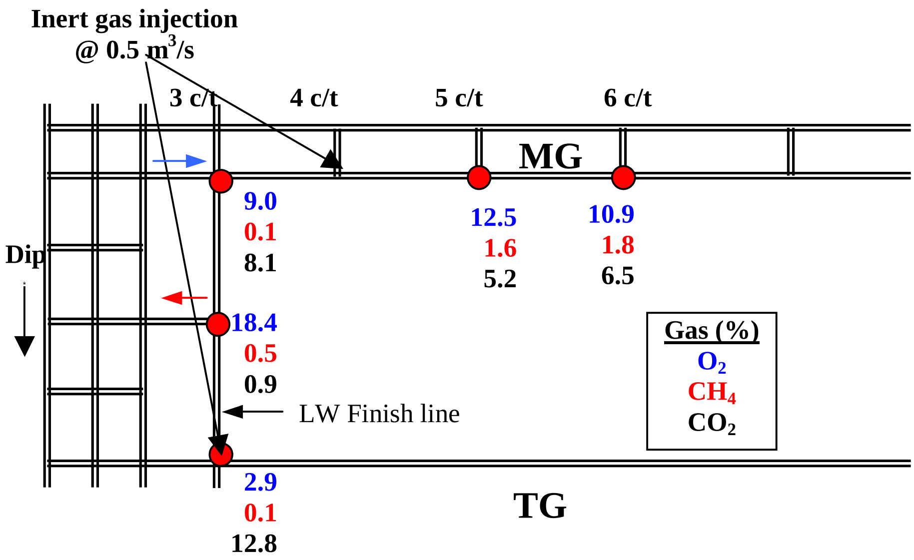

Figure 2.37 Gas distribution in the goaf – 6 hours after panel sealing – Case 6

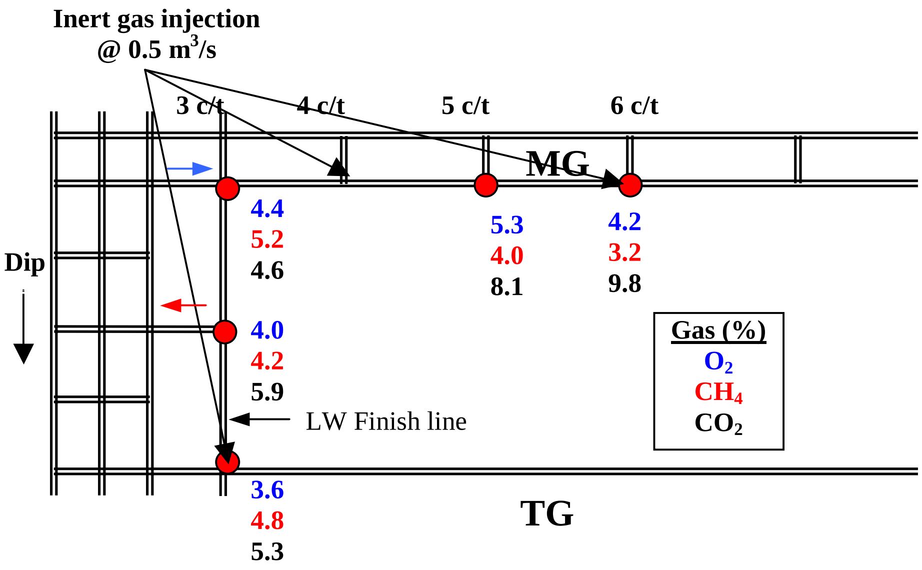

Figure 2.38 Gas distribution in the goaf – 3 days after panel sealing – Case 6

In summary, analysis of the results in this case showed that although explosive gas compositions were not developed in the goaf due to low goaf gas emissions, oxygen levels in the goaf were above 12% even at 300 m behind the face finish line area after one day of panel sealing and inertisation.

2.4 SUMMARY AND CONCLUSIONS

Longwall goaf inertisation is being carried out in some Australian mines on a regular basis to reduce the potential risk of explosions during the panel sealing-off period. Inertisation data has been collected from 6 longwall panels to conduct a detailed review and analysis of the effects of inertisation. Each of the six panels employed different inertisation schemes. The review covered three different mines with different gas emission rates and panel characteristics.

Analysis of data from Mines A and B showed that the initial/trial inertisation schemes implemented were not effective in preventing the formation of explosive gas mixtures near the longwall finish line for up to 2 days after panel sealing. Results from Mine C showed that although the inertisation schemes employed at that mine were relatively more effective when compared with results of other cases, oxygen levels in the goaf were still above 12% for up to two days after panel sealing.

The results from the above studies indicate that just injecting inert gas through MG or TG seals does not achieve the objective of quick inertisation of longwall goafs. Analysis of results indicated that the effect of inert gas injection through MG/TG seals on goaf gas composition at inbye locations was negligible for up to two days after sealing. It was also noted that development of positive pressure in the goaf alone, even at 500 Pa, does not indicate goaf inertisation.

These review studies indicated that there is a need for optimisation of inertisation strategies to achieve the desired objective of goaf inertisation within a few hours of sealing. Development of optimum strategies requires a detailed understanding of inert gas dispersion patterns in the goaf and their effect on goaf gas distribution.

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CHAPTER 3

LABORATORY EXPERIMENTS

3.1 INTRODUCTION

A critical review of the inertisation operations carried out in the field to control heatings shows that in a number of cases, heatings erupted again after stopping the inert gas injection. In many cases inertisation had to be carried out repeatedly for months to control the heatings. In some successful cases, heatings were brought completely under control in less than a week and heatings did not come back after stopping inertisation. The widely varied results of these past inertisation operations indicated that the current knowledge on the effects of inertisation operations on spontaneous combustion (sponcom) heatings in the goaf is limited.

During most of these inertisation operations it was not feasible to monitor the temperature changes in the goaf and only gas concentration levels could be monitored. Even the goaf gas monitoring could be carried out at only the peripheral seals of the longwall goaf. The gas composition near the seals depends on design of inertisation operations with respect to the sampling points and in most cases may just show the inert gas composition. In most cases, the gas concentration values measured at the seals were not representative of the actual gas composition in the goaf or the heating area.

To improve our understanding of the effects of inertisation on goaf heatings, a number of laboratory studies were carried out at SIMTARS spontaneous combustion (sponcom) testing facility. The objective of these preliminary studies was to investigate the effect of different inertisation strategies on temperature changes, gas flow mechanics and gas concentration levels around the heating area. The details of the laboratory facilities, experimental procedure and results are presented in this chapter.

3.2 LABORATORY SET-UP

A large-scale spontaneous combustion testing facility was constructed at SIMTARS laboratories in order to improve the accuracy of extrapolation of laboratory test results to full scale mines. It is believed that large scale testing of coal for spontaneous combustibility, whilst retaining much of the clinical control of laboratory testing, allows better simulation of mining situations. Inertisation experiments were carried out at this SIMTARS's testing facility after completion of their spontaneous combustion (sponcom) tests.

The large-scale sponcom testing reactor (rig) layout is shown in Figure 3.1, which was designed to contain 16 m^3 of coal (Cliff et al. 2000a, b). The inner dimensions of the reactor were 2 m wide, 2.2 m high and 6 m long. Approximately 15 tonnes of either crushed or run-of-mine coal was placed between the two block walls during various sponcom tests. Air circulation through the coal pile was allowed in an attempt to produce a spontaneous heating. One metre long chambers were established on both ends of the coal test section for uniform circulation of air through the coal. Both ends of the reactor were sealed with steel panels allowing ingress of air only through the inlet chamber and egress of air via the outlet chamber. Two blowers capable of supplying air at a rate of 200 l/min each were installed to maintain air supply directly to the inlet chamber. Airflow was varied over the range of approximately 50 l/min to 400 l/min during various stages of sponcom tests.

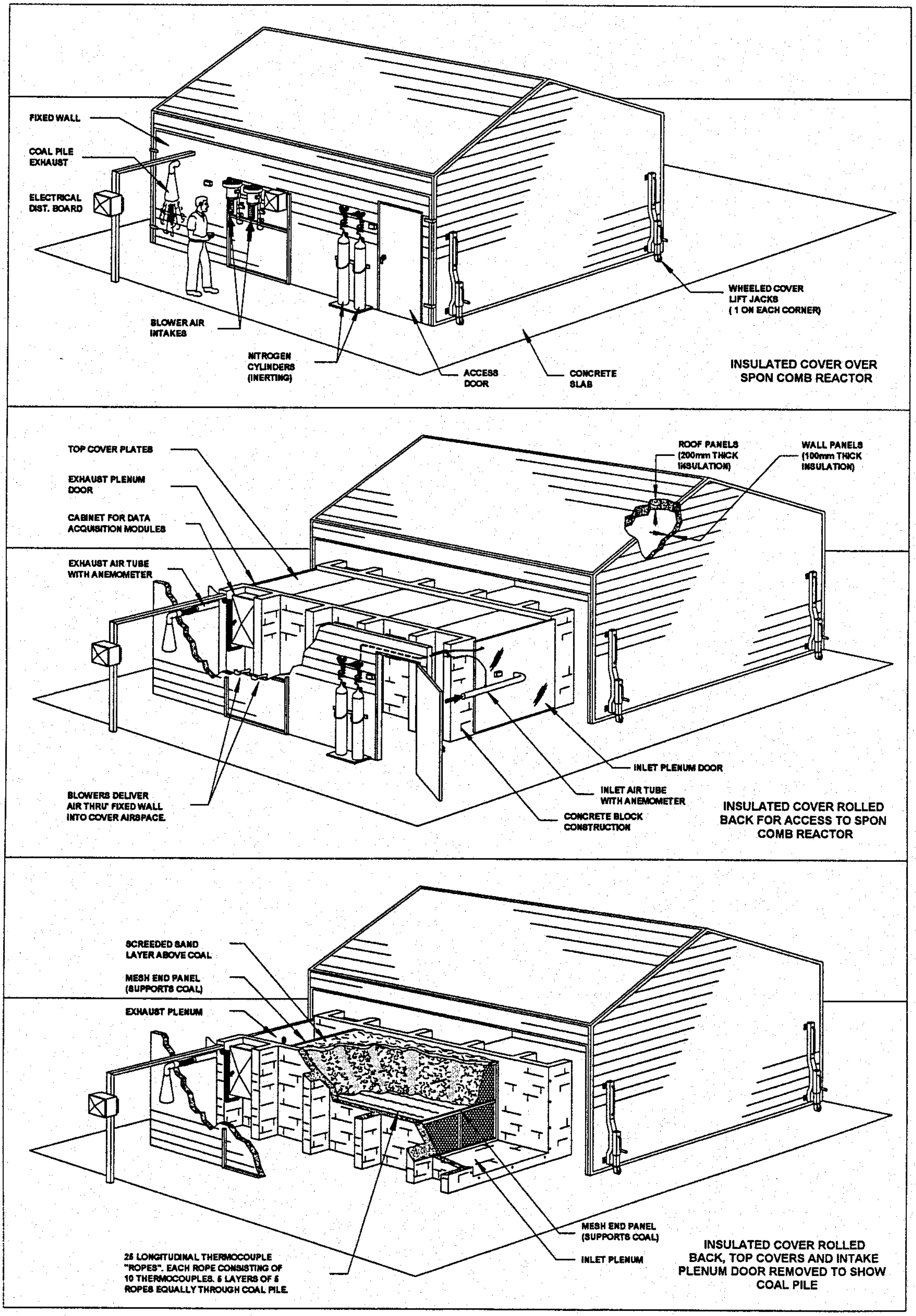


Figure 3.1 Layout of SIMTARS Sponcom and inertisation testing rig (after Cliff et al. 2000a)

A total of 250 thermocouples, in five layers with 50 in each layer, were used to continuously monitor the temperature changes throughout the coal pile. In each layer there were five lines consisting of 10 thermocouples in each line. The first thermocouple and the last thermocouple in any layer were 0.2 m from the respective grids. Similarly the top layer was 0.2 m below the top level of coal in the pile and the bottom layer was 0.2 m above ground level in the test section. Distance between any two thermocouples in the pile was 0.4 m. Fifteen (15) gas sampling tubes were also installed along and across the central axes of the reactor at various elevations. The location of the gas sampling tubes in the coal pile are shown in Figure 3.2.

The top-layer in Figure 3.2 corresponds to the top layer of thermocouples, which was located 0.2 m below the roof level of the coal pile. Similarly, the base-layer was located at 0.2 m above the floor level. Spacing between two layers was about 0.4 m. Out of the fifteen tubes, only 4 to 6 tubes (Tube numbers 1, 2, 4, 5, 7, 8) near the heating area were utilised during the experiments to collect gas samples.

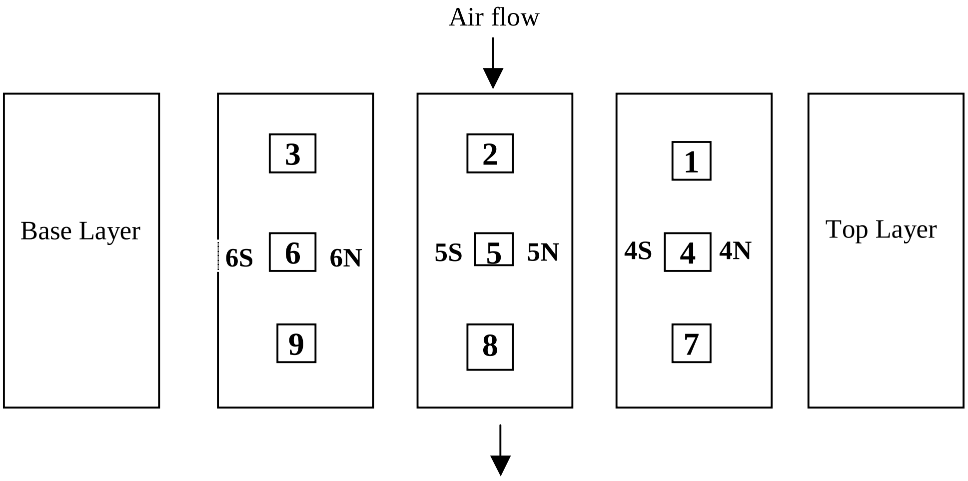


Figure 3.2 Location of gas sampling tubes in the inertisation testing rig

The apparatus included a thermal cover in an effort to reduce the heat losses and facilitate the self-heating of the coal pile and a series of heaters in the area between the reactor and the cover to pre-heat the air to approximately the edge temperatures of the coal. The heated air space reduces heat losses from the coal artificially and thus simulates a larger body of coal. This would allow a better study of the nature of heatings and the gases produced. Additional details of the testing facility are presented in the ACARP Report No: C5031 (Cliff et al. 2000a), with detailed drawings and other information.

3.3 EXPERIMENTAL PROCEDURE AND DETAILS

A number of experiments were carried out in the SIMTARS sponcom reactor to investigate the effect of different inertisation strategies on temperature changes, gas flow mechanics and gas concentration levels around the heating area. Sponcom reactor safety management plan dictates that temperature inside the reactor should not be allowed to rise above 300 ^{o}C to prevent the risk of explosion or open fires or damage to the rig. Therefore, most of the inertisation experiments were carried out between the peak temperatures of 100 ^{o}C and 275 ^{o}C in the testing rig. The specific objective of each experiment and an outline of the procedure involved in various experiments are described in this section.

Experiment 1

Aim:

- To investigate the effect of heating on air inducement

Procedure:

- No forced (fan) airflow into the chamber
- Airflow pipes open - to allow airflow inducement into the chamber
- No inert gas injection

Duration:

- 1 hour to 3 hours - depending on the peak temperature in the rig

Sampling:

- Temperature data – through all the sensors at 15 minutes interval
- Gas data – through 6 tubes near the heating area, after 1 hour

Experiment 2

Aim:

- To investigate the effect of sealing-off on heating rate for first few hours

Procedure:

- No forced (fan) airflow into the chamber,
- Airflow pipes closed to stop any airflow into the chamber
- All the reactor covers in-place
- No inertisation

Duration:

- 1 hours to 4 hours – depending on the peak temperature in the testing rig

Sampling:

- Temperature data – through all the sensors at 15 minutes interval
- Gas data – through 6 tubes near the heating area, after 1 hour

Experiment 3

Aim:

- To investigate the effect of rapid inertisation on heating

Procedure:

- No forced (fan) airflow into the chamber and airflow pipes closed
- Inertisation at rapid rate – N_2 gas at the flow rate of @ 50 l/min

Duration:

- 6 hours

Sampling:

- Temperature data – through all the sensors at 15 minutes interval
- Gas data – through 4 tubes, once every 2 hours

Experiment 4

Aim:

- To investigate the effect of fresh air introduction after rapid inertisation

Procedure:

- Fresh airflow into the chamber using fans at 200 l/min to 400 l/min (equivalent to the airflow before start of experiments)
- Surrounding temperature maintained at more than 50 degrees C (similar to the conditions before start of experiments)

Duration:

- 1 to 4 days – depending on the rate of temperature changes in the rig

Sampling:

- Temperature data – through all the sensors at 15 minutes interval
- Gas data – through 4 tubes, once every 24 hours

Experiment 5

Aim:

- To investigate the effect of rapid inertisation on heating – second time

Procedure:

- No forced (fan) airflow into the chamber and airflow pipes closed
- Inertisation at rapid rate – N_2 gas at the flow rate of @ 50 l/min

Duration:

- 6 hours

Sampling:

- Temperature data – through all the sensors at 15 minutes interval
- Gas data – through 4 tubes, once every 2 hours

Experiment 6

Aim:

- To investigate the effect of small air leakage after inertisation

Procedure:

- Oxygen flow into the chamber (at 7% O_2) – flow rate @ 5 l/min - to simulate small air leakages into the goafs.
- Surrounding temperature maintained at 50 degrees C.

Duration:

- 2 to 4 days – depending on the rate of temperature changes in the rig

Sampling:

- Temperature data – through all the sensors at 15 minutes interval
- Gas data – through 4 tubes, once every 24 hours

Experiment 7

Aim:

- To investigate the effect of fresh air introduction after few days

Procedure:

- Fresh airflow into the chamber using fans at 200 l/min to 400 l/min.

- Surrounding temperature maintained at 50 degrees C.

Duration:

- 1 day – depending on the rate of temperature changes in the rig

Sampling:

- Temperature data – through all the sensors at 15 minutes interval
- Gas data – through 4 tubes, once every 24 hours

Experiment 8

Aim:

- To investigate the effect of slow inertisation on heating

Procedure:

- No forced (fan) airflow into the chamber and airflow pipes closed
- Inertisation at slow rate – – N_2 gas at the flow rate of @ 5 l/min.

Duration:

- 7 to10 days

Sampling:

- Temperature data – through all the sensors at 15 minutes interval
- Gas data – through 4 tubes, once every 24 hours

Experiment 9

Aim:

- To investigate the effect of fresh air introduction after slow inertisation

Procedure:

- Fresh airflow into the chamber using fans at 200 l/min to 400 l/min.
- Surrounding temperature maintained at 50 degrees C.

Duration:

- 1 day – depending on the rate of temperature changes in the rig

Sampling:

- Temperature data – through all the sensors at 15 minutes interval
- Gas data – through 4 tubes, once every 24 hours

Experiment 10

Aim:

- To investigate the effect of just sealing-off on heating rate

Procedure:

- No forced (fan) airflow into the chamber and airflow pipes closed
- No inertisation

Duration:

- 1 to 2 months – depending on the temperature changes inside the rig.

Sampling:

- Temperature data – through all the sensors at 1 day intervals

As the sponcom reactor safety plan dictates that temperature inside the rig should not exceed 300 ^{o}C, the duration of the experiments was changed slightly during the studies depending on the rate of temperatures changes in the rig. The exact timing and duration of the experiments are presented in Table 3.1.

Table 3.1 Summary of laboratory experimental details

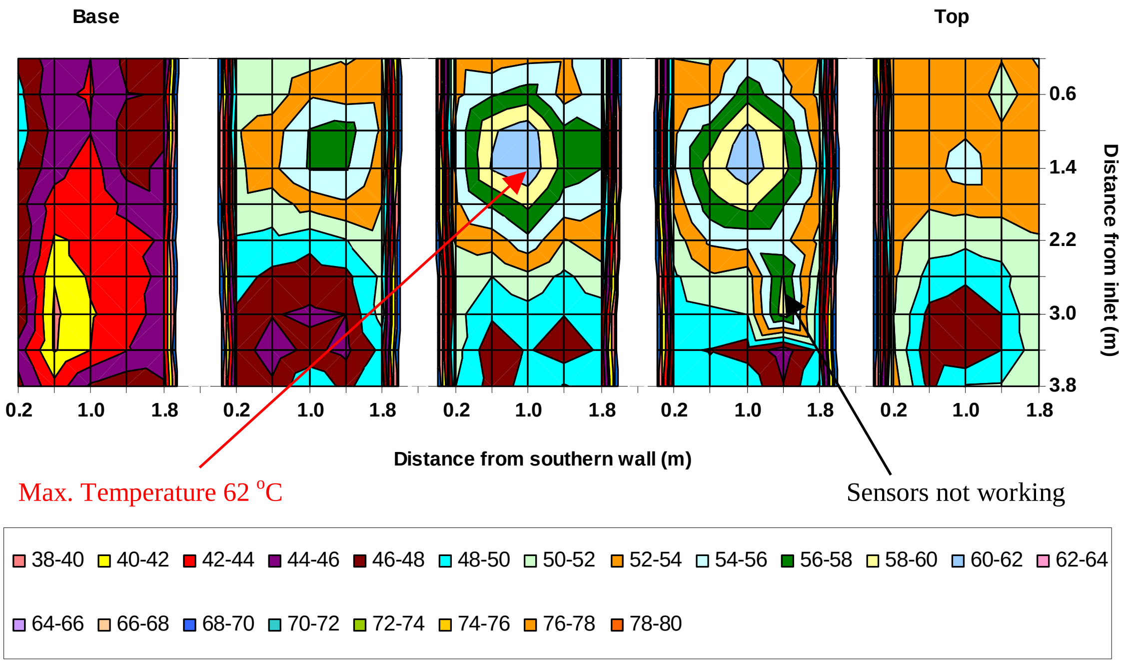
Exp. No.	**Description**	**Start time**	**Finish time**	**Duration**
1	Air inducement due to heating	20-03-01, 11:00	20-03-01, 12:25	1.5 hours
2	Sealing effect – first few hours	20-03-01, 12:30	20-03-01, 14:30	2 hours
3	Rapid inertisation	20-03-01, 14:35	20-03-01, 21:00	6 hours
4	Fresh air introduction	20-03-01, 21:15	22-03-01, 10:45	1.5 days
5	Rapid inertisation – 2nd time	22-03-01, 11:00	22-03-01, 17:15	6 hours
6	Oxygen leakage	22-03-01, 17:30	24-03-01, 08:15	1.5 days
7	Fresh air introduction	24-03-01, 08:30	24-03-01, 21:00	half day
8	Slow inertisation	24-03-01, 21:15	02-04-01, 09:15	8.5 days
9	Fresh air introduction	02-04-01, 09:30	03-04-01, 09:15	1 day
10	Sealing off	03-04-01	15-05-01	6 weeks

All the above experiments were carried out after completion of the SIMTARS spontaneous combustion tests. The reactor was filled with run-of-mine coal from an underground coal mine and sponcom tests were carried out for one year. During the sponcom experiments airflow through the coal was gradually increased from 100 l/min to 400 l/min to supply enough oxygen during the heating phase. The temperature around the coal pile was maintained at above 50 ^{o}C to prevent heat loss from coal to the surroundings via radiation, particularly during cold winter periods. However, the coal pile in the reactor failed to self heat even after one year and it was decided to call-off the spontaneous combustion tests.

At that stage, heating in the pile was stimulated by switching on the embedded heating element at the centre of the pile. The thermostat setting of the heater element was set to 400 ^{o}C on 12-03-01. The aim of the use of the heater was to use it as little as possible to only catalyse a self heating without modifying the actual test conditions too unrealistically, so that a self heating could then become established. The heater was switched off on 19-03-01 after the coal pile in the reactor reached the self heating phase. The heater element was switched off permanently at that stage and was not used again during inertisation tests. Inertisation tests started on 20-03-01 and involved a number of inert gas injection and fresh air introduction phases. Results from the above experiments with a detailed analysis are presented in the following section.

3.4 RESULTS AND ANALYSIS

The extent of heating within the coal pile and temperature contours at the end of the initial self heating phase are shown in Figure 3.3. In this figure temperature contours are presented in five layers starting from base layer to the top layer. As mentioned earlier each layer was spaced at 0.4 m height. Peak temperature in the coal pile was near the intake side of the rig and at a height of 0.5 to 1.0 m below the roof level. Analysis of the sponcom test results showed that a hot spot started on the return side and migrated towards intake side of the pile. The maximum temperature in the rig was about 62 ^{o}C and was stagnant at that temperature for almost two months. The coal pile temperature began to fall at that stage and a decision was taken by SIMTARS to stop their sponcom tests and to stimulate heating in the rig in order to carry out the designed inertisation experiments. Self-heating was stimulated in the rig by switching on the embedded heating element at the centre of the pile.

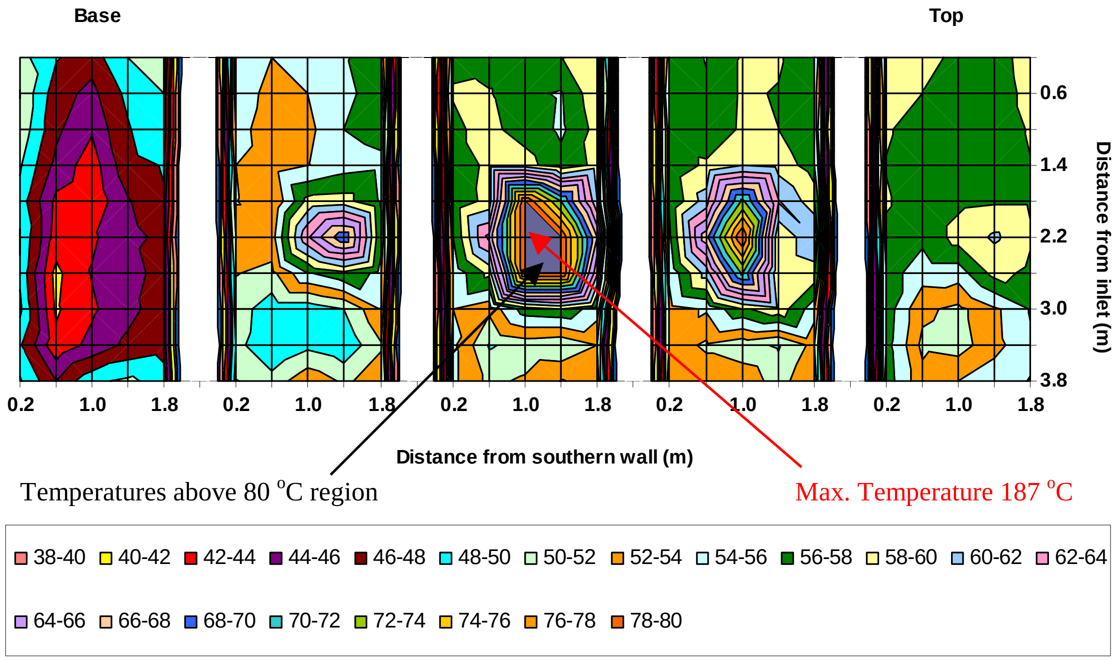


Max. Temperature 62 ^{o}C

Sensors not working

Figure 3.3 Temperature contours in the rig – at the end of initial self heating phase

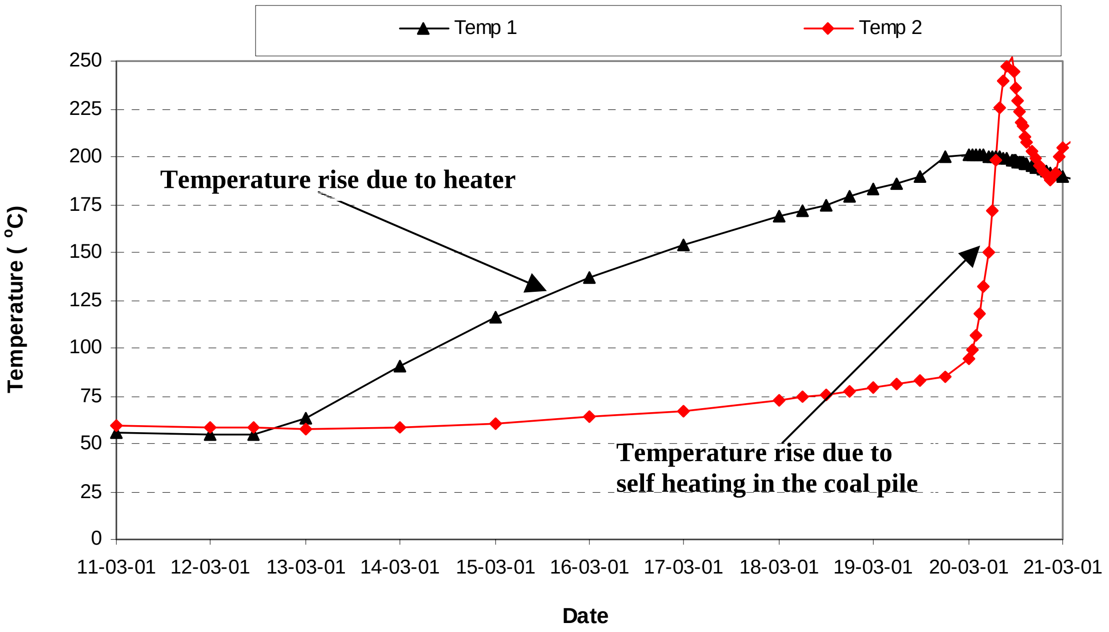
The temperature contours and extent of heating area in the rig one week after starting the heater are shown in Figure 3.4. Figure shows that hot spot reached a peak temperature of 187 ^{o}C around the heater. Analysis of the results showed that temperature rise in the coal pile was just around the heating element up to that stage. On day 7, it was observed that the coal temperature started to rise in the adjacent locations also. The heater was switched off immediately to allow the self heating of the coal pile. Temperature rise in the adjacent location due to self heating is shown in Figure 3.5, along with the temperature rise profile due to the heater.



Temperatures above 80 °C region

Max. Temperature 187 °C

Figure 3.4 Temperature contours in the rig – one week after starting heater

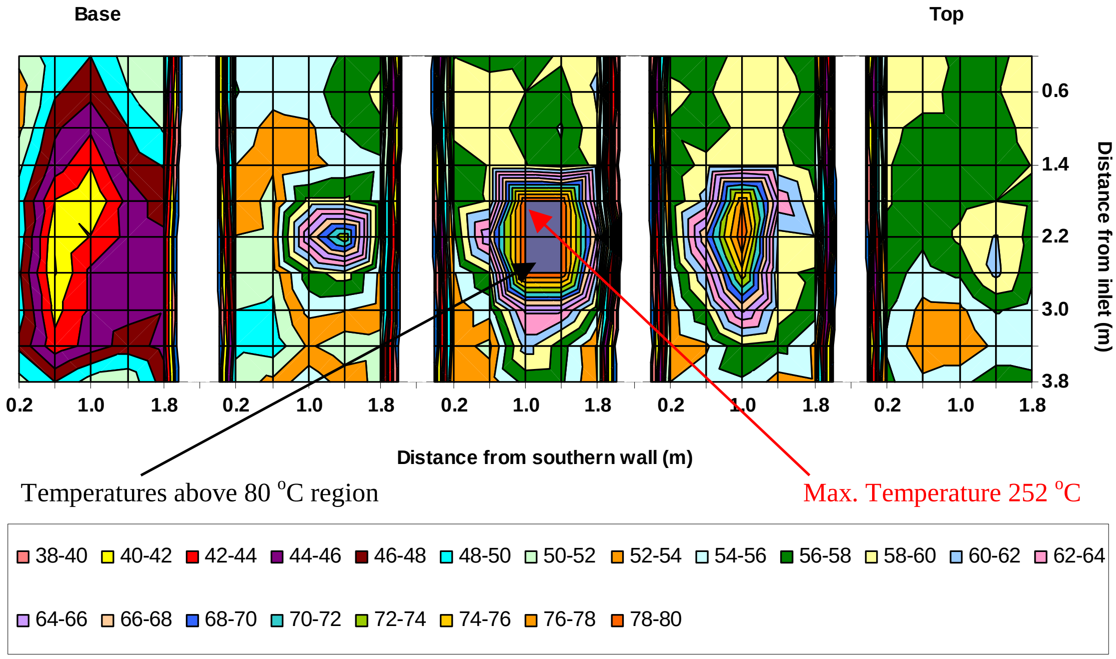


Temperature rise due to heater

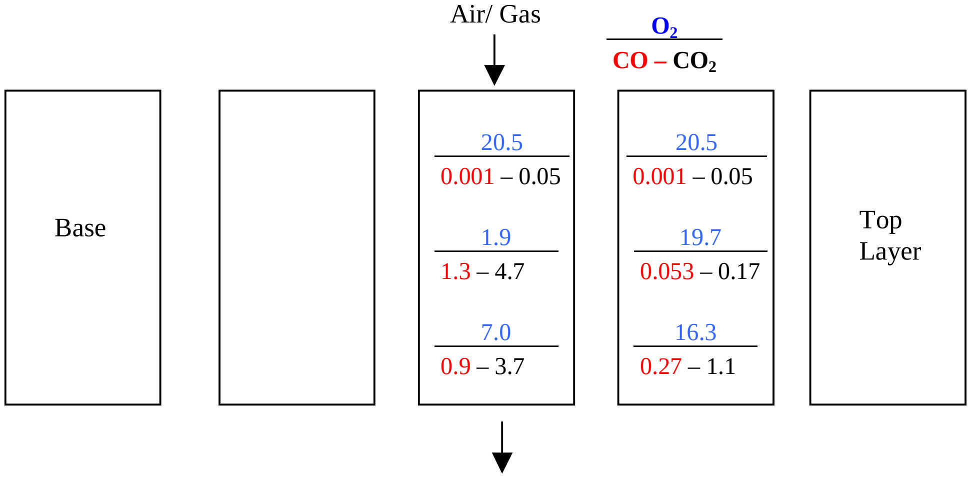
Temperature rise due to self heating in the coal pile

Figure 3.5 Peak temperature profiles in the rig – during heating element usage and self-heating phases

During this self-heating phase the temperature in the reactor increased steeply at the rate of more than 10 °C per hour at another location adjacent to the hot spot created by the heater. One day after stopping the heater, the temperature at that location increased from 95 to 252 °C in 11 hours. Temperature contours at various elevations in the coal pile just before the inertisation experiments are shown in Figure 3.6(a). Results show that temperature contour gradients were very steep near the heating area. Inertisation experiments in the rig started after the coal pile temperature reached 250 °C, as all the experiments had to be conducted below the safe temperature limit of 300 °C.



(a) Temperature contours in the rig



(b) Gas concentration levels in the rig

Figure 3.6 Temperature and gas conditions in the rig - just before the start of the inertisation tests

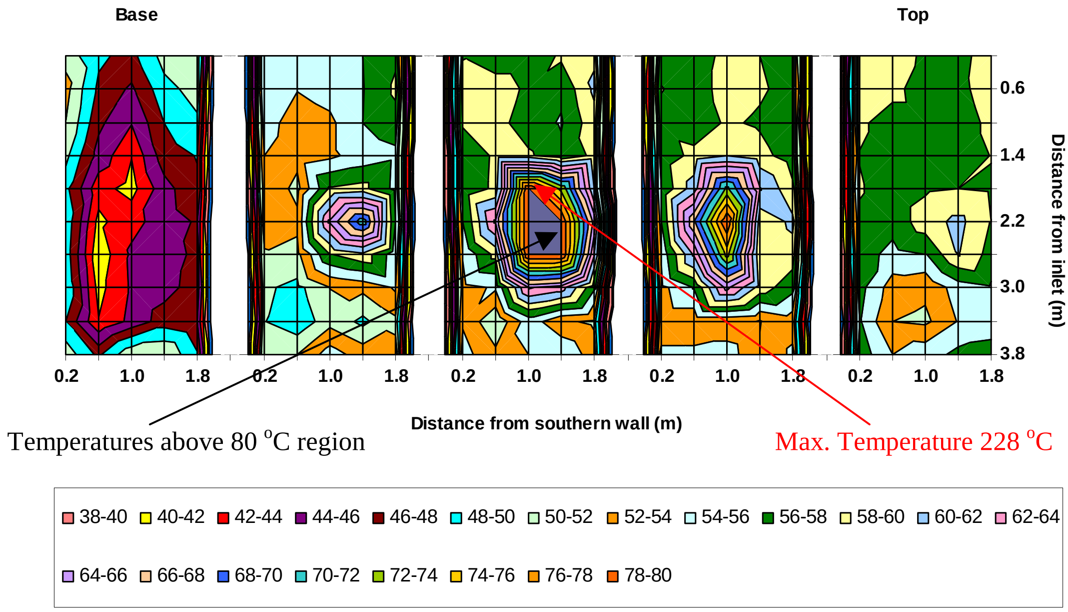
Gas bag samples were also collected from the sampling tubes near the heating area, i.e., from tubes 1, 4, 7 in top second layer and tubes 2, 5, 8 in mid-layer area. Gas bag samples were analysed for all the gases including higher hydrocarbons. Concentration levels of the main gases O_2, CO and CO_2 are shown in Figure 3.6(b) at respective sampling locations. Results show that gas concentration levels change rapidly near the heating area. For example, CO concentration level decreased from 1.3% at heating area to 0.9% within 0.8 m on the downwind side, even at low airflow rate of 0.0067 m^3/s (400 l/min). The detailed gas composition at various sampling tubes is presented in Table 3.2. The peak temperature in the rig was about 250 ^oC at that stage. Results show that the concentration of ethylene and ethane at all locations was less than 0.002%, except near the hot spot. Carbon monoxide levels varied from 0.0005% to 0.9% at various locations. Results and analysis of various inertisation experiments are presented in the following sub-sections.

Table 3.2 Gas composition at various locations in the rig – just before the start of inertisation tests

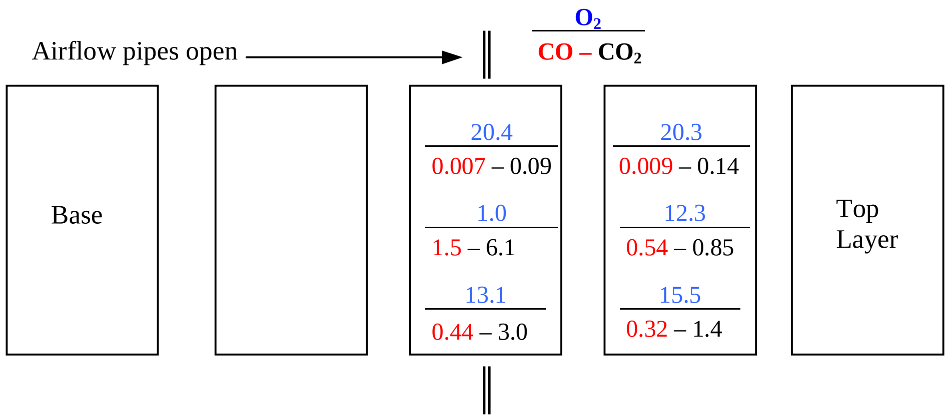
S.No.	**Gas**	**Tube 1**	**Tube 2**	**Tube 4**	**Tube 5**	**Tube 7**	**Tube 8**
		% vol	% vol	% vol	% vol	% vol	% vol
1	Hydrogen	<0.001	<0.001	0.003	0.016	0.006	0.01
2	Oxygen	20.5	20.5	19.7	1.9	16.3	7.0
3	Nitrogen	78.5	78.6	79.1	91.0	81.4	87.4
4	Methane	<0.01	<0.01	<0.01	0.02	<0.01	0.02
5	Carbon monxide	0.001	<0.0005	0.053	1.3	0.27	0.9
6	Carbon dioxide	0.05	0.05	0.17	4.7	1.1	3.7
7	Ethylene	<0.002	<0.002	<0.002	0.005	<0.002	0.003
8	Ethane	<0.002	<0.002	<0.002	0.008	<0.002	0.006
9	TOTAL	99.1	99.2	99.0	98.9	99.1	99.0

Experiment 1

The objective of the first experiment was to investigate whether the heating inside the reactor was able to induce airflow into the hot spot area to sustain the self-heating phase, without the help of fans to force airflow into the reactor. The experiment started after the coal pile in the reactor entered the self-heating mode and temperature exceeded 250 °C. The experiment involved just stopping the fan with no changes to other conditions and no inert gas injection. The experiment was carried out for one and half hours with temperature monitoring at 15 minute intervals and gas sample collection after one hour. Temperature contours in the rig and gas sample results are presented in Figure 3.7.



(a) Temperature contours



(b) Gas concentration levels

Figure 3.7 Temperature contours and gas concentration levels in the rig during Exp. 1.

Results showed that the peak temperature in the rig dropped from 252 to 228 ^{o}C during the test due to lack of fresh oxygen supply to the hot spot. Comparison of figures 3.5 and 3.6 shows that oxygen levels near top 2nd layer also decreased significantly. Absence of positive ventilation pressure from intake to return side might have contributed to the increase in oxygen level on the return side of the hot spot. Results indicate that ventilation pressures developed due to the heating were very small and were not enough to induce any fresh airflow into the rig. The relatively small size of the hot spot, location of heating in the centre of a 15 tonne coal pile and temperatures below 300 ^{o}C could have been the limiting factors for absence of airflow inducement. The experiment was stopped at that stage as the rig peak temperature was decreasing towards 200 ^{o}C. Second experiment was commenced immediately after completion of the first test.

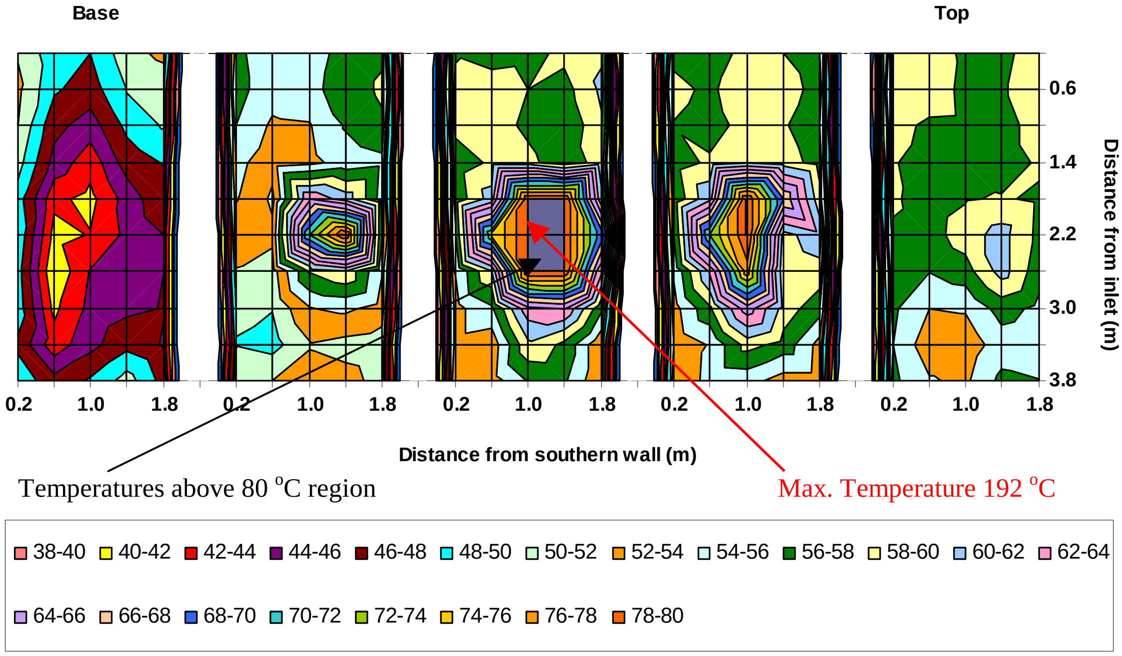
Experiment 2

Experiment 2 was aimed to investigate the effect of sealing on the heating rate and air flow for the first few hours. This experiment involved sealing of the airflow pipes into the rig in addition to stoppage of the fan. Inert gas was not used during the experiment. The experiment was carried out for about two hours with temperature monitoring at 15 minute intervals and gas sample collection towards the end of the experiment. Results showed that there was no major change in extent of the heating area or gas concentration levels, except that peak temperature in the rig reduced further from 228 ^{o}C to 210 ^{o}C.

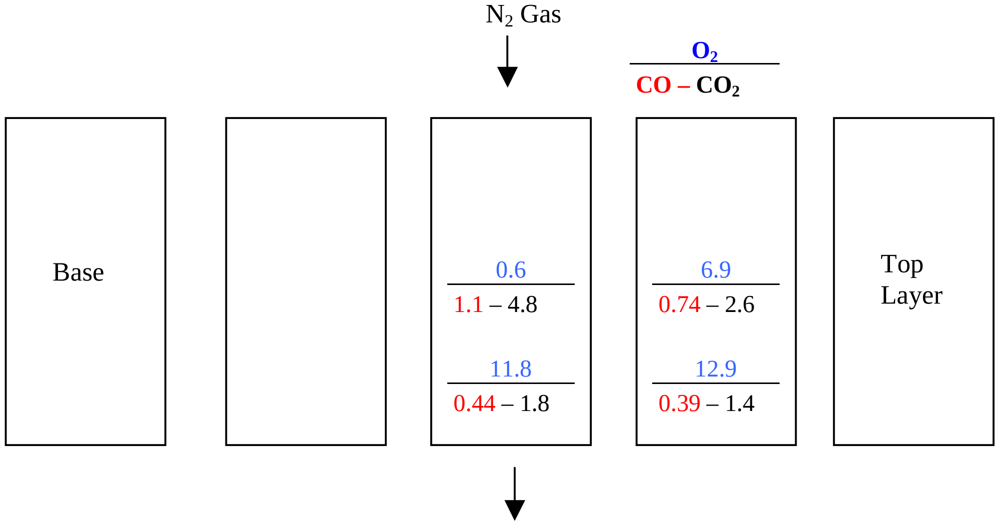
Experiment 3

The objective of the experiment 3 was to study the effect of rapid rate of inertisation for short periods on heating's in a coal pile. Nitrogen gas was introduced into the rig at the rate of 50 l/min to represent a case of high inert gas flow rates. The experiment was carried out for 6 hours immediately after stoppage of the previous test. Temperature in the rig was monitored continuously at 15 minute intervals and gas samples were collected every 2 hours from four sampling tubes located near the heating area. Temperature contours in the rig and gas sample results are presented in Figure 3.8.

Analysis of the results showed that inert gas injection for 6 hours, even at high flow rates, did not have a major impact on temperature distribution inside the rig. The peak temperature in the rig reduced by only 18 ^{o}C, i.e. from 210 ^{o}C to 192 ^{o}C in 6 hours. However, results show that inert gas injection has significantly reduced the oxygen concentration in the rig. There was no major change in other gases composition, including higher hydrocarbons levels. Results also indicated that the heating area migrated to the adjacent locations during this sealing-off and inertisation period. The heat migration could lead to stimulation of spontaneous combustion in the adjacent areas. These results indicate that rapid inertisation at higher flow rates for a few hours may not be an appropriate strategy to control heatings in coal piles or longwall goafs.



(a) Temperature contours in the rig

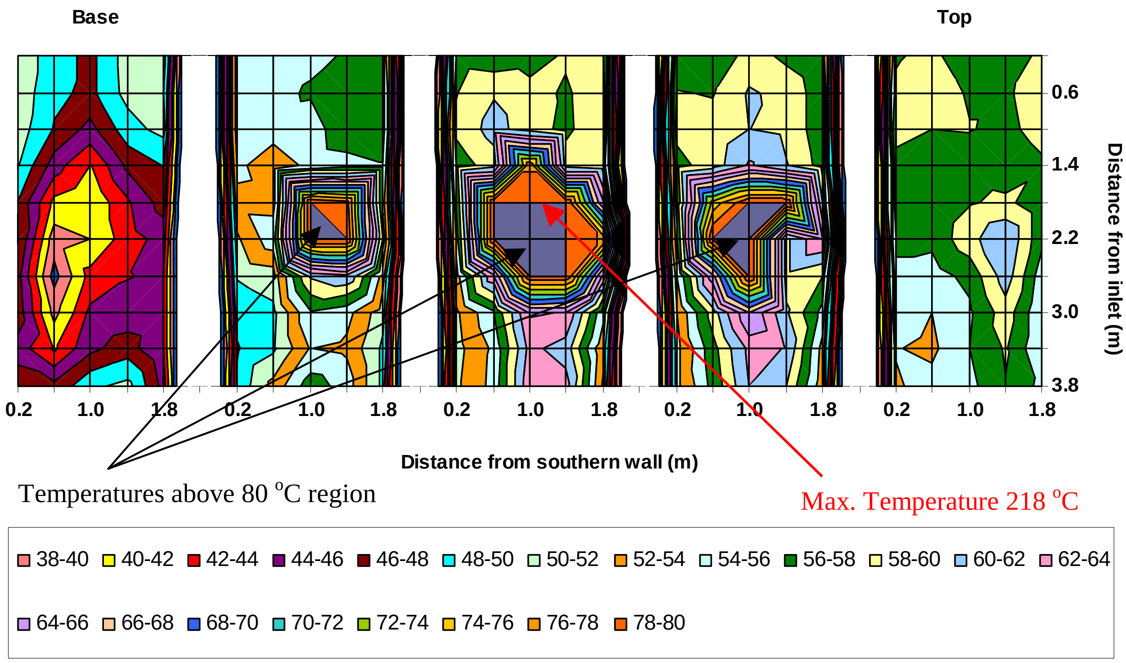


(b) Gas concentration levels

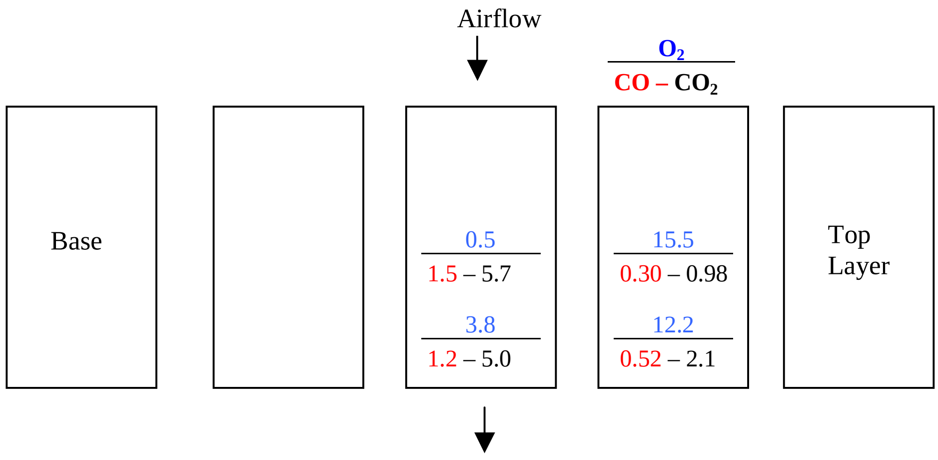
Figure 3.8 Temperature and gas concentration levels in the rig – after first rapid inertisation test (Exp3)

Experiment 4

In this experiment, fresh air was forced back into the rig using fan blowers to investigate its effect on heating. Airflow was introduced at the rate of 400 l/min, which was similar to the airflow conditions before the start of the inertisation experiments. During this test, temperature around the rig was also maintained at 50 °C to simulate the original conditions. Results of the experiment are presented in Figure 3.9.



(a) Temperature contours in the rig



(b) Gas concentration levels

Figure 3.9 Temperature contours and gas concentration levels in the rig – 38 hours after fresh air introduction (Exp 4)

Analysis of the results showed that fresh air introduction after short inertisation resulted in revival of self heating in the coal pile. Results showed self heating started at another location adjacent to the previous hot spot. The temperature at the previous hot spot had increased only slightly from 190 ^{o}C to 220 ^{o}C in 36 hours. However, the temperature at the new self heating point increased rapidly from 100 ^{o}C to 210 ^{o}C. The rate of temperature change at both these locations during the previous inertisation phase and the fresh air introduction phase are shown in Figure 3.10. During experiment 4 the extent of heating extended to a wider area and started consuming more oxygen in terms of l/min. The blower airflow capacity of 400 l/min was found to be insufficient to sustain self heating over such a wide area in the coal pile. At that stage, it was decided to proceed to the next experiment. These results indicate that fresh air should not be allowed to enter into the heating area immediately after inertisation.

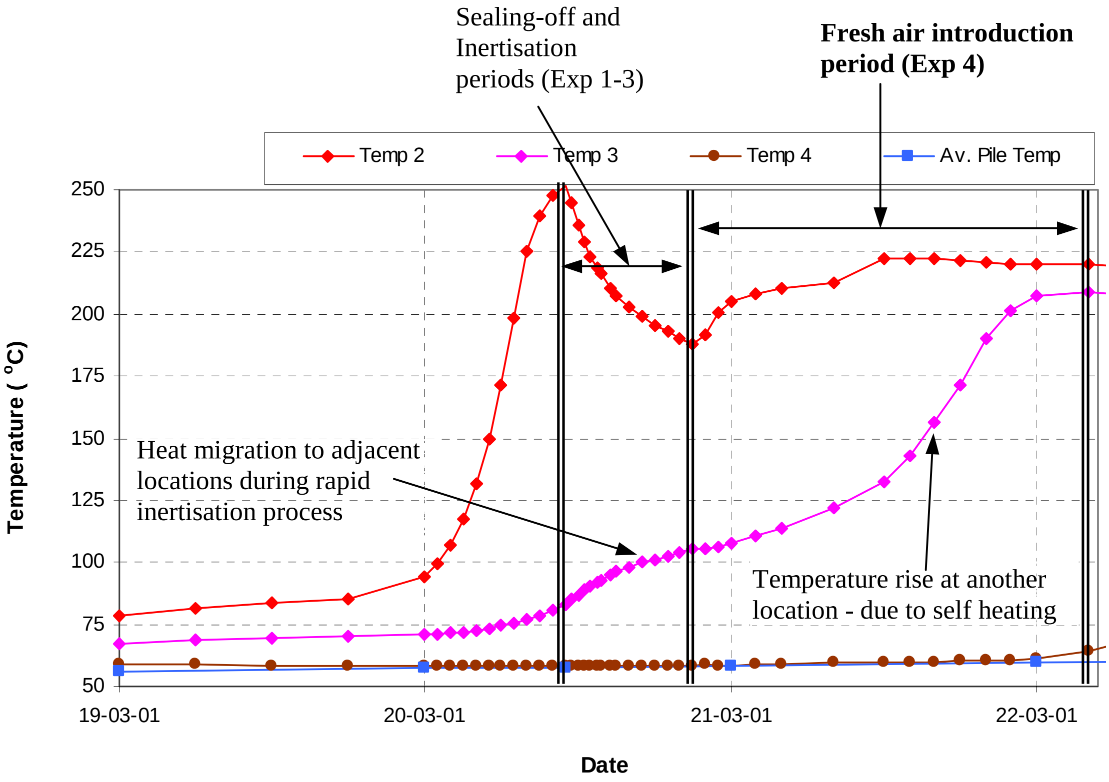


Figure 3.10 Peak temperature profiles in the rig – 38 hours after fresh air introduction (Exp 4)

Experiment 5

In this phase of the investigations, rapid inertisation was carried out again to confirm its effects on heating and to allow the next experiment to proceed under conditions similar to the start of experiment 4. Nitrogen gas was introduced into the rig at the rate of 50 l/min for 6 hours immediately after stoppage of the previous test. Temperature in the rig was monitored continuously at 15 minute intervals and gas samples were collected every 2 hours from four sampling tubes located near the heating area.

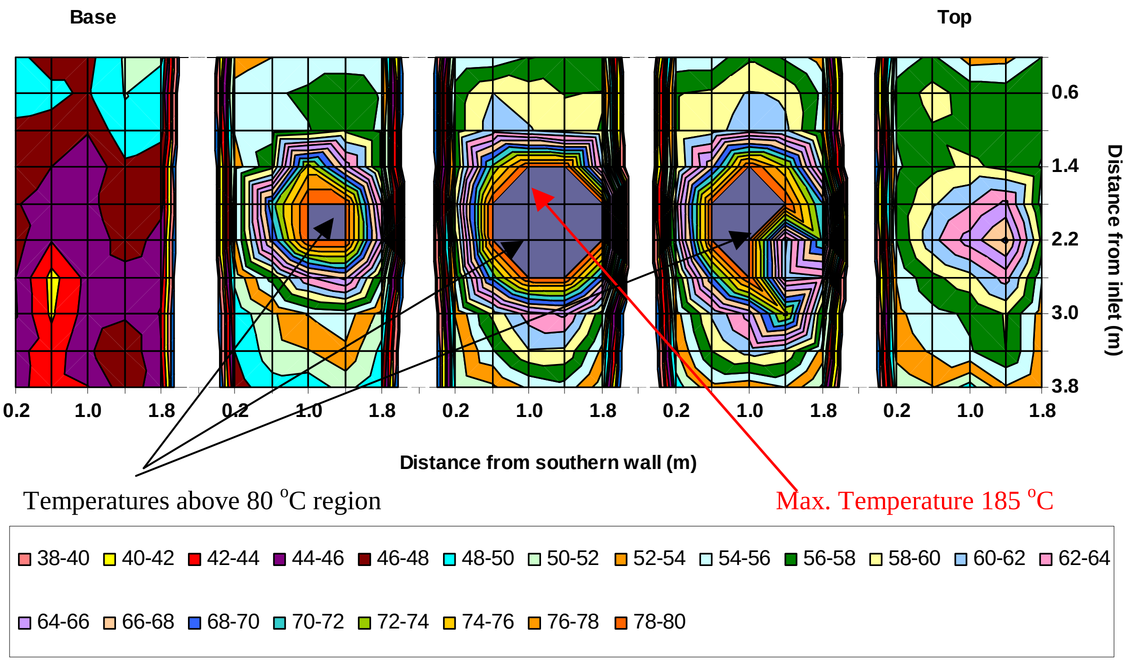
Analysis of the results confirmed that rapid inertisation for short period did not have a major effect on temperature distribution inside the rig. The peak temperature in the rig reduced only 2 ^{o}C, i.e. from 218 ^{o}C to 216 ^{o}C, in 6 hours. However, results show that inert gas injection has significantly reduced the oxygen concentration in the rig. The failure of the rapid inertisation process to significantly reduce peak temperatures could be attributed to the lack of flow paths near the hot spot, which could have been due to small size (<20 mm) coal pieces in the reactor.

Results indicated that the heating area migrated to the adjacent locations even during the second rapid inertisation period. This heat migration may result in development of new self heating zones in the rig and could lead to stimulation of spontaneous combustion. These results also indicate that rapid inertisation at higher flow rates for a few hours may not be an appropriate strategy to control heatings in the longwall goafs, and needs to be investigated further to study its effects under different conditions.

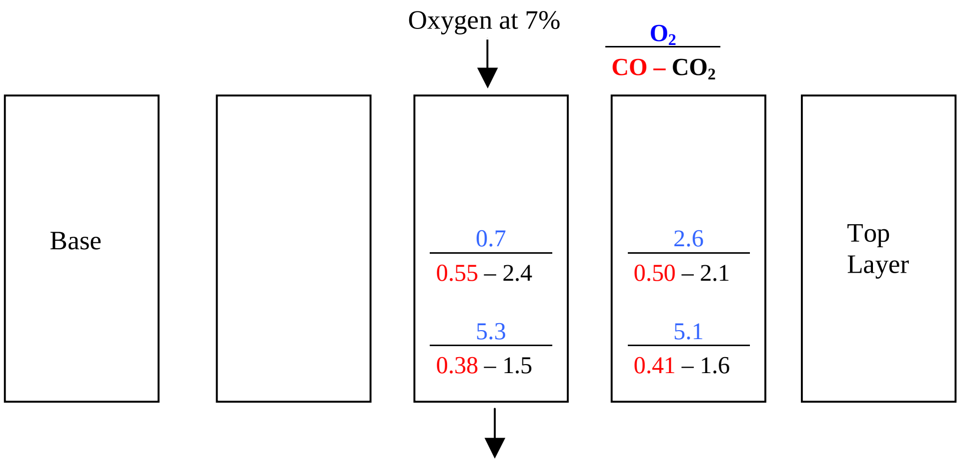
Experiment 6

Experiment 6 involves introduction of 7% oxygen gas composition to study its effects on heating. Oxygen gas was released from cylinders at the slow rate of 5 l/min to simulate small air leakage into the longwall goaf in underground mines. The experiment was carried out for 2 days and temperatures in the rig were monitored continuously. Temperature around the rig was also maintained at more than 50 ^{o}C to simulate the original rig conditions. Temperature contours in the rig two days after introducing oxygen gas are shown in Figure 3.11. Temperature profiles at the previous hot spots and at the newly developed self-heating zone are shown in Figure 3.12.

Results showed that although the peak temperature reduced significantly during the test, there was no significant change in temperature at the newly developed self heating zone. Peak temperature at the previous hot-spot zones reduced from 216 ^{o}C to 185 ^{o}C. However, temperature at the self-heating zone remained constant at above 100 ^{o}C. Gas concentration distribution in the rig showed that oxygen gas level was around 5%. These tests results indicate that heatings in the goaf can survive for long periods even at low oxygen levels of 5%. Therefore, it is very important to prevent air leakages into the sealed area as it can keep the heatings active for long periods.



(a) Temperature contours in the rig



(b) Gas concentration levels

Figure 3.11 Temperature contours and gas concentration levels in the testing rig – 38 hours after allowing O_2 leakage (Exp 6)

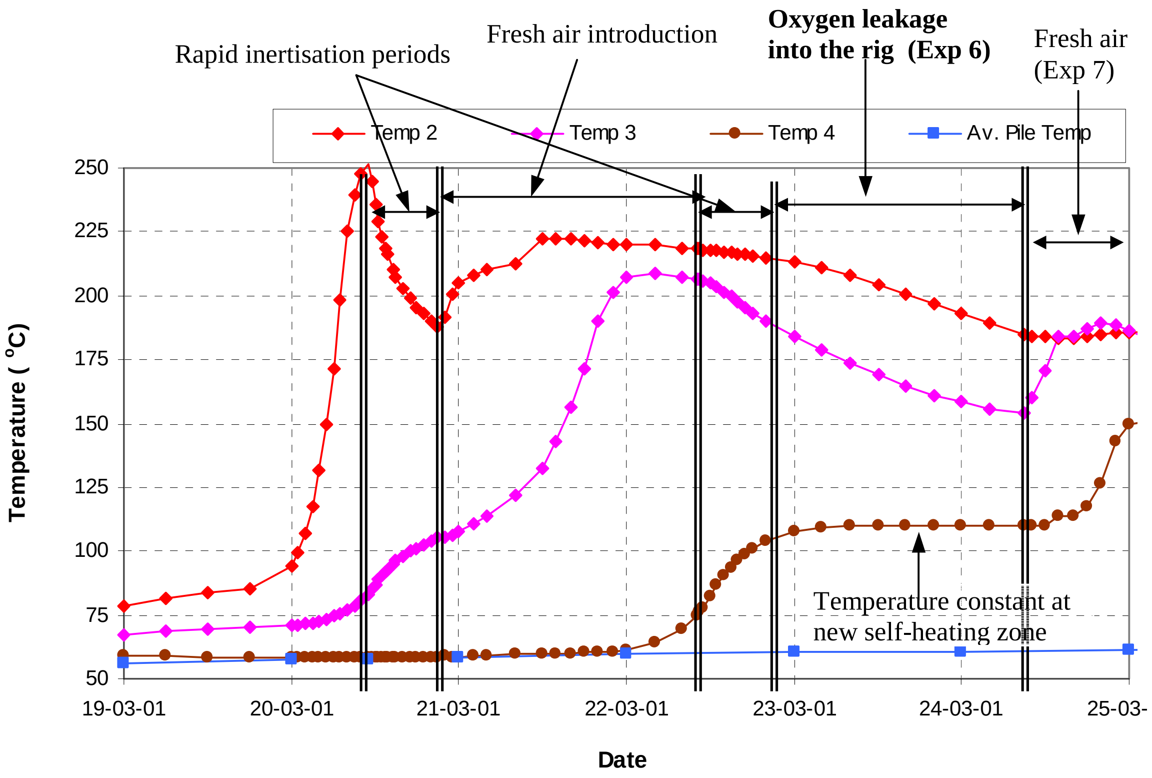


Figure 3.12 Peak temperature profiles – after O_2 leakage and then fresh air (Exp 6 & 7)

Experiment 7

Fresh air was forced back into the rig to study its effect on heatings after rapid inertisation and two days of air leakage into the rig. Airflow was introduced at the rate of 400 l/min, to simulate airflow conditions before the start of the experiments. Results showed that temperature at the self-heating zone started to increase steeply again at the rate of 5 ^{o}C per hour, as shown in Figure 3.12. The experiment was stopped at that stage to proceed to the next test. Results showed that heatings could flare up again if fresh air is introduced shortly after rapid inertisation or even after a few days of air leakage into the heating area. Results indicated that any fresh air introduction even after long periods of air leakage could result in revival of heatings in the goaf.

Experiments 8 and 9

The objective of the experiment 8 was to study the effect of injecting inert gas at an optimum rate (slow rate) for one or two weeks on heating's in the coal pile. Nitrogen gas was introduced at the rate of 5 l/min to represent a case of low rate inert gas injection. This experiment was carried out for 9 days with continuous monitoring of temperature distribution in the rig. Temperature contours in the rig are shown in Figure 3.13. The rate of temperature changes at various hot spots and self heating zones is shown in Figure 3.14.

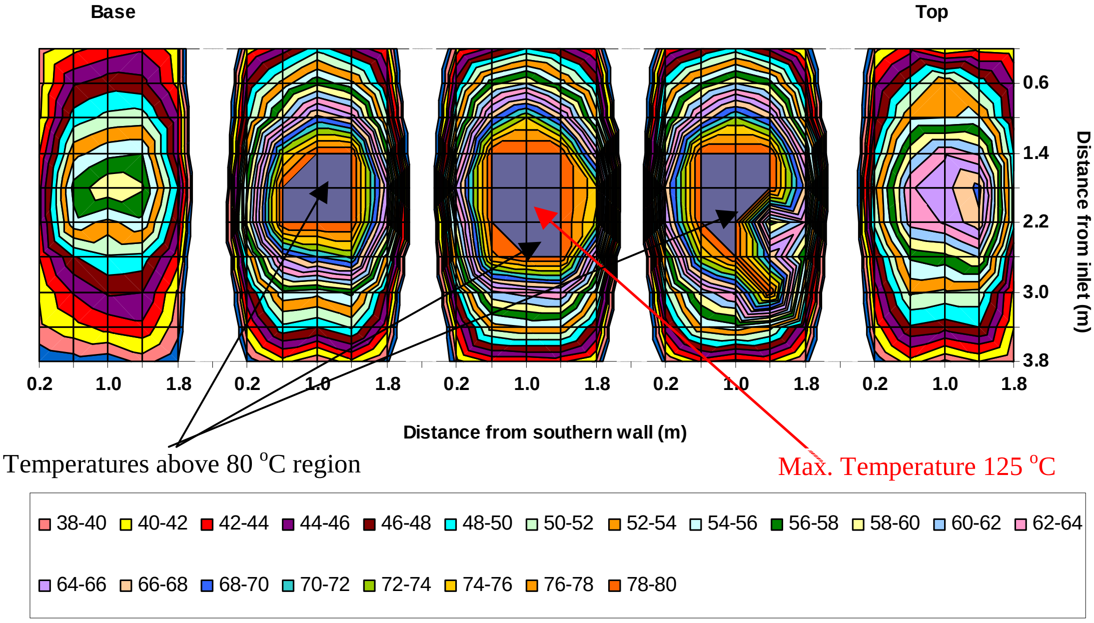


Figure 3.13 Temperature contours – slow inertisation test – after 1 week (Exp 8)

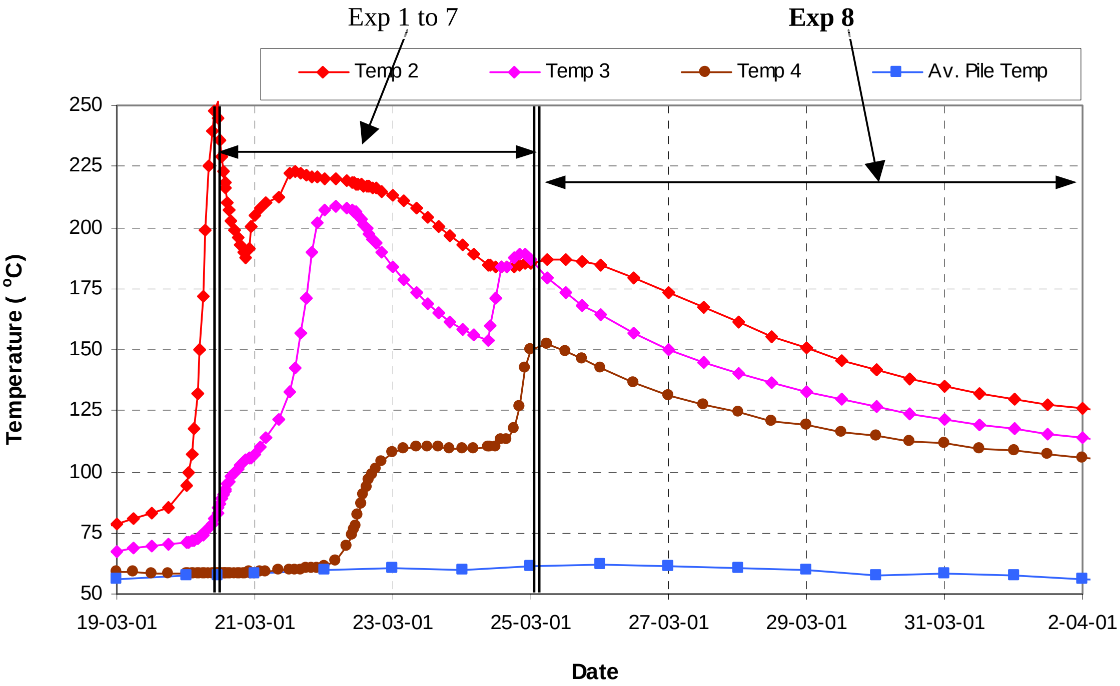


Figure 3.14 Peak temperature profiles in the testing rig – slow inertisation test (Exp8)

Temperature contours (Figure 3.13) indicated that slow inertisation resulted in uniform dispersion of heating zones in the rig. Figure 3.14 show that temperature decreased uniformly at all the hot spot locations and there was no sign of any new self heating zones development in the rig. Peak temperatures in the rig reduced down to 100 to 125°C at various locations. However, results showed that even slow inertisation for one week was not effective in completely cooling down the heating area in the rig. Peak temperatures should be reduced down to 70 to 80 °C to prevent any revival of heatings.

It is to be noted that self heating in the rig was stimulated by a heater at the centre of the coal pile. However, normal self heating in the rig would have developed towards the intake side of the rig, but not at the centre of the rig. The intake side area would have reasonable flow paths for inert gas to act on the heating. In addition, small size coal pieces used in the reactor could have resulted in fewer flow paths towards the centre of the rig and contributed to a slower rate of cooling in the rig.

In experiment 9, fresh air was introduced again into the rig and resulted in a rise of temperatures in the rig. This test also confirmed that temperatures in the rig should be reduced down to 80 °C to prevent any revival of heatings.

Experiment 10

In the last experiment, the rig was allowed to cool down on its own by stopping all blower fans and inert gas injections. The objective of this test was to measure the rate of temperature changes in the rig and to determine the time required for cooling down of the rig to temperatures below 50 °C. Results of the test are shown in Figure 3.15. Test results show that the heating in the rig took 6 weeks to cool down to temperatures below 50 °C. Projections of these results to underground situations indicate that it may take months for any major heating to cool off without inert gas injection.

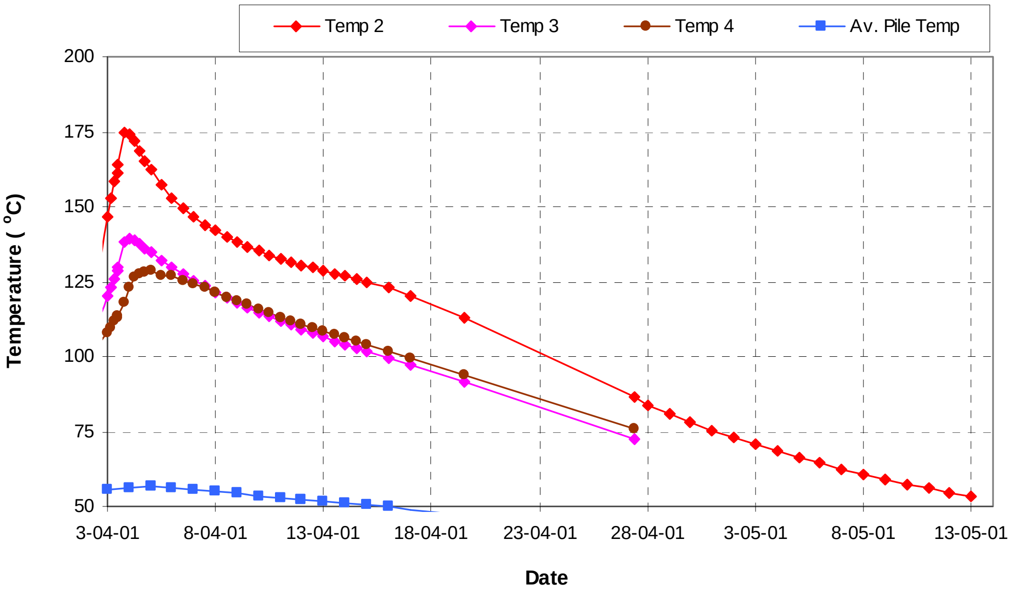


Figure 3.15 Peak temperature profiles – during testing rig cooling down stage (Exp10)

3.5 SUMMARY AND CONCLUSIONS

A number of experiments were carried out in the SIMTARS sponcom reactor to investigate the effect of different inertisation strategies on temperature changes, gas flow mechanics and gas concentration levels around the heating area. Most of the inertisation experiments were carried out between the peak temperatures of 100 and 300 ^{o}C to prevent the risk of major fires in the testing rig. Inertisation experiments involved injection of inert gas at different flow rates, different inertisation durations and fresh air introduction into the rig.

Analysis of the results showed that rapid inertisation for short periods of a few hours resulted in only marginal decrease in peak temperatures. Results showed that rapid inertisation resulted in migration of heating zones to adjacent locations in the testing rig. This heat migration has led to the development of new self heating zones adjacent to the previous hot spots in the rig. Tests indicated that rapid inertisation at higher flow rates for short durations may not be an appropriate strategy to control all the major heatings in the longwall goafs and needs to be investigated further.

Test results showed that introduction of fresh air into the rig immediately after rapid inertisation resulted in revival of heating in the coal pile. Temperatures started to increase steeply at the newly developed self heating zones. Results also indicated that any fresh air introduction even after few days of air leakage into the goaf could result in revival of heatings.

Tests with air leakage into the rig at just 7% oxygen showed that temperatures at the self heating zone did not change significantly during the test period. Temperatures remained constant at above 100 ^{o}C. Test results indicate that heatings in the goaf can survive for long periods even at low oxygen levels of 7%. Therefore, it is very important to prevent air leakages into the sealed area as it can keep the heatings active for very long periods.

Experiments with inert gas injection at lower flow rates showed that slow inertisation resulted in uniform dispersion of heating zones in the rig. Results showed that the temperature decreased uniformly at all the hot spot locations and there was no sign of any new self heating zone development in the rig. Results indicate that inert gas needs to be injected at an optimum flow rate depending on the size and location of the heatings in the goaf.

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CHAPTER 4

COMPUTATIONAL FLUID DYNAMICS (CFD) MODELLING

4.1 INTRODUCTION

A detailed understanding of the flow patterns and distribution of gas in the goaf is necessary to improve the design process of inertisation operations. This requires innovative modelling of goaf gas flow dynamics to study the effect of various parameters on inert gas dispersion patterns and development of high oxygen/explosive gas pockets in the sealed goafs. Numerical modelling studies can then be used to determine the optimum location and flow rate for inert gas injection into the longwall goafs. Simulation techniques can also be used to develop effective inertisation strategies for different mine geometries and/or ventilation systems.

Previous attempts to understand goaf gas flow mechanics have used physical scale models, field studies and 2D modelling, which were limited in application. The improved performance of today's computers and availability of powerful computational fluid dynamics (CFD) codes provides new opportunities for the development of new techniques and models. This research project overcame the limitations of the previous studies by adopting a CFD based approach for detailed investigation of the inert gas flow dynamics and goaf gas distribution. A brief review of the previous modelling studies, CFD model development, validation of base model and results of the extensive parametric studies are presented in this chapter.

4.2 CFD MODEL DEVELOPMENT

The gas flow pattern in a goaf is complex as many factors such as ventilation, gas densities, buoyancy and goaf permeability are involved. Most of the modelling work carried out so far in the goaf areas has been on estimation of gas emission quantities. Previous attempts on understanding of goaf airflow dynamics have used physical scale models and limited field studies. There has been some work reported on the airflow dynamics of a goaf area, but only in two dimensions. This research project has used computational fluid dynamics (CFD) modelling approach to simulate the inert gas dispersion patterns. A brief background on applications of CFD modelling in mining is presented below.

4.2.1 CFD Modelling Background

Computational fluid dynamics is a powerful tool being used in a wide range of industrial and non-industrial application areas including aerospace, nuclear, automobile, manufacturing industries and environmental engineering. Early versions of software were expensive to use because they were very demanding in terms of computing resources and in the past were used almost exclusively in aerospace applications. The improved performance of today's computers and advances in parallel processing has reduced the computational limitations in CFD applications. Also, today’s codes are more general in nature and can be used for most real world problems.

Applications of CFD in mining engineering are rare but emerging in recent years. CFD codes have been successfully used in South Africa and Australia in areas such as simulation of airflow patterns around coal cutting machines in development headings and longwall faces (Sullivan & Van Heerden 1993, Srinivasa Rao et al. 1993). Recently, CFD codes are being used in USA, UK and Australia for development of fire simulators, heading ventilation models and goaf gas flow models (Brunner et al. 1995, Moloney et al. 1999, Balusu et al. 2001). In France, CFD modelling has also been used to optimise nitrogen injection into the working panel longwall goafs to reduce spontaneous combustion (Pokryszka et al. 1997). The modelling work in France has been carried out in only 2D and has identified the need for 3D modelling for effective simulation of flow patterns in the longwall goafs. In addition, it is to be noted that the flow patterns in sealed goafs are different from working panel flow patterns and sealed goaf modelling requires transient simulation techniques.

After an extensive review of the in-house and commercial CFD codes and their capabilities for modelling goaf gas conditions, a commercial CFD code “FLUENT” was selected for modelling in this project. The FLUENT code was used to simulate the flow mechanics inside the longwall goaf region and surrounding roadways. FLUENT is a finite volume computational fluid dynamics code that solves the Navier-Stokes equations for incompressible and compressible flows. An elementary calculation of transfers to and from the neighbouring volumes is performed for each surface of the mesh. These exchanges depend on the incoming and outgoing flows and on the intrinsic characteristics of the flow regions.

4.2.2 Longwall Goaf Inertisation Model Development

The modelling of inertisation process in longwall goafs consists of a number of stages, including:

- Field studies to obtain the basic information on longwall panel, goaf geometries and other parameters.
- Construction of 3D finite element model of the longwall goaf.
- Setting up flow models and boundary conditions through user-defined subroutines.
- Base case model simulations
- Model calibration and validation using field measured data
- Extensive parametric studies using validated CFD models

Field studies were conducted in the beginning of the project to obtain the basic information on geometry of the longwall goaf, gas emissions, ventilation system, caving characteristics and inertisation practices and system details. These initial studies also involved a detailed monitoring of the gas distribution changes in the goaf during standard inertisation operations in order to collect field data for base-case model calibration and validation purposes.

Information obtained from the above field studies was used to construct the base-case longwall inertisation model. A hybrid meshing technique was used to construct the model to improve the efficiency of calculations, particularly in simulating the effects of buoyancy. The mesh used higher density mesh with hexahedral elements in the areas of high turbulence and/or velocity. These areas were linked by an unstructured tetrahedral mesh in areas of lesser gradients of flow properties. A typical mesh used in longwall goaf inertisation models is shown in Figure 4.1.

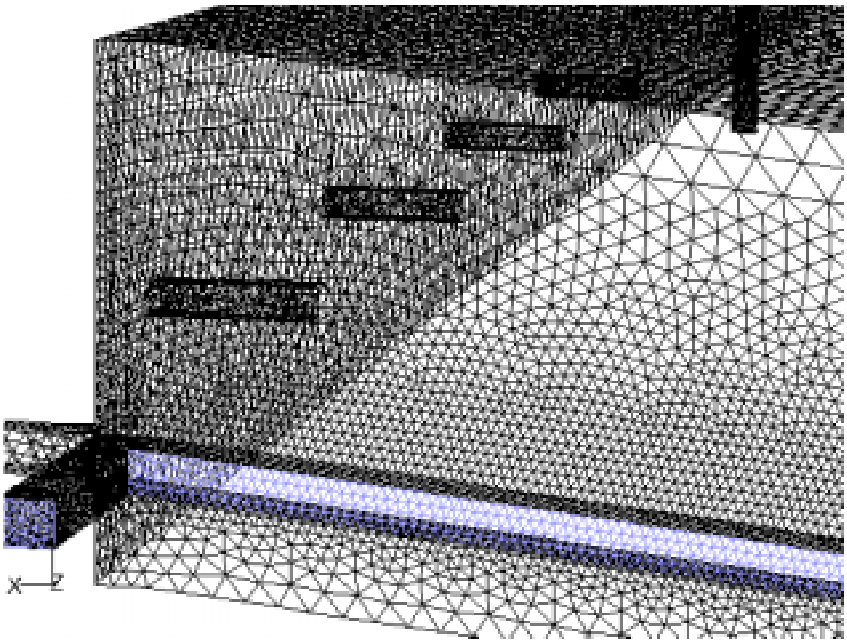

Figure 4.1 Mesh used in the CFD simulations of longwall goaf inertisation

The distribution of goaf porosity was derived from results of typical longwall geomechanics models. Pressure, flow rate and gas distribution in a typical longwall goaf were used to calibrate the initial models and further refine the distribution of goaf permeability. The permeability distribution in the goaf ranged from 10^{-4} m^2 to 10^{-9} m^2. A standard two equation k-e model was used to estimate the turbulent transport through the flow region and the flow near the boundaries was approximated by the use of standard wall functions. Flow through goaf was handled using custom written subroutines, which were added to the “flow through porous media” modules of the basic code. In these subroutines/modules, flow through the porous goaf regions was simulated by adding a momentum sink to the momentum equations. The sink had viscous part proportional to the viscosity and an inertial component proportional to the kinetic energy of the gases. A number of subroutines were written to represent the goaf gas emissions and inertisation scenarios, which were then combined with the main FLUENT program to carry out the simulations.

Initial simulations were carried out using the base-case longwall inertisation model. These simulations were carried out with two scenarios representing goaf conditions during face bolting period and sealing-off periods. The details of the input parameters and boundary conditions are presented in the following section.

The next stage in CFD modelling was the calibration and validation of the base-case models. This phase involved a series of steps in which the results of the base-case model were compared with measured field data and adjustments were made to the values of the estimated parameters such as permeability. The field data used for model validation include the concentration of various gases and flow directions at certain key locations in the goaf. They also include data obtained by specific field tests such as tracer gas studies, gas leakages and face gas profile surveys. The model parameters are fitted in successive iterations until the differences were regarded as acceptable. Results of the validated base case models are presented in section 4.3.

The validated model was then used for extensive parametric studies involving changes in ventilation systems, goaf gas emissions, inertisation locations, inert gas flow rates and different inertisation strategies. These parametric studies were used to investigate the effect of various factors on goaf inertisation and to arrive at optimal inertisation strategies. The details of the parametric studies and results of various investigations are discussed in section 4.4. Development of optimum inertisation strategy through simulations of various alternative systems with field site conditions are presented in section 4.5

4.3 LONGWALL INERTISATION SIMULATIONS – BASE MODEL

The base model for the longwall inertisation studies was 1 km in length along the panel, 205 m in width and 50 m in height to cover the immediate high porosity caving regions in the goaf. The seam and roadways were 4 m high and all roadways were 5 m wide. Goaf gas emission was varied between 100 l/s and 600 l/s to represent typical longwall panels in highly critical low gas environments. This was also equal to the gas emission rates of the panels used for model calibration and validation. The maingate inlet was set at an elevation 20 m higher than the tailgate return to represent the field case scenario. A “U” ventilation system was used in both the base-case models, with the maingate as intake and tailgate as return roadway. The details of the modelling parameters are presented in the Table 4.1.

Two sets of base-case simulations were carried out to represent the conditions during face bolting and panel sealing-off periods. The intake airflow rate through the maingate was kept at 50 m^3/s in the first base case set, which represents goaf environmental conditions during face bolting period. In the second base case, intake airflow was reduced to 10 m^3/s to represent goaf conditions just before sealing off the panel. These base-case simulations were carried out under different gas emission flow rates. Main features of the different base cases are:

(i) Base case 1(a) – 50 m^3/s airflow and 0.6 m^3/s (600 l/s) goaf gas emissions
(ii) Base case 1(b) – 50 m^3/s airflow and 0.3 m^3/s (300 l/s) goaf gas emissions

(iii) Base case 2(a) – 10 m^3/s airflow and 0.6 m^3/s (600 l/s) goaf gas emissions
(iv) Base case 2(b) – 10 m^3/s airflow and 0.3 m^3/s (300 l/s) goaf gas emissions
(v) Base case 2(c) – 10 m^3/s airflow and 0.1 m^3/s (100 l/s) goaf gas emissions

Table 4.1 Base case parameters for CFD simulations

S.No.	Model parameter	Value
1	Longwall panel dimensions	1.0 km long, 200 m wide and 4.0 m height
2	CFD Model dimensions	50 m height – covering 36 m above and 10 m below working section
3	Cut-through spacing (on maingate side)	100 m
4	Face finish line	At 1 cut-through (i.e 3 c/t at 200 m behind face finish line)
5	Seam gradient	1 in 10 from maingate to tailgate (i.e., maingate intake at higher elevation)
6	Ventilation system, flow rate	“U” type ventilation, 10 m^3/s to 50 m^3/s
7	Goaf gas emission flow rate	0.1 m^3/s to 0.6 m^3/s
8	Goaf gas drainage	Nil

The results of the base-case simulations in 3D view are presented in Figures 4.2 to 4.6, showing the oxygen gas distribution in the goaf under different airflow and gas conditions. The 3D view figures show two slices along the longwall panel. The horizontal slice is midway through the seam and the vertical slice is 50 m from the tailgate rib. In the colour coding scale of the figures, 0.21 represents 21% oxygen, i.e. fresh air composition. Figure 4.2 shows the oxygen distribution in the goaf with base case 1(a) simulations, i.e., with 50 m^3/s airflow and 0.6 m^3/s methane goaf gas emissions. Results show that oxygen ingress into the goaf was more on the maingate intake side compared with tailgate return side. For example, oxygen level was around 20% on the maingate side and 16% on the tailgate side of the goaf at 60 m behind the face.

Other important points to be noted from the results presented in Figure 4.2 are:

- Oxygen levels presented in the figure represents only goaf gas distribution near the bolted-up area of the panel near the finish line, but not a standard goaf gas distribution under normal caving conditions. (In normal caving zones, high oxygen concentration zone penetration distance into the goaf will be significantly less due to higher consolidation of the goaf material at the centre part of the panel).
- The vertical section in the figure clearly shows the air/gas layering in the goaf with higher oxygen concentration near the working seam level. This figure shows the buoyancy effect of methane gas in displacing air/oxygen at the higher elevation parts of the caving zones and its contribution to gas layering in the goaf.
- However, Figure 4.2 shows that even though tailgate return was at lower elevation, the oxygen gas concentration levels were higher in the maingate area. This indicates that during longwall retreat operations, ventilation pressures and gas emissions had a major influence on goaf gas distribution compared to the effect of methane gas buoyancy forces.
- It is also to be noted that although the oxygen concentration levels were lower near the tailgate area, air penetration distance into the goaf was higher on tailgate side with 10% oxygen at 200 m behind the face.

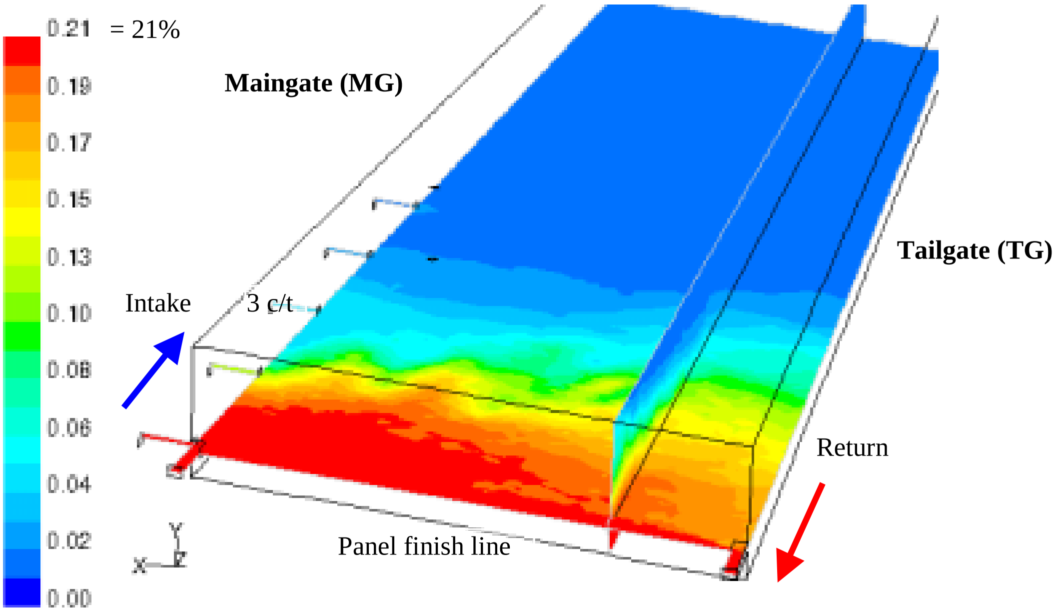

Figure 4.2 Oxygen gas distribution in the longwall goaf – Base case 1(a)
(Airflow 50 m^3/s + Goaf gas 0.6 m^3/s)

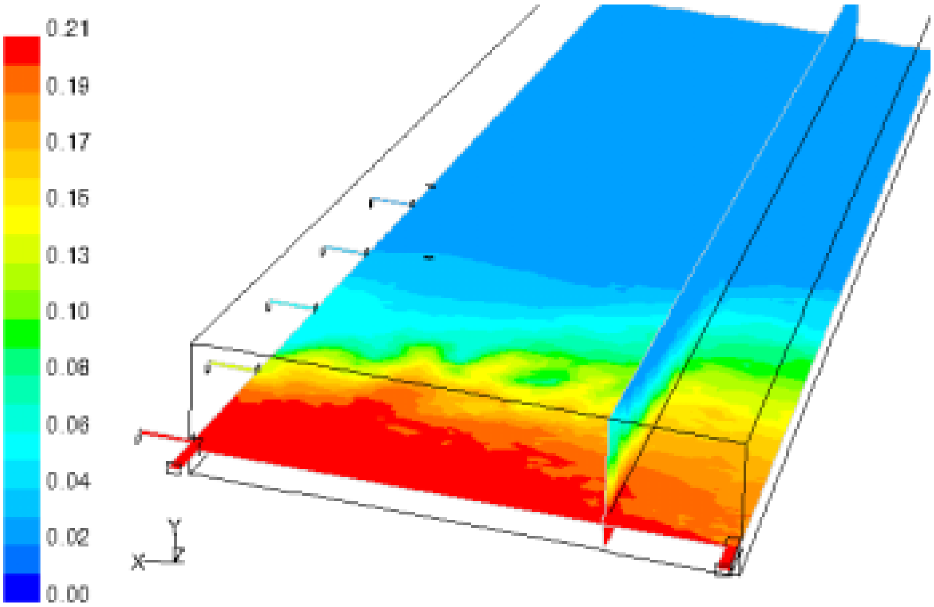

Figure 4.3 Oxygen gas distribution in the longwall goaf – Base case 1(b)
(Airflow 50 m^3/s + Goaf gas 0.3 m^3/s)

Figure 4.3 presents the results of simulations for base-case 1(b), with 50 m^3/s airflow and 0.3 m^3/s methane goaf gas emissions. Results show that oxygen gas concentration level was significantly higher near the tailgate return side when compared with previous case 1(a) results. Lower methane gas emissions seem to have contributed to this change in goaf gas concentration near the tailgate area of the goaf.

In the base case 2 series simulations, airflow in the panel was reduced to 10 m^3/s to represent goaf conditions just before sealing off the panel. Results of simulations for base case 2(a), i.e., with 10 m^3/s airflow and 0.6 m^3/s goaf gas emissions, are shown in shown in Figure 4.4. Oxygen distribution presented in the Figure 4.4 shows that oxygen concentration levels and penetration distance were higher on the tailgate return side of the goaf. Oxygen penetration distance extended up to 300 m on the tailgate side of the goaf. This is in contrast to the oxygen distribution for base case 1(a), presented in Figure 4.2, where oxygen concentration levels were higher on the maingate intake side.

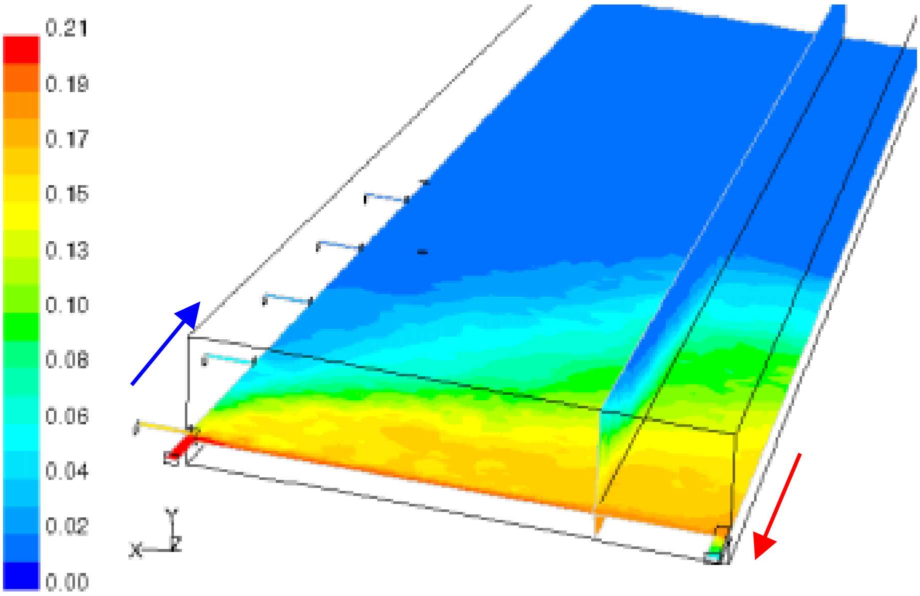

Figure 4.4 Oxygen gas distribution in the longwall goaf – Base case 2(a)
(Airflow 10 m^3/s + Goaf gas 0.6 m^3/s)

Comparison of the results for base cases 1(a) and 2(a), presented in Figures 4.2 and 4.4, shows that intake airflow rate and the consequent air velocity and ventilation pressures have a major influence on gas distribution in the goaf. Reducing the intake airflow in the panel during chock recovery operations has considerably reduced the oxygen penetration on the intake side of the goaf and drastically changed the goaf gas distribution pattern. In addition, reducing the intake airflow also resulted in extension of buoyancy force effect down to working seam level in the goaf.

Oxygen distribution in the goaf for base-case 2(b) conditions, i.e. with 10 m^3/s airflow and 0.3 m^3/s goaf gas emissions, is shown in Figure 4.5. Results show that oxygen concentration levels in the area immediately behind the face were higher in this case due to low rate of goaf gas emissions. For example, oxygen level in the goaf at 50 m behind the face on maingate side increased from 10% in base-case 2(a) to 17% in base case 2(b). Results also showed that oxygen penetration distance on the tailgate side increased significantly due to low goaf gas emissions.

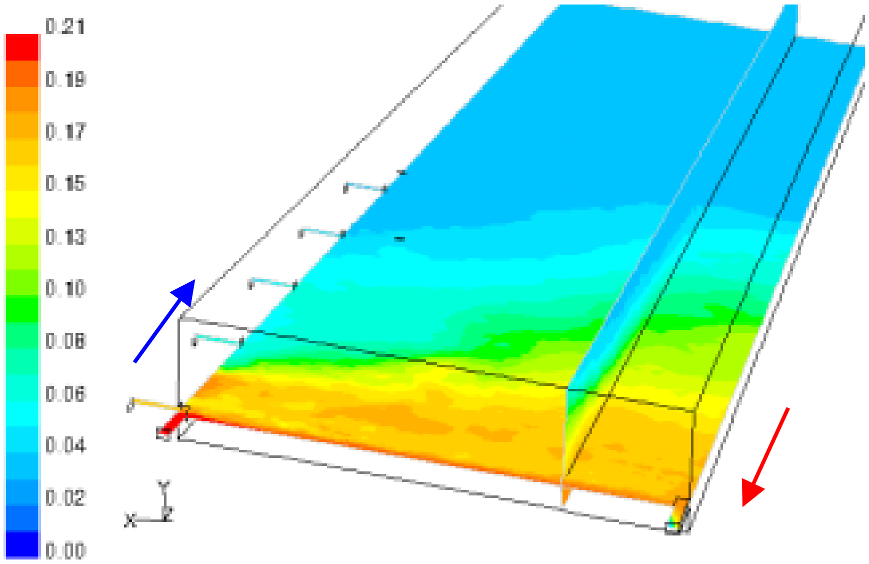

Figure 4.5 Oxygen distribution in the longwall goaf – Base case 2(b) (10 m^3/s air + 0.3 m^3/s gas)

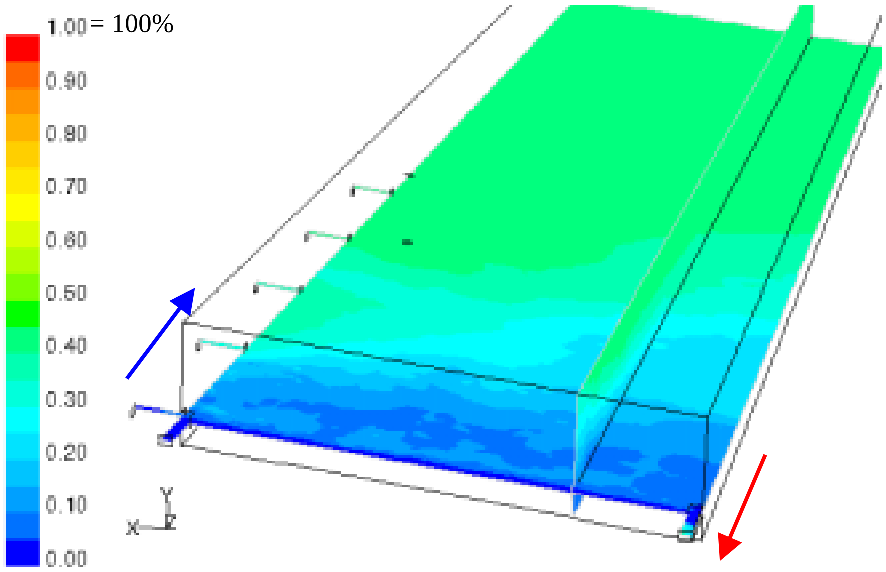

Figure 4.6 Methane distribution in the longwall goaf – Base case 2(c) (10 m^3/s air + 0.1 m^3/s gas)

Methane concentration levels in the goaf for base case 2(c) conditions, i.e with 10 m^3/s airflow and 0.1 m3/s gas emissions, are presented in Figure 4.6. Simulation results show that fresh air ingress into the goaf increased further with reduction in goaf gas emissions to 0.1 m^3/s. Results also show that the maximum concentration level of methane in the goaf was less than 50%. Simulations also indicate that the explosive gas mixture zone extends to a wider area in the goaf with lower goaf gas emissions. Results shown in these base case models compared well with the field measured gas concentration values.

4.4 PARAMETRIC STUDIES

The validated base case models were then used for extensive parametric studies to investigate the effect of ventilation, seam gradients and various inertisation strategies on goaf gas distribution. Parametric studies were conducted under both steady state and transient conditions. Steady state modelling simulates the conditions before sealing off the panel. Transient modelling techniques were used to simulate the goaf conditions at regular time intervals after sealing off the panel. These transient simulations take a very long time as numerical simulations had to reach stable solutions at every time step. Therefore, in these modelling investigations, 4 hour intervals were used to minimise the total time required for numerical simulations. Goaf conditions were simulated for up to 5 days after sealing off the longwall panel with various inertisation strategies. Studies included simulating the following scenarios:

(i) the effect of intake airflow on goaf oxygen distribution,
(ii) the effect of inert gas composition on goaf inertisation,
(iii) the effect of seam gradients on goaf gas distribution, and
(iv) the effect of various stratagies on goaf inertisation.

Simulations showed that all these factors had a significant effect on goaf gas distribution and inertisation. Results of some of the typical parametric simulations are presented in the following sub-sections.

4.4.1 Steady state simulations

(a) Effect of airflow rate (Comparison – high and low airflow rates)

In these studies only airflow into the panel was changed to simulate its effect on goaf gas distribution. Airflow was changed from 50 m^3/s in the first model to 10 m^3/s in the second model. All other model parameters and boundary conditions remained identical in both the models. Oxygen distribution in the goaf under 50 m^3/s and 10 m^3/s airflow conditions are presented in Figures 4.7 and 4.8 respectively. Goaf gas emission flow rate was about 0.6 m^3/s of methane in both the models.

Comparison of the figures 4.7 and 4.8 shows a wide variation in goaf gas distribution. For example, Figure 4.7 shows that intake airflow/oxygen has penetrated up to 100 m behind the face on maingate side even against the buoyancy pressure of methane gas. Whereas in the case of low airflow rate conditions, buoyancy forces seem to have major effect on goaf gas distribution, as shown in Figure 4.8. In this case, fresh air penetration into the goaf on intake side was very short at less than 30 m. However, the air and gas mixture penetrated deep into the goaf at lower elevation tailgate side due to buoyancy effects. For example, oxygen concentration was above 10% even at 250 m behind the face on tailgate side. These simulation results indicate that intake airflow rate would have a significant effect on goaf gas flow mechanics during longwall retreat operations.

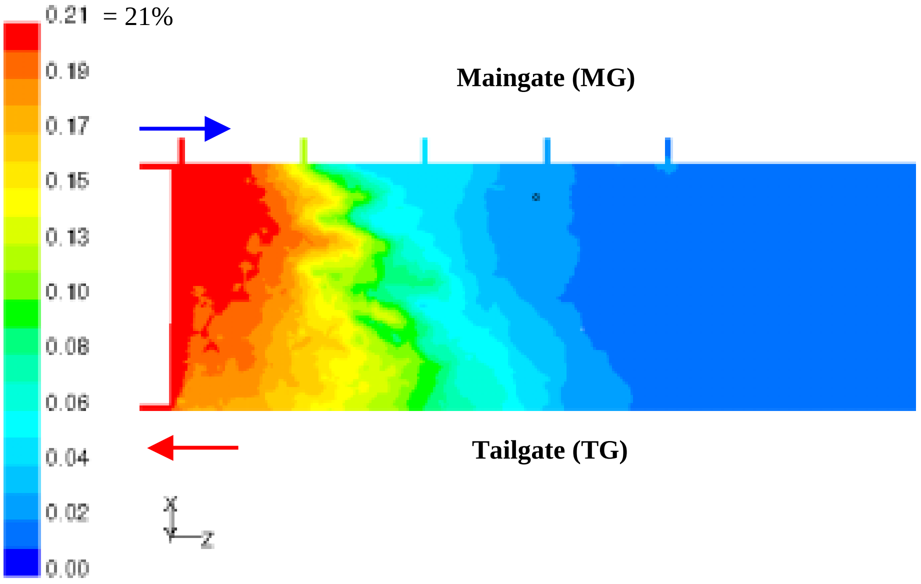

Figure 4.7 Oxygen distribution with high airflow rate (50 m^3/s)

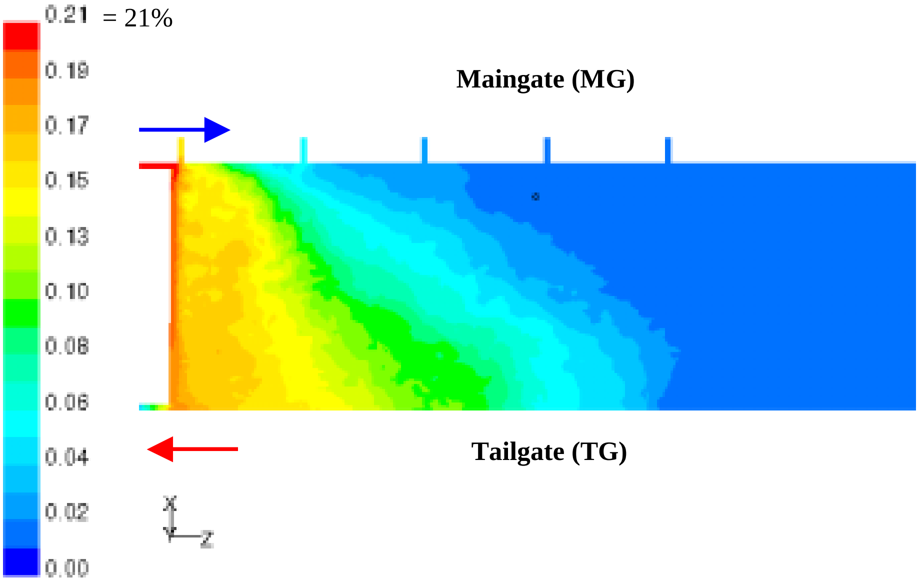

Figure 4.8 Oxygen distribution with low airflow rate (10 m^3/s)

(b) Effect of inert gas injection location (Comparison – inert gas through 1 c/t and 3 c/t)

The effect of two different inert gas injection locations on goaf inertisation was simulated in separate models. In the first model, inert gas was injected through the MG seal location, which is the standard practice for longwall goaf inertisation. In the second model, inert gas was injected through 3 c/t seal on the maingate side. These simulations were carried out under steady state conditions with 50 m^3/s airflow through the panel, i.e.

with conditions at the start of the chock withdrawal process in the panel. Results of the simulations for both models are presented in Figures 4.9 and 4.10, which show oxygen distribution profiles in the goaf.

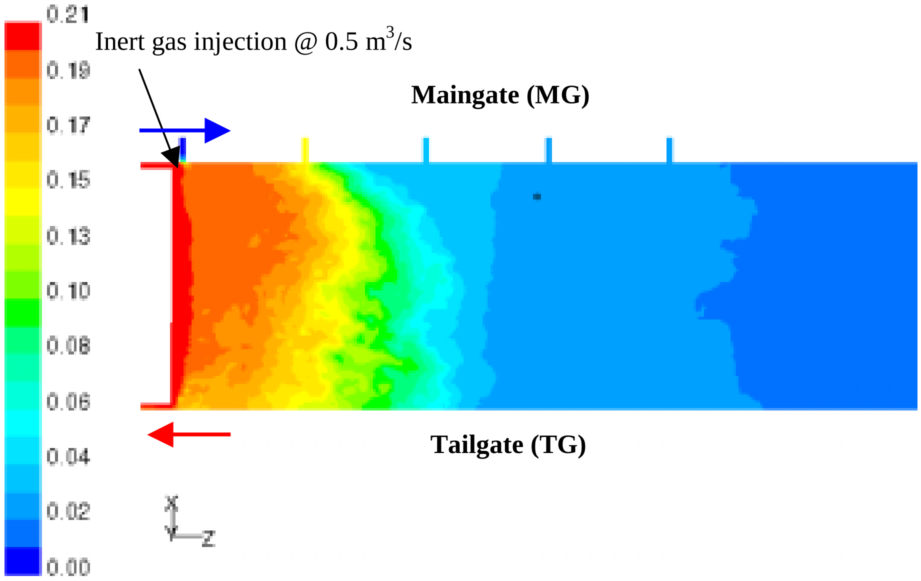

Figure 4.9 Oxygen distribution in the goaf – inert gas through MG (Airflow 50 m^3/s)

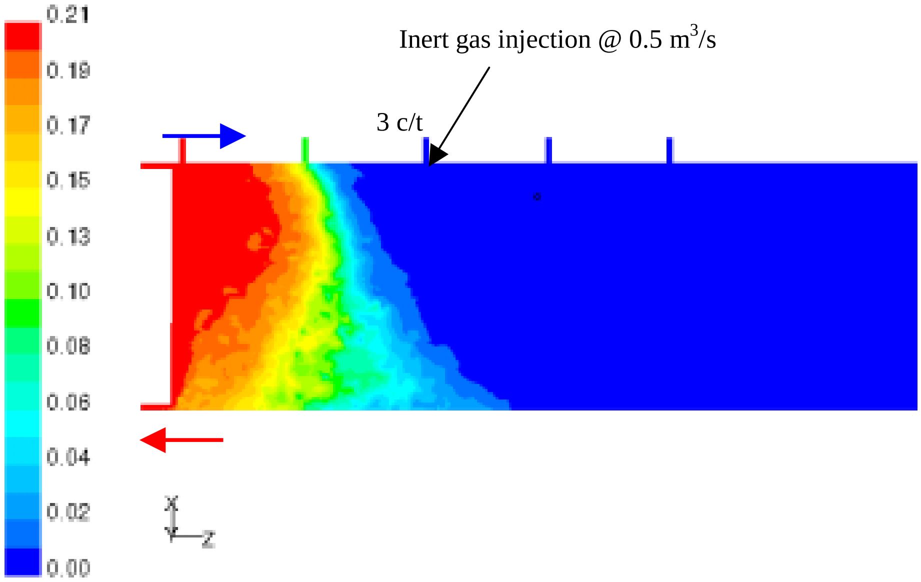

Figure 4.10 Oxygen distribution in the goaf – inert gas through 3 c/t seal (Airflow 50 m^3/s)

Figure 4.9 shows that injection of inert gas through MG or 1 c/t seal resulted in reduction of oxygen concentration from 21% to 17% within the immediate vicinity of the maingate seal. However, air and gas mixture zone with 12% to 14% oxygen was pushed back into the goaf up to 200 m behind the face. Figure 4.9 also indicated that explosive gas mixture zone was expanded to a wider area in the goaf. Figure 4.10 shows that injection of inert gas through 3 c/t on the maingate side, i.e., at a location 200 m behind the face, resulted in migration of the air and gas mixture zone towards the face finish line. Results also indicated narrowing down of the explosive gas mixture zone to a smaller area in the goaf. These simulation results indicate that inert gas injection from maingate side at 100 to 200 m behind the face reduces the oxygen level in the high sponcom risk area of the goaf and helps in sponcom control during face retreat operations.

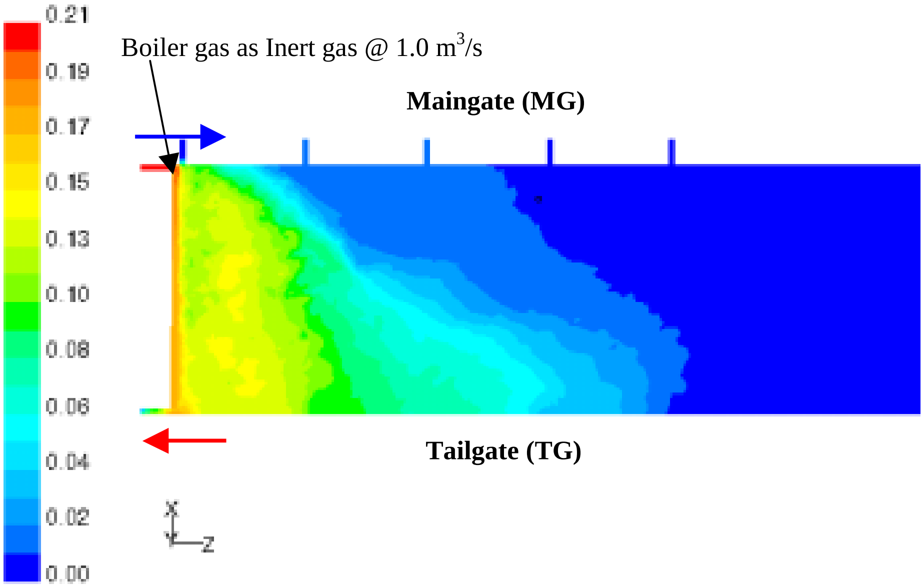

Figure 4.11 Oxygen distribution in the goaf – Boiler gas as inert gas (Airflow 10 m^3/s)

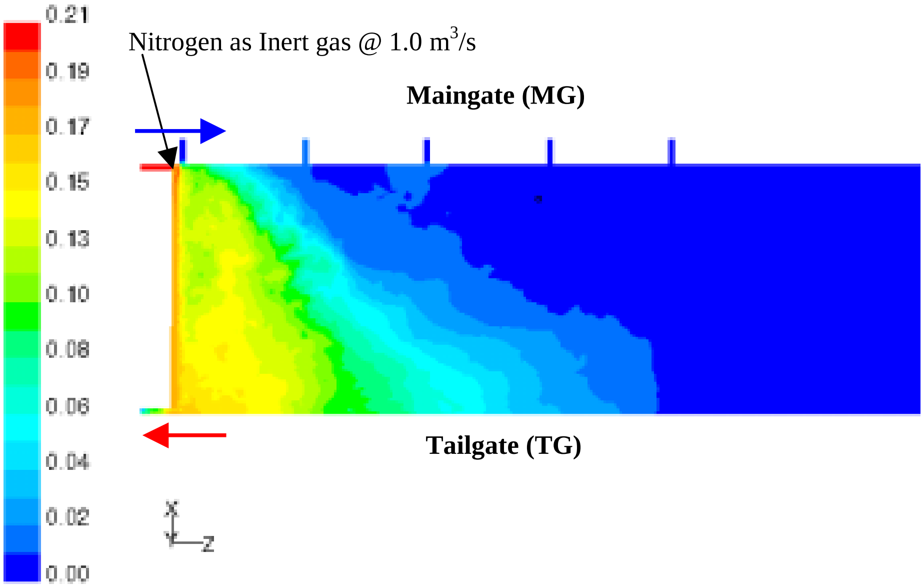

Figure 4.12 Oxygen distribution in the goaf – Nitrogen as inert gas (Airflow 10 m^3/s)

(c) Effect of inert gas composition (Comparison – boiler gas and Nitrogen inert gases)

The effect of inert gas composition on goaf inertisation was investigated in these modelling simulations. In the first model, Tomlinson Boiler gas was used as inert gas for goaf inertisation. In the second model, 100% Nitrogen was used as inert gas. Inert gas was introduced at the rate of 1.0 m^3/s from MG seal location (or 1 c/t) in both the models. These simulations were also carried out under steady state conditions, but with only 10 m^3/s airflow through the panel to represent conditions just before sealing off of the panel. Results of the simulations for both models are presented in Figures 4.11 and 4.12.

Results show that there were only minor differences in goaf gas distribution between the two models at the tailgate end of the face. Oxygen concentration near the tailgate was lower at around 12 to 14% in the first case with boiler gas injection compared with oxygen levels of 14 to 16% in the second case with Nitrogen injection. In addition, oxygen was dispersed deeper into the goaf in the first case with boiler gas injection.

These results in conjunction with the previous section results indicates that although the composition of inert gas has a minor effect on goaf gas distribution, the inertisation strategy, i.e. inert gas injection location has a major influence on goaf inertisation. Therefore, the inert gas injection location is the most important factor to be considered for design of inertisation strategies. Choice of type of inert gas is generally dictated by cost and location of the mines.

4.4.2 Transient simulations

To model the gas conditions in the goafs after sealing-off of the panels, transient simulation techniques were used in these studies. These transient simulations started from the results of base case steady state solutions. Sealing of the panels as taken as time zero and goaf gas conditions were then modelled at regular time steps of 4 hours for up to 5 days. Effects of various factors and inertisation strategies on sealed goaf gas conditions are investigated in these studies.

(a) Effect of seam gradients

In these simulations the effect of seam gradients and ventilation system on sealed goaf inertisation was investigated. In the first model simulations, standard longwall panel conditions, as described in the base case section, were used. In this model, seam gradient was about 1 in 10 dipping towards the tailgate side, i.e. the tailgate was at lower elevation. Before sealing of the panel, the maingate was used as intake and the tailgate as the return airway in the "U" ventilation system used in the panel. In the second model, it was assumed that both maingate and tailgate were at the same elevation, i.e. flat seam gradient across the panel. In both the models, boiler inert gas was injected through the MG seal at the rate of 0.5 m^3/s. Oxygen distribution in the goaf one day after sealing off the goaf are presented in Figures 4.13 and 4.14.

Results show a significant difference in goaf gas distribution between the two models, particularly near the face finish line. In the first case with seam dipping at 1 in 10, boiler gas seems to have dispersed quickly towards the tailgate end of the face and resulted in a reduction of oxygen concentration levels near the maingate and finish line areas down to

10% within a day of panel sealing. However, the oxygen level inside the goaf on the tailgate side was still above 15%. In the second case with flat seam gradients, high concentration oxygen distribution was uniform across the panel. These results indicate that seam gradients do play a significant role in goaf gas distribution and needs to be considered during development of goaf inertisation strategies.

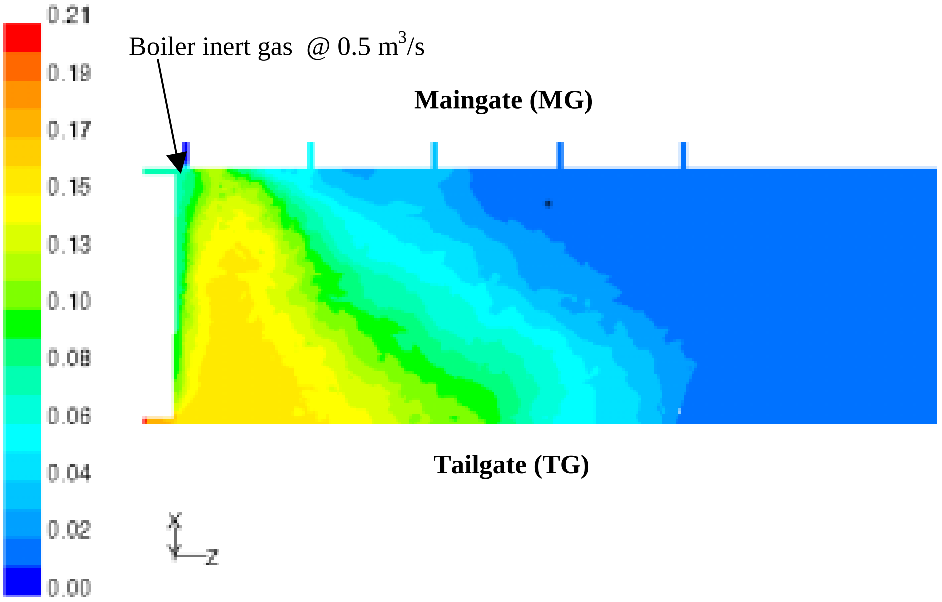

Figure 4.13 Oxygen distribution in the goaf – 1 day after sealing – TG at lower elevation (Boiler gas through MG seal at 0.5 m^3/s)

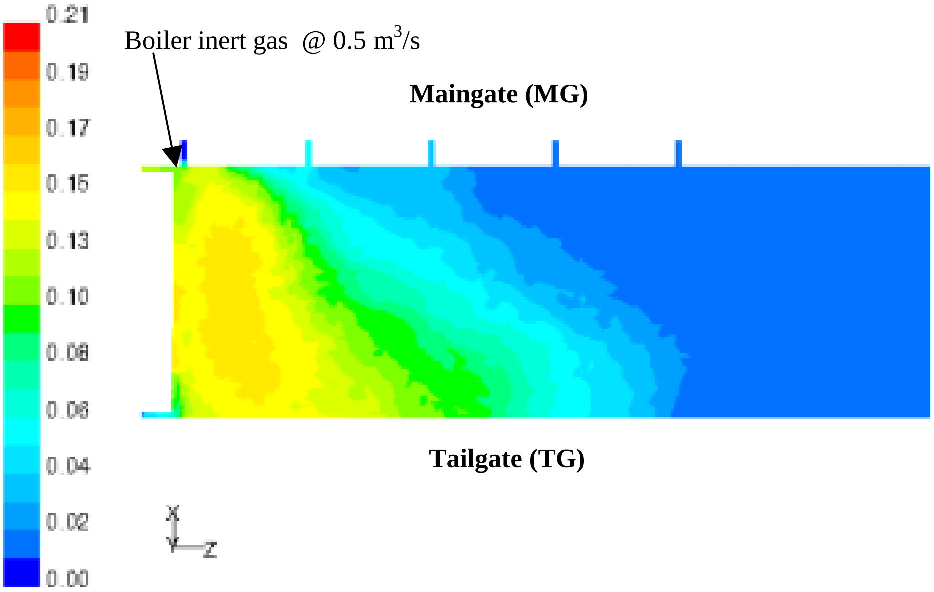

Figure 4.14 Oxygen distribution in the goaf – 1 day after sealing – TG and MG at same elevation (Boiler gas through MG seal at 0.5 m^3/s)

(b) Effect of inert gas composition (Comparison – Boiler and N2 gases)

The effects of two different inert gases on goaf inertisation were investigated in these studies. In the first model boiler exhaust gas was used as inert gas whereas in the second model nitrogen gas was used for goaf inertisation. In both the models inert gas was injected through the MG seal at the higher flow rate of 1.0 m^3/s. In both the models, seam gradient was set at 1 in 10 dipping towards the tailgate side. All other parameters were the same in both models. These modelling studies were carried out with transient parameters to simulate the goaf conditions immediately after sealing of the panel. Results of the simulations are presented in Figures 4.15 and 4.16.

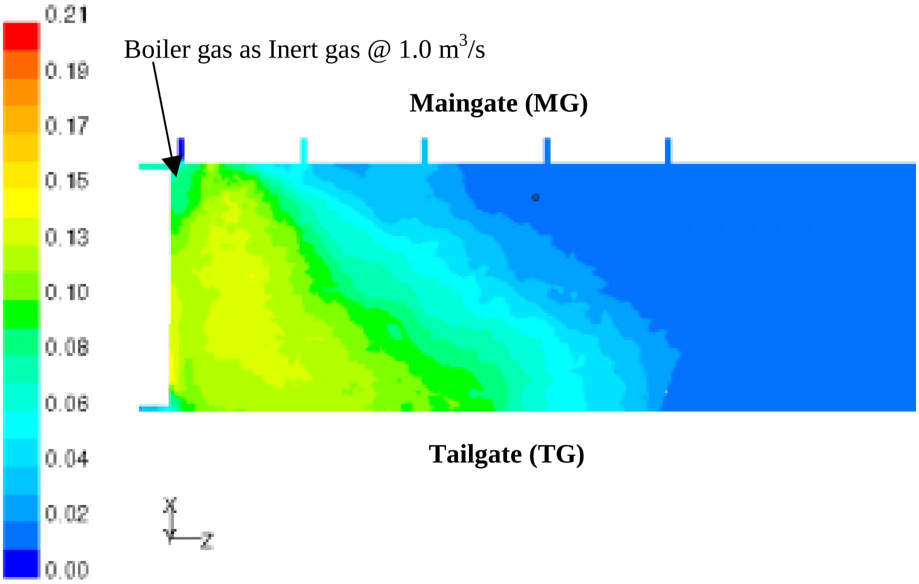

Figure 4.15 Oxygen distribution in the goaf – 1 day after sealing - Boiler gas as inert gas

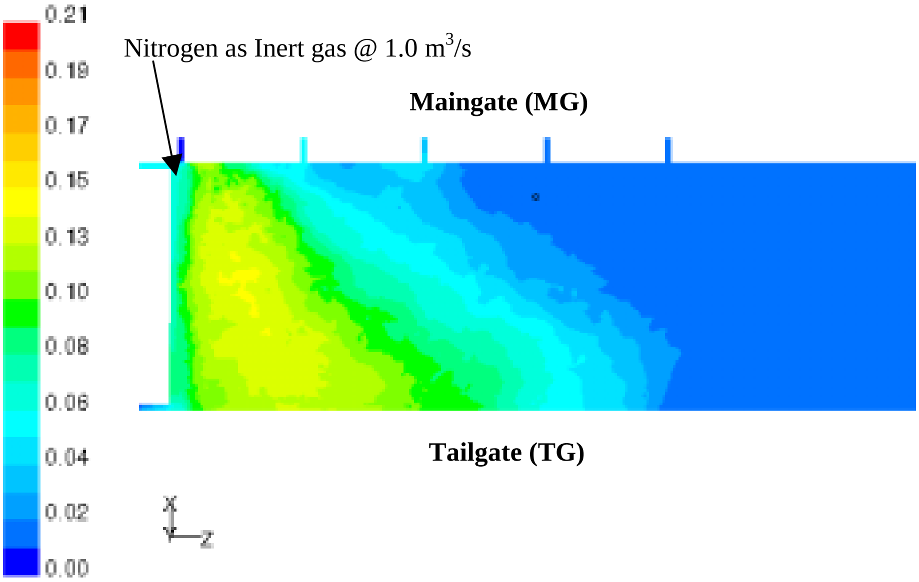

Figure 4.16 Oxygen distribution in the goaf – 1 day after sealing - Nitrogen as inert gas

Results show that there were no major differences in goaf gas distribution between the two cases under the modelled parameters. In both cases the oxygen level was reduced to only 14% after 24 hours of inert gas injection. Results show that there was no major difference in effectiveness of boiler gas or nitrogen on goaf inertisation. These results indicate that although inert gas composition might have an effect on goaf inertisation under certain conditions, it is not the major factor that would make an inertisation process a success or a failure, particularly under sealed goaf conditions.

(c) Effect of inert gas injection location (Comparison – inert gas through 1 c/t and 3 c/t)

The effect of two different inert gas injection locations on goaf inertisation was studied in separate models with transient parameters to simulate goaf conditions after panel sealing. In the first model inert gas was injected through the MG seal and in the second model inert gas was injected through 3 c/t seal on the maingate side. All other conditions and parameters were the same in both cases. Oxygen distribution in the goaf for both models after 24 hours of inert gas injection is presented in Figures 4.17 and 4.18.

Results show that different inert gas injection locations resulted in entirely different goaf gas distribution for the two cases. Figure 4.17 shows that injection of inert gas through MG seal resulted in reduction of oxygen concentration only near the point of injection, i.e. near maingate area. The oxygen concentration level in this area reduced down to 8 to 10%. However, oxygen level near the tailgate area was very high at 15 to 17% even after 24 hours of inert gas injection. Results presented in Figure 4.18 shows that inert gas injection through 3 c/t on the maingate side resulted in reduction of oxygen concentration levels down to 10 to 12% over a wider area near the finish line. There was only a narrow area in the goaf with oxygen levels in the range of 13 to 15%.

Oxygen distribution in the goaf after 2 days of inert gas injection is presented in Figures 4.19 and 4.20. These figures present the oxygen concentration levels in 2D plan view at middle of the working section. Figure 4.19 shows that in the first case oxygen concentration was above 14% over a wider area even after 2 days of inert gas injection. Figure 4.20 shows that in the second case oxygen concentration was below 12% across the entire goaf.

Analysis of the figures indicate that the strategy of inert gas injection through the MG seal was not as effective as the alternative strategy of inert gas injection through 3 c/t. Results also indicated that inert gas injection through the MG seal results in pushing the fresh air zone towards the goaf and consequently requires a longer time for goaf inertisation. It is to be noted that open goaf simulation results presented in section 4.7(b) also indicated that inert gas injection from maingate side at 100 to 200 m behind the face reduces the oxygen level in the high sponcom risk area of the goaf and helps in sponcom control during face retreat.

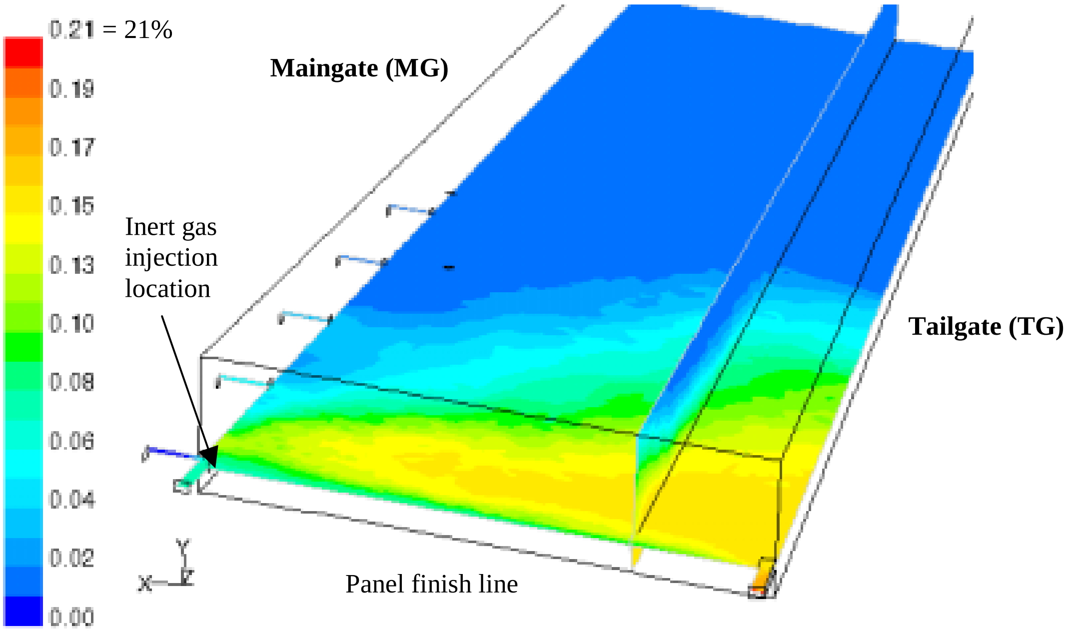

Figure 4.17 Oxygen distribution in the goaf – 1 day after sealing - inert gas injection through MG seal @ 0.5 m^3/s

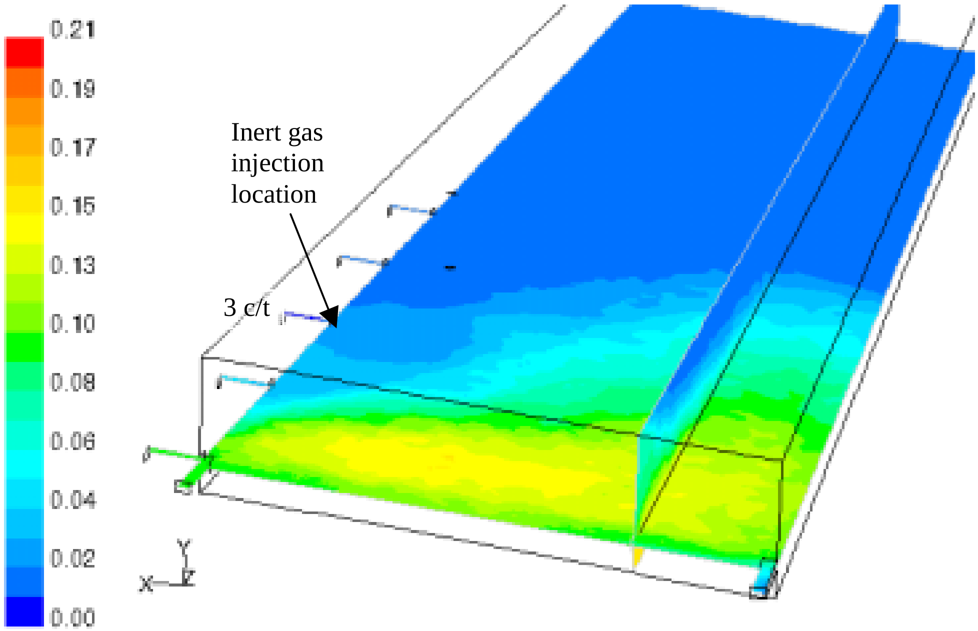

Figure 4.18 Oxygen distribution in the goaf – 1 day after sealing - inert gas injection through 3 c/t seal @ 0.5 m^3/s

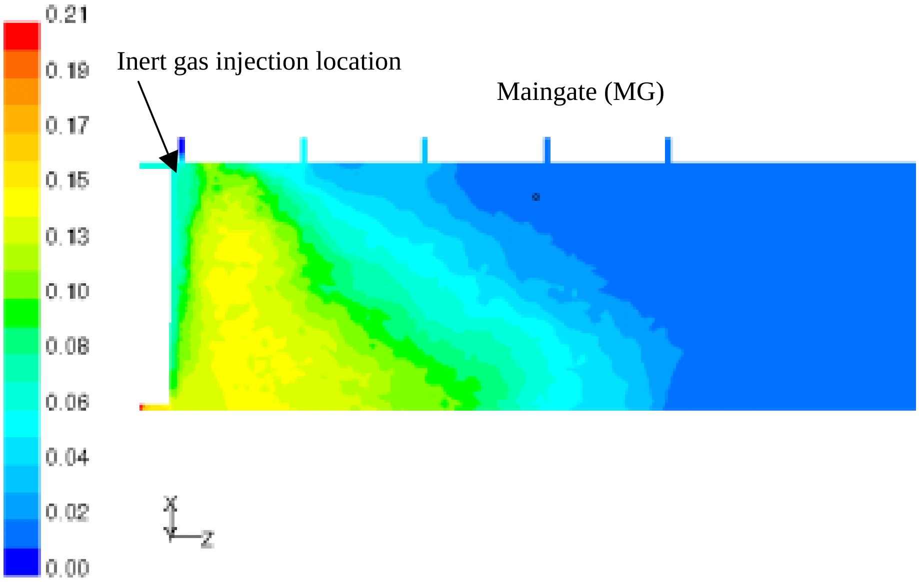

Figure 4.19 Oxygen distribution in the goaf – 2 days after sealing - inert gas through MG seal

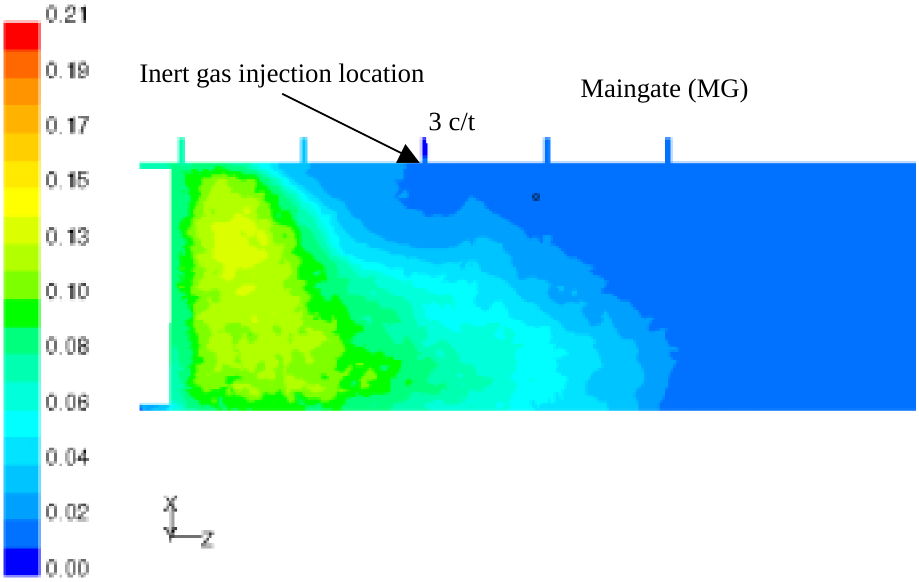

Figure 4.20 Oxygen distribution in the goaf – 2 days after sealing - inert gas through 3 c/t seal

(d) Effect of inert gas flow rate (Comparison –boiler gas at 0.5 m^3/s *and 1.0* m^3/s*)*

The effect of inert gas flow rate on sealed goaf inertisation process was investigated in these modelling studies. In the first model, inert gas was injected at the rate of 0.5 m^3/s and in the second model inert gas was injected at the rate of 1.0 m^3/s. In both the cases, inert gas was injected through the MG seal and all other parameters were same in both the models. Results of the simulations are presented in Figures 4.21 and 4.22. These figures show the oxygen distribution in the goaf at mid-seam level after 1 day of inert gas injection.

Results show that in the first case oxygen concentration was above 15% over a wider area in the goaf (Figure 4.21), whereas in the second case the oxygen level was below 13% in the goaf. These results indicate that inert gas flow rate also has significant influence on goaf inertisation process and needs to be considered in the design of inertisation operations. Analysis of various simulation results indicates that inert gas flow rate is also one of the most important design parameters to be optimised during development of an inertisation strategy. Results indicate that an inert gas flow rate of around 1.0 m^3/s would be required under less gassy conditions.

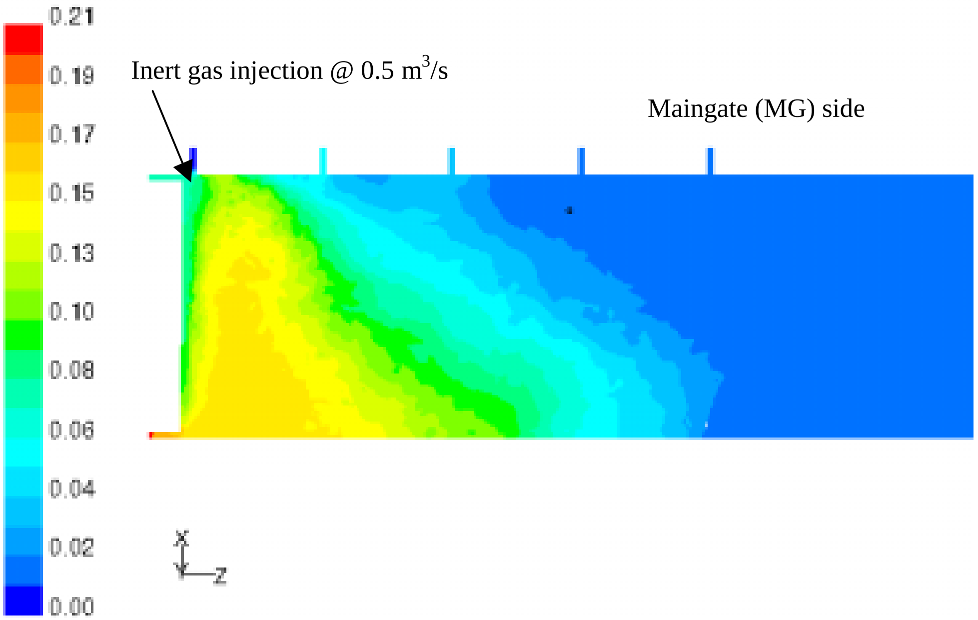

Figure 4.21 Oxygen distribution in the goaf – 1 day after sealing – inert gas @ 0.5 m^3/s

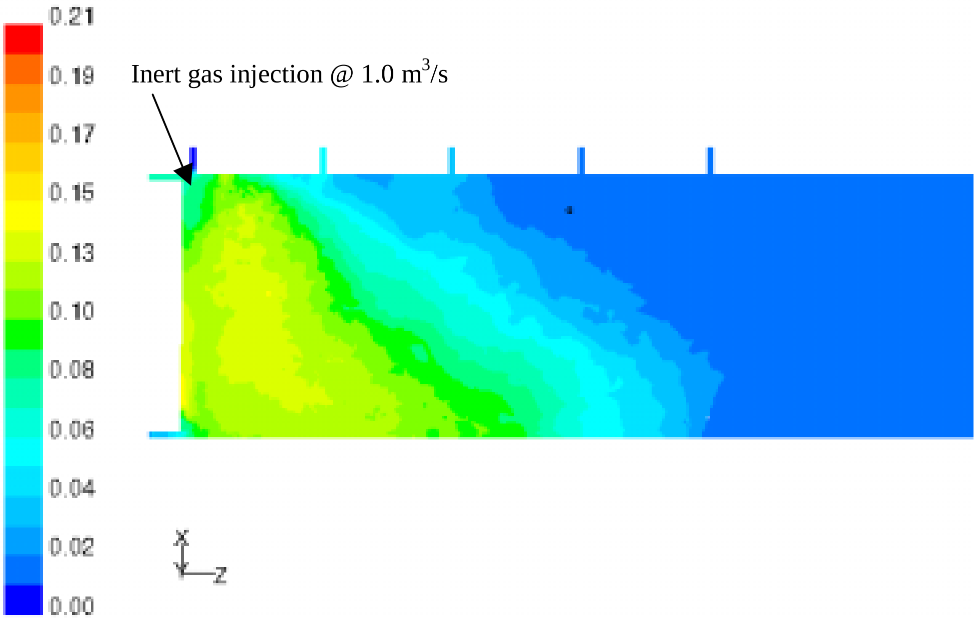

Figure 4.22 Oxygen distribution in the goaf – 1 day after sealing – inert gas @ 1.0 m^3/s

4.5 INERTISATION OPTIMISATION STUDIES

The objective of these studies was to develop an optimum inertisation strategy for the selected field site conditions, i.e. for Newlands Colliery site conditions. During face retreat operations, a “U” ventilation system was employed in the longwall panels with the maingate as intake and tailgate as return airway. At this mine site the panel orientation was such that maingate intake was at a higher elevation than the tailgate roadway. At Newlands Colliery, the panel layout consists of an additional chute roadway from mains to the panel finish line to simplify the chock withdrawal process.

At this mine site, longwall recovery operations start at the TG side of the face. Ventilation at that stage was from maingate to tailgate. However, after recovery of chocks up to the chute road, ventilation airflow was allowed to return through chute roadway and the TG was sealed off. During the face recovery operations airflow through the panel was about 10 m^3/s. The gas emissions in the panels were about 300 l/s (0.3 m^3/s). Detailed information on Newland Colliery and its longwall panels is presented in Chapter 5. Field site longwall panel geometry and all other site parameters were used in these CFD modelling optimisation studies. During these CFD optimisation studies, effects of various inertisation schemes on goaf gas distribution were investigated in detail. Based on the results of the various modelling studies, an optimum inertisation strategy was developed. Results of some of the typical inertisation procedures and optimum strategies are presented in this section.

(a) Before sealing off the panel (Steady state simulation)

Newlands Colliery longwall goaf gas conditions prior to sealing off the panel were simulated in these modelling studies under steady state conditions. The field site panel geometry and existing mining parameters were used in these simulations. Airflow through the panel was around 10 m^3/s and goaf gas emissions were around 0.3 m^3/s. The model simulated the goaf gas conditions in the panel halfway through the chock withdrawal process with MG, Chute road and TG roadways still open. Ventilation return was through the chute roadway. The results of the simulations in 3D and 2D views are presented in Figures 4.23 and 4.24 respectively. Although all the major goaf gases were simulated in the modelling studies, only oxygen gas distribution in the goaf is presented in all the simulation result figures for comparison purposes.

The 3D view in figure 4.23 shows two slices along the longwall panel. The vertical slice is 50 m from the tailgate rib and is superimposed on the horizontal slice midway through the seam. These results represent the base case goaf gas conditions for the field site. Figures 4.23 and 4.24 show that oxygen concentration was above 19% near the face finish line from the MG to the chute roadway. However, the high (> 12%) oxygen concentration zone was narrow near the maingate area. Oxygen concentration levels were above 12% over a wider area near the tailgate side of the goaf. Oxygen gas ingress distance on the tailgate side extended up to 150 m behind the face. Results also show that buoyancy pressures in the goaf had a major influence on gas distribution in the longwall goaf.

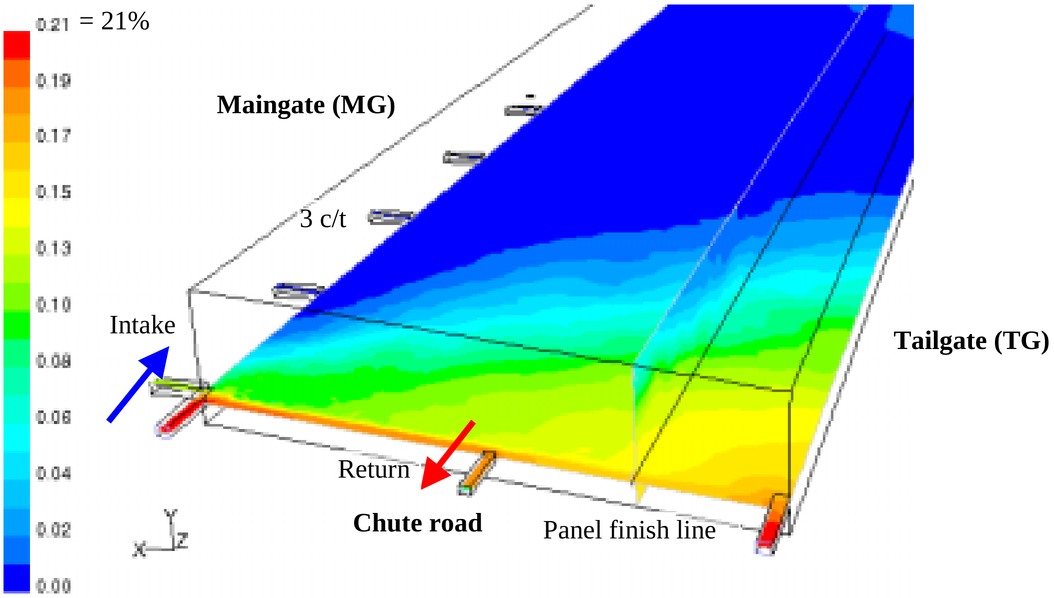

Figure 4.23 Oxygen distribution in the goaf – 3D view – Just after chock recovery
(Newlands longwall geometry and chock withdrawal & panel sealing sequence)

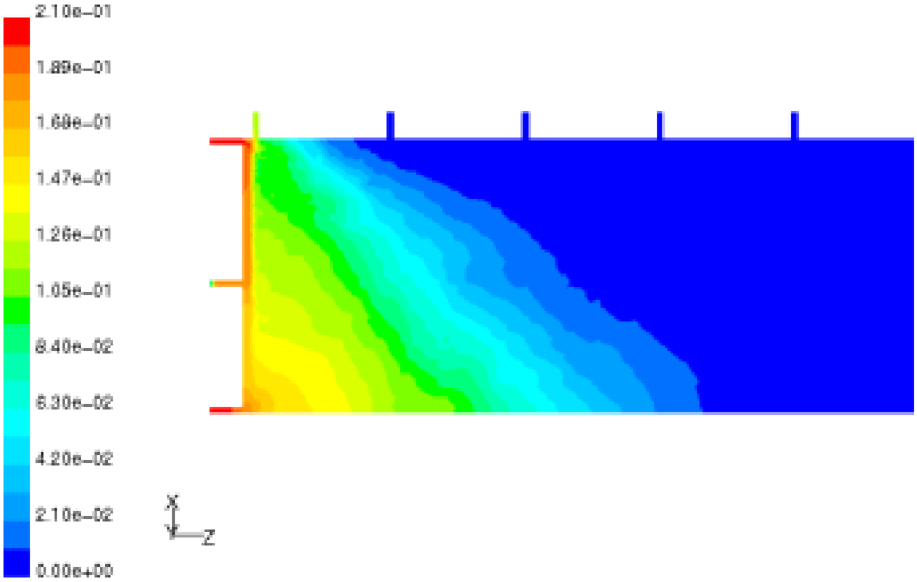

Figure 4.24 Oxygen distribution in the goaf – 2D view – Just after chock recovery

Transient simulations

(b) Inert gas through TG seal – after sealing all gateroads

The effect of inert gas injection through the TG seal was investigated in these modelling studies. Immediately after sealing the panel, inert gas was injected through the TG seal for 3 days at the rate of 0.5 m^3/s in these models. The modelling was carried out using transient simulation techniques to study goaf conditions immediately after panel sealing at fixed time intervals. Oxygen distribution in the goaf one day after and two days after panel sealing are presented in Figures 4.25 and 4.26 respectively.

Figure 4.25 shows that the oxygen level was above 14% near the finish line and above 10% over a wide area in the goaf even after one day of inert gas injection through the TG. Figure 4.26 shows that oxygen concentration was still above 12% near the finish line, particularly near the MG seal, even after two days of inert gas injection. These results show that although inert gas injection through the TG was effective in controlling the goaf atmosphere near the TG roadway, its effect on oxygen levels near maingate roadway was only marginal even after two days. Simulations indicate that the strategy of inert gas injection through the TG seal only would not be effective or optimum for sealed goaf inertisation under the site conditions.

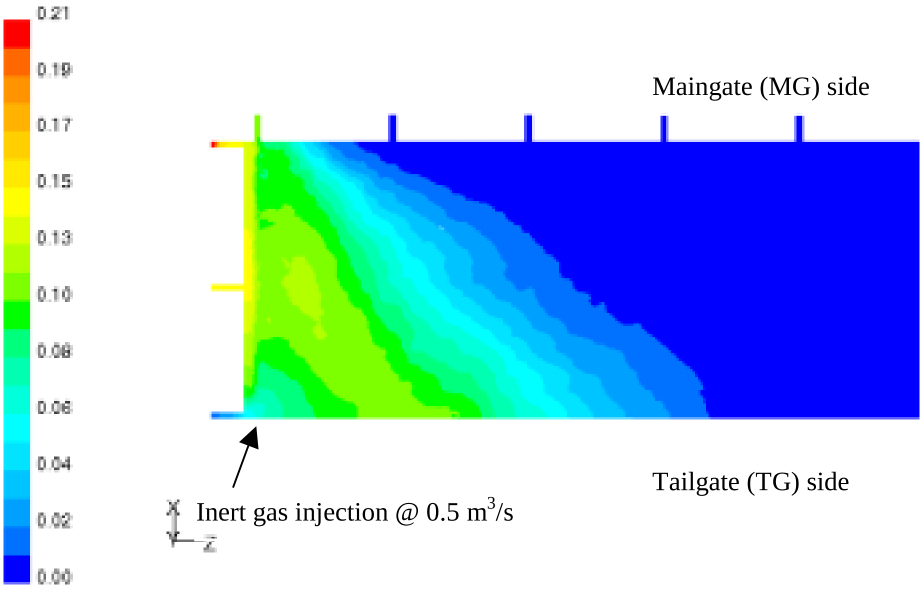

Figure 4.25 Oxygen distribution in the goaf – 1 day after sealing – Inert gas through TG seal

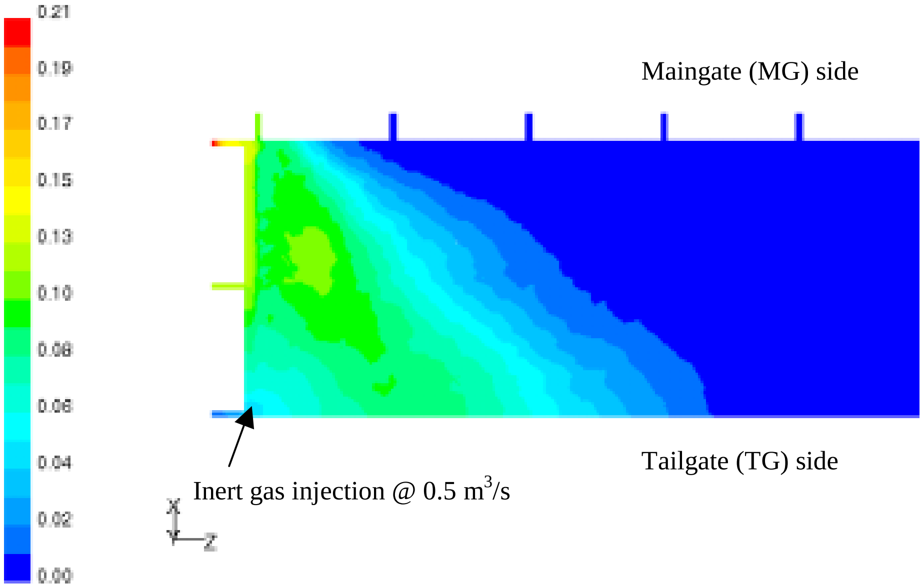

Figure 4.26 Oxygen distribution in the goaf – 2 days after sealing – Inert gas through TG seal

(c) Inert gas through the MG seal – with pre-injection through TG

Based on the results of above modelling, a new inertisation scheme was developed to tackle the high oxygen concentration problem near the maingate area. In this model, inert gas was injected through the TG for two days immediately after its sealing during the chock withdrawal process. Two days later the panel was completely sealed off with seals at the MG and chute roadways. After completion of the panel sealing, inert gas was injected through the MG seal for 3 more days. Oxygen distribution in the goaf one day after panel sealing is shown in Figure 4.27.

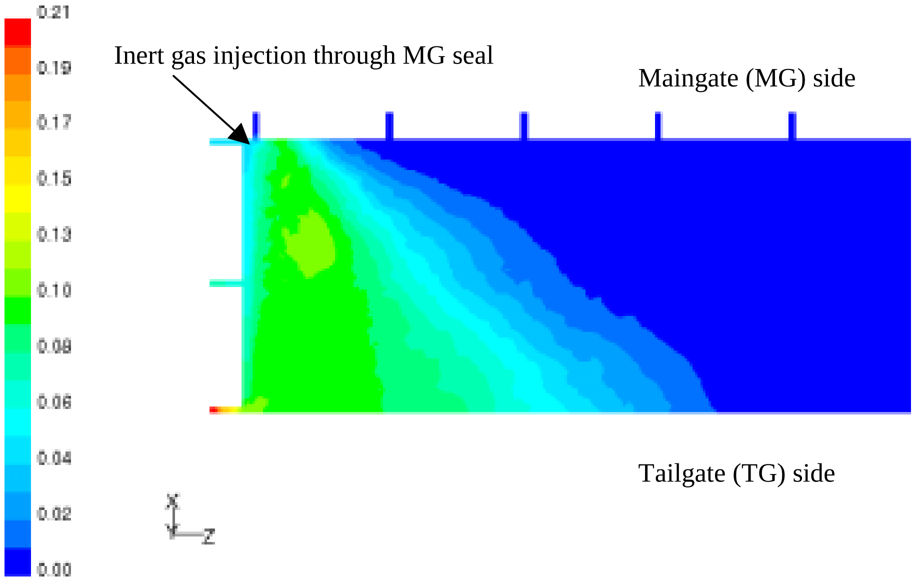

Figure 4.27 Oxygen distribution in the goaf – 1 day after sealing – Inert gas through MG seal (with inert gas injection from TG for 2 days before panel sealing)

Results show that injection of inert gas through MG seal resulted in reduction of oxygen levels down to 5% along the face finish line. However, oxygen concentration was still around 10 to 12% at 50 m behind the finish line on maingate side. The goaf atmosphere became inert after two to three days of inert gas injection through the MG seal. Results showed that although this inertisation scheme resulted in better goaf inertisation compared with the previous scheme, there is a need for alternative strategies to control high oxygen concentration levels near the maingate area.

(d) Inert gas through 3 c/t seal – no pre-injection through TG

To control the high oxygen concentration zones near the maingate area, inert gas was injected through 3 c/t for two days in this model, while the door on the chute road seal was still open. It is to be noted that at this mine site the TG was sealed off during the chock withdrawal process itself with the chute roadway acting as return airway. Oxygen distribution in the goaf after one day of inert gas injection is shown in Figure 4.28. Results show that oxygen concentration near the maingate and tailgate areas was around 10% and 14% respectively.

In the following simulations, the panel was completely sealed off with continuation of inert gas injection through 3 c/t seal. Oxygen distribution in the goaf one day after panel sealing is shown in Figure 4.29. Results show that oxygen concentration was around 10 to 12% near the tailgate area. Results indicate that this inertisation scheme was effective in reducing the oxygen levels near the maingate area. However, results also indicated a need for modification of the inertisation scheme, probably additional inert gas injection through the TG in view of the site conditions and sealing procedure adopted at the mine.

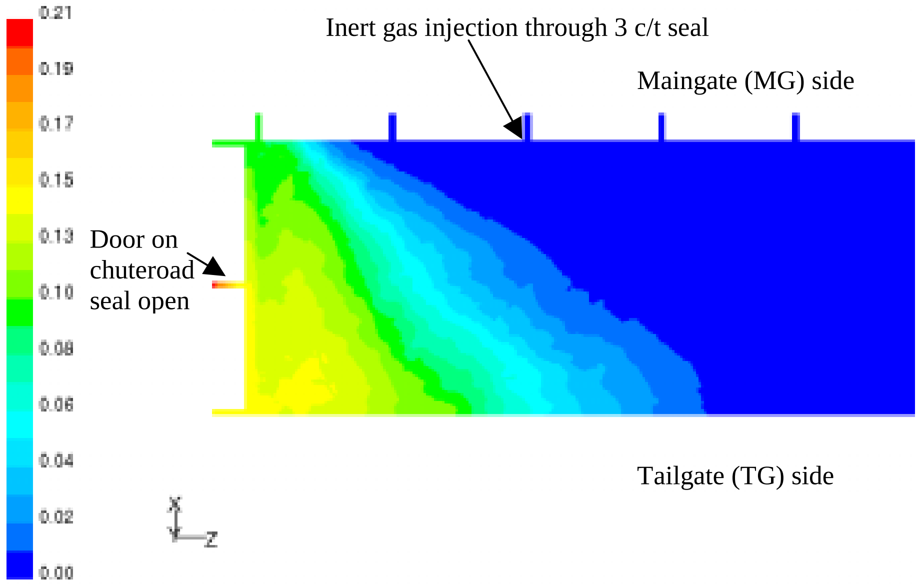

Figure 4.28 Oxygen distribution in the goaf – before panel sealing –after 24 hours of inert gas injection through 3 c/t seal (No inert gas injection through TG)

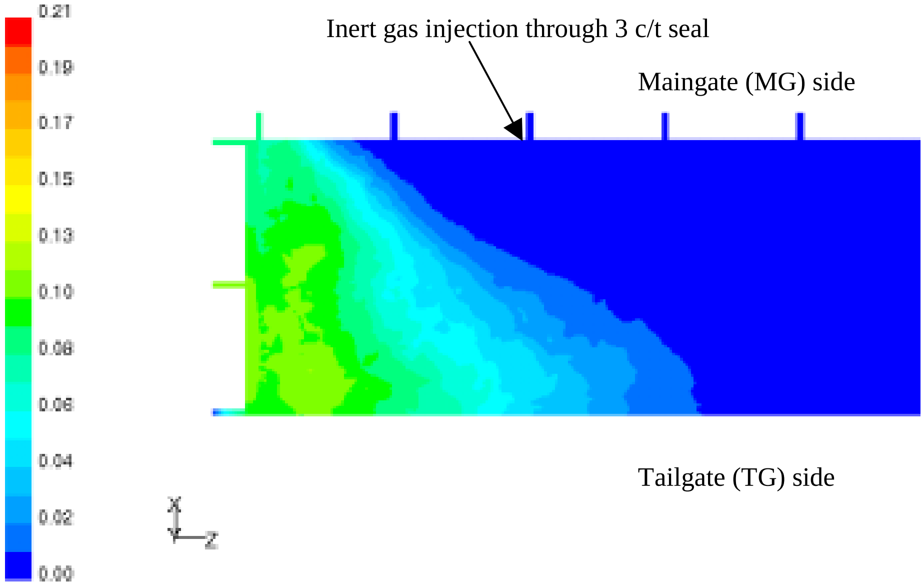

Figure 4.29 Oxygen distribution in the goaf – 1 day after panel sealing – continuation of inert gas injection through 3 c/t seal (No inert gas injection through TG)

(e) Inert gas through 3 c/t seal – with pre-injection through TG

In these modelling studies inert gas was injected through the TG for 2 days before sealing off the panel. After completion of panel sealing, inert gas was injected through 3 c/t seal on the maingate side. Oxygen distribution in the goaf after one day of inert gas injection through 3 c/t is shown in Figure 4.30. Results show that oxygen concentration near the face finish line was around 14%. Analysis of the simulation results shows that the high oxygen concentration zone was very narrow and close to the chute roadway seal.

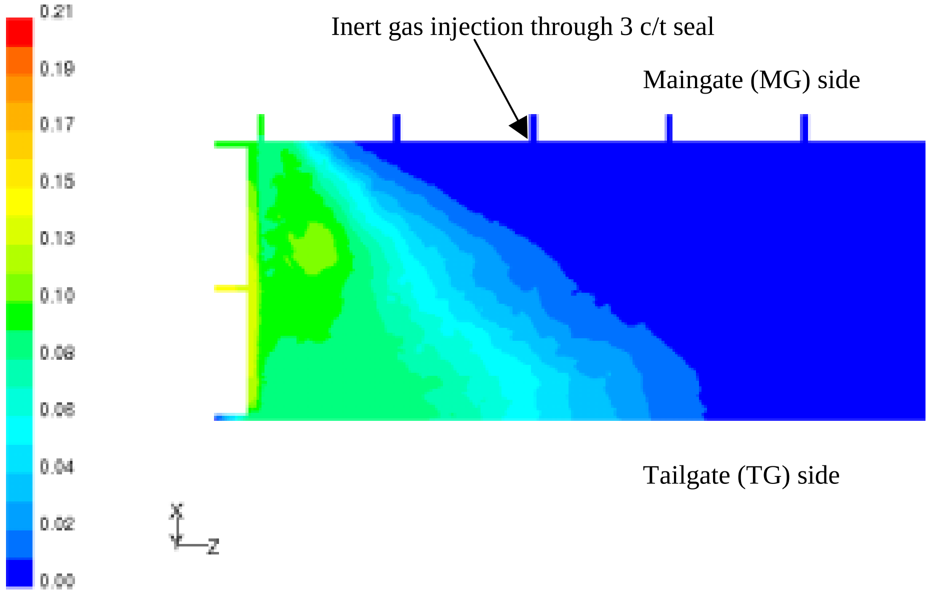

Figure 4.30 Oxygen distribution in the goaf – 1 day after sealing – inert gas injection through 3 c/t after panel seal off (with inert gas injection through TG for 2 days before sealing)

Simulation results presented in the above Figures 4.23 to 4.30 (sections (a) to (e)) showed the effects of various inertisation schemes on goaf gas distribution. Results showed that although none of the above schemes achieved complete goaf inertisation within one day of sealing, various inertisation schemes had considerable effects on certain zones in the goaf. Detailed analysis of the simulations indicated that a combination of the above inertisation schemes would achieve the objective of goaf inertisation within one day of sealing the panel.

(f) optimum inertisation strategy – for the field site conditions

Based on the results of above simulations, an optimum inertisation strategy was developed taking into consideration the positive effects of various inertisation schemes and the field site conditions. The optimum strategy developed basically involved the following three steps:

- (i) inert gas injection (@ 0.5 m^3/s) through TG for two days before panel sealing
- (ii) inert gas injection through 3 c/t for one day with door on chute road seal open
- (iii) panel sealing and continuation of inert gas injection through 3 c/t. Modelling simulated the goaf gas conditions for three more days after panel sealing.

This inertisation strategy was implemented in the transient CFD modelling simulations to study its effect on goaf gas distribution, particularly oxygen concentration levels in the goaf. Inert gas was injected at the rate of 0.5 m^3/s through the TG seal initially and then through 3 c/t seal on the maingate side, as outlined above. Results of the simulations at various stages of the inertisation process are presented in Figures 4.31 to 4.34.

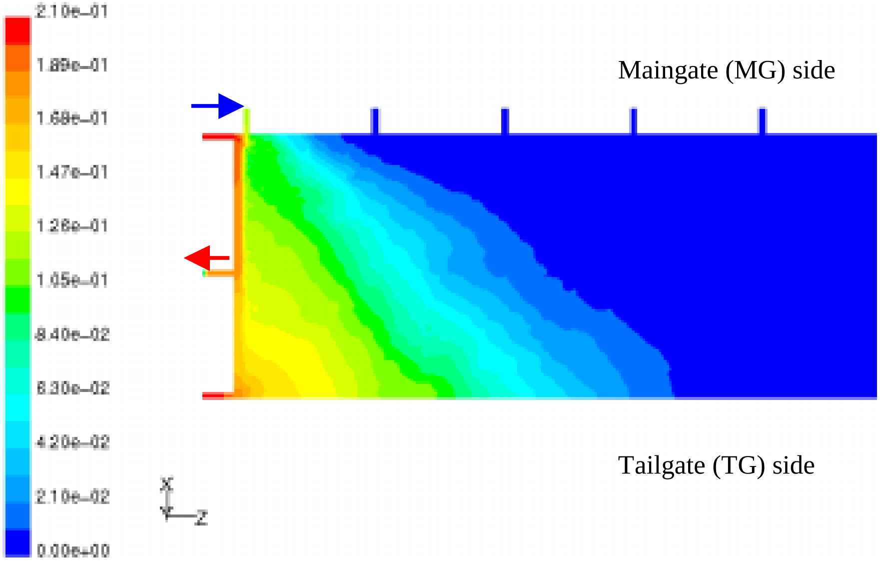

Figure 4.31 Newlands case - oxygen distribution in the longwall goaf – just after chock recovery

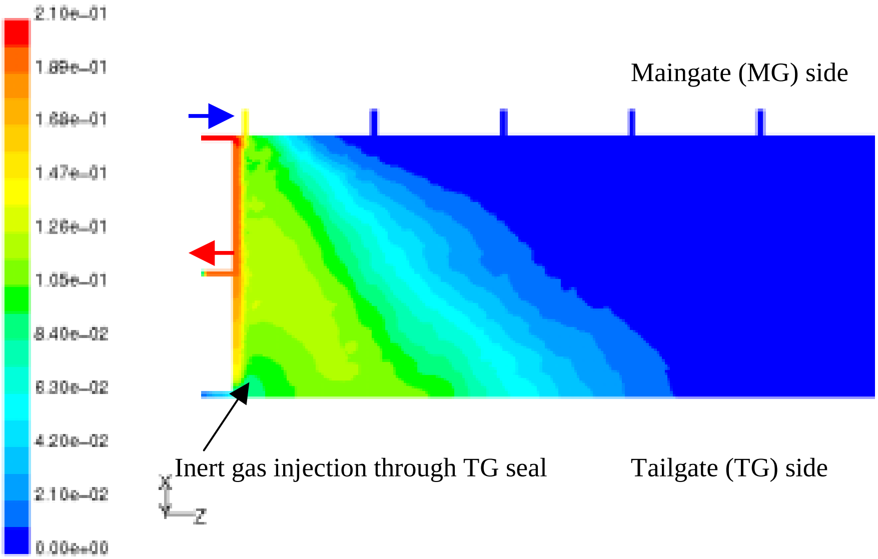

Figure 4.32 Newlands case - oxygen distribution in the goaf – after 24 hours of inert gas injection through TG

Figure 4.31 shows the oxygen distribution in the goaf during (halfway through) the chock withdrawal process. At that stage airflow was returning through the chute roadway at the rate of 10 m^3/s due to collapse of the face finish line between the chute road and TG after withdrawal of chocks in that section. Results show that oxygen concentration was above 19% near the face finish line from MG to chute roadway. Results also showed that the high oxygen concentration zone (> 12% O_2) was narrow near the maingate side and oxygen levels were above 12% over a wider area near the tailgate side of the goaf.

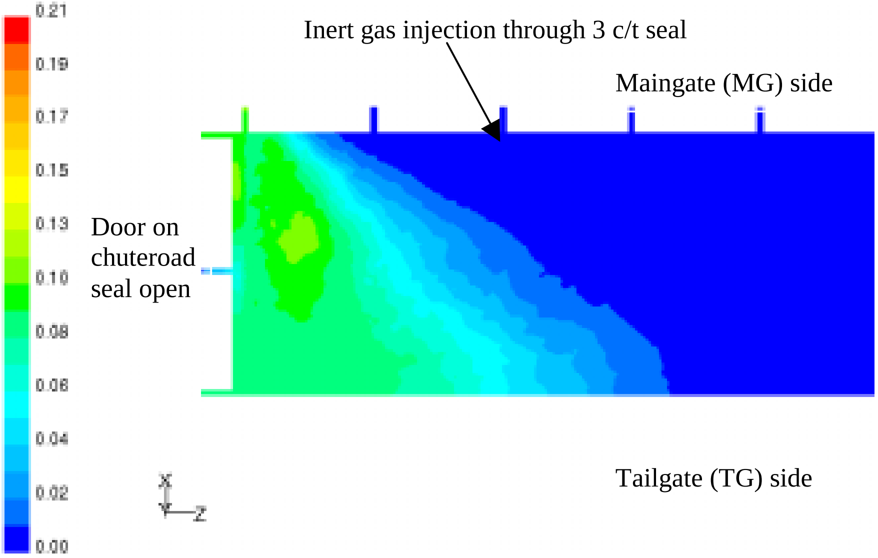

Figure 4.33 Newlands case - oxygen distribution in the goaf – inert gas injection through 3 c/t with door on chuteroad seal still open (1 day before sealing)

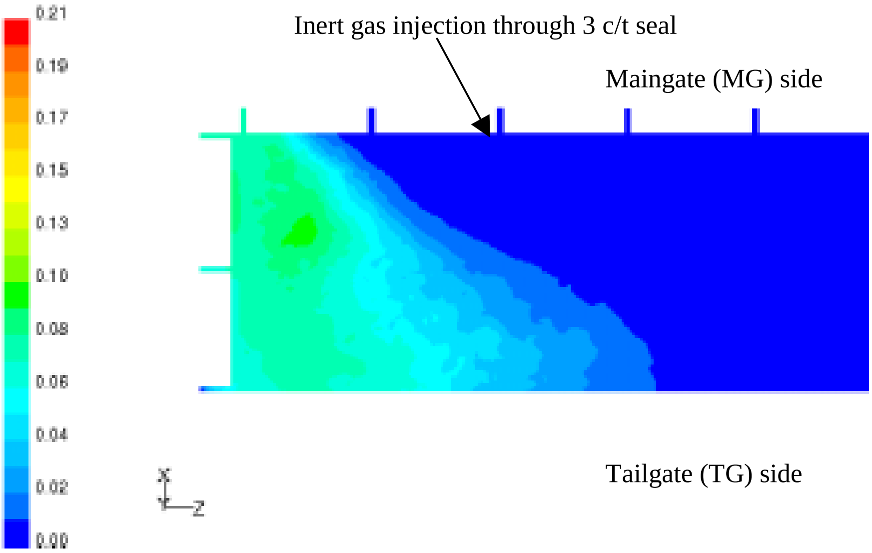

Figure 4.34 Newlands case - oxygen distribution in the goaf – 1 day after panel sealing

Oxygen distribution in the goaf after one day of inert gas injection through the TG is shown in Figure 4.32. Results showed that the oxygen concentration reduced to 10% near the tailgate area. However, results show that this inert gas injection through the TG did not have any significant effect on the 19% oxygen concentration area near the chute road. Results indicated that ventilation pressures still had a major influence on gas distribution near the chute road.

Results of the simulation after one day of inert gas injection through 3 c/t on maingate side are shown in Figure 4.33. Results show that oxygen levels in the goaf were below 12% at all locations. Oxygen distribution in the goaf one day after panel sealing is shown in Figure 4.34. Oxygen concentration levels were below 9% across the entire area of the goaf.

Analysis of the results showed that this optimum inertisation strategy had achieved the objective of goaf inertisation within a few hours of panel sealing. Results show that this inertisation strategy has effectively reduced the oxygen concentration at all locations in the goaf to below 12% levels even before panel sealing.

4.6 SUMMARY AND CONCLUSIONS

Computational fluid dynamics (CFD) modelling investigations were carried out to obtain a detailed understanding of the flow patterns and gas distribution in the longwall goafs to improve the design process of inertisation operations. Base case CFD models for longwall inertisation were developed using the information obtained from initial field studies on goaf geometry, gas emissions, ventilation system, caving characteristics and standard inertisation practices. Steady state modelling was carried out to simulate the goaf conditions before the sealing off period and transient modelling techniques were used to simulate the sealed goaf atmosphere at regular time intervals after panel sealing.

Base case simulation results showed that at airflow rates of 50 m^3/s, ventilation system and gas emission flow rates had a major influence on goaf gas distribution at working seam level when compared with the effects of methane buoyancy pressures. For example, the oxygen concentration level at 50 m behind the face was around 20% on the intake side and around 16% on the return side located at lower elevation. However, when the airflow rate was reduced to 10 m^3/s during panel sealing off periods, methane buoyancy pressure seems to play a major role on goaf gas distribution even at working seam level. In this case oxygen concentration levels and penetration distance were higher on the return side of the goaf.

The base case CFD models were calibrated and validated based on the information obtained from previous inertisation studies and gas monitoring. The validated models were then used for extensive parametric studies involving changes in inert gas injection locations, seam gradients, inert gas flow rates, inert gas composition and different inertisation strategies to investigate their effect on goaf inertisation.

Results showed that inert gas injection through various locations resulted in entirely different inertisation patterns in the goaf. Inert gas injection through the MG seal resulted in reduction of oxygen concentration only near the point of injection within the first 24 hours. Inert gas injection through 3 c/t resulted in oxygen concentration reductions over a wider area in the goaf. Results indicated that the strategy of inert gas injection through the MG seal was not as effective as the alternative strategy of injecting inert gas through 3 c/t seal under the modelled conditions. Simulations indicated that even during longwall retreat operations injection of inert gas at 50 m to 200 m behind the face on the intake reduces the spontaneous combustion risk in the goaf.

Computer simulations with different seam geometries showed that seam gradient plays a significant role in goaf gas distribution and needs to be considered during development of goaf inertisation strategies. Analysis of the simulation results also indicated that inert gas flow rate is also one of the most important design parameters to be optimised during development of an inertisation strategy. Modelling simulations indicated that a minimum inert gas flow rate of 0.5 to 1.0 m^3/s is required for inertisation during longwall sealing off operations. It is to be noted that inert gas flow rate requirement also depends on site specific conditions and other inertisation strategies. Various simulations with boiler gas and nitrogen showed that there was no major difference in effectiveness of these gases on goaf inertisation under the modelled conditions.

Analysis of the various simulation results also indicated that longwall panel geometry, goaf characteristics near the panel finish line, gateroad conditions in the goaf, goaf gas emission rates and composition, ventilation during panel sealing off period, chock withdrawal and panel sealing sequence would also have a significant influence on goaf gas distribution and inertisation.

CFD modelling simulations with field site geometry and conditions showed that the strategy of inert gas injection through the TG seal only would not be effective or optimum for goaf inertisation. Simulations with inert gas injection through the MG showed that although this inertisation scheme resulted in better goaf inertisation compared with the previous scheme, it did not achieve the objective of goaf inertisation within a few hours of panel sealing. Based on the results of various simulations, an optimum inertisation strategy was developed taking into consideration the positive effects of various inertisation schemes and the field site conditions. The optimum strategy developed basically involved the following three steps:

(i) inert gas injection through the TG for two days before panel sealing
(ii) inert gas injection through maingate 3 c/t for one day with the door on the chute road seal still open
(iii) panel sealing and continuation of inert gas injection through 3 c/t.

Analysis of the modelling results showed that the above optimum inertisation strategy had achieved goaf inertisation within a few hours of panel sealing. Results showed that the optimum strategy has effectively reduced the oxygen concentration at all locations in the goaf to below 12% levels even before panel sealing.

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CHAPTER 5

FIELD DEMONSTRATION STUDIES

5.1 INTRODUCTION

The field demonstration studies were carried out in longwall panel N4B of Newlands Colliery during panel sealing off operations. Newlands Colliery is one of the less gassy mines in Australia, with goaf gas emissions in the range of 100 l/s to 500 l/s. It is to be noted that effective inertisation of a sealed goaf may take a longer time in less gassy mines. Therefore, Newlands Colliery presented one of the difficult conditions for goaf inertisation, which was ideal for field demonstration studies.

Based on the results and analysis of the review studies, laboratory tests and modelling investigations presented in chapters 2, 3 and 4, an optimum inertisation strategy had been developed to achieve the project objective of reducing oxygen concentration in the goaf to below 8% within a few hours of sealing the panel. The new strategy developed during the course of the project has been implemented in the field demonstration studies. Tracer gas studies were also carried out to map the inert gas dispersion patterns in the goaf. During these field studies surface boreholes were drilled into the goaf and an extensive gas monitoring system, with sampling from 12 locations in the goaf, was implemented to study the changes in goaf gas distribution over a wide area during inertisation.

The mine background, details of field studies, monitoring system, inertisation strategy and results of the field studies are presented in this chapter. Results of the tracer gas studies and gas flow patterns in the goaf are also discussed in this chapter.

5.2 MINE BACKGROUND

The Newlands Colliery is located in the northern Bowen Basin near Glenden township, which is about 180 km west of Mackay city in Queensland. The mine operates a single longwall face employing 2 leg high reach 1000 T capacity chocks and produced about 5.5 Mt in 2000. The mine extracts the upper Newlands seam, which averages 6 m in thickness in that region. The longwall mining height is about 4.8 m. The width of the longwall panels was about 250 m and the length ranged from 1,600 m to 2,500 m. The depth of the longwall panels ranges from 80 m to 250 m in the current mining block.

The gas content of the coal seams ranges from 4 m^3/t to 10 m^3/t and consists mostly of CH_4 gas. The mine employed a long hole pre-drainage system and was able to extract a higher proportion of the in-situ gas before longwall extraction due to high permeability of the coal seams in that region, which ranges from 10 to 30 millidarcy (md). Therefore, goaf gas emissions in the longwall were relatively lower, ranging from 100 l/s to 500 l/s. The mine did not employ any post-drainage system in the longwall panels. All the pre-drainage holes were connected to a surface borehole and pre-drainage gas blows out to the atmosphere with positive pressure. No gas drainage plants were installed at the mine. Seam gas pressure and high gas desorption rate seemed to be high enough for free venting of the pre-drainage gas.

The mine layout was primarily a 6-roadway system for mains and a 2-entry gateroad system for longwall panel development, as shown in Figure 5.1. The mine has a history of spontaneous heatings in the pillars and a high rate of CO production in the longwall goafs. The orientation of the north-side longwall panels was such that outbye tailgate corner was the point of lowest elevation in the panel.

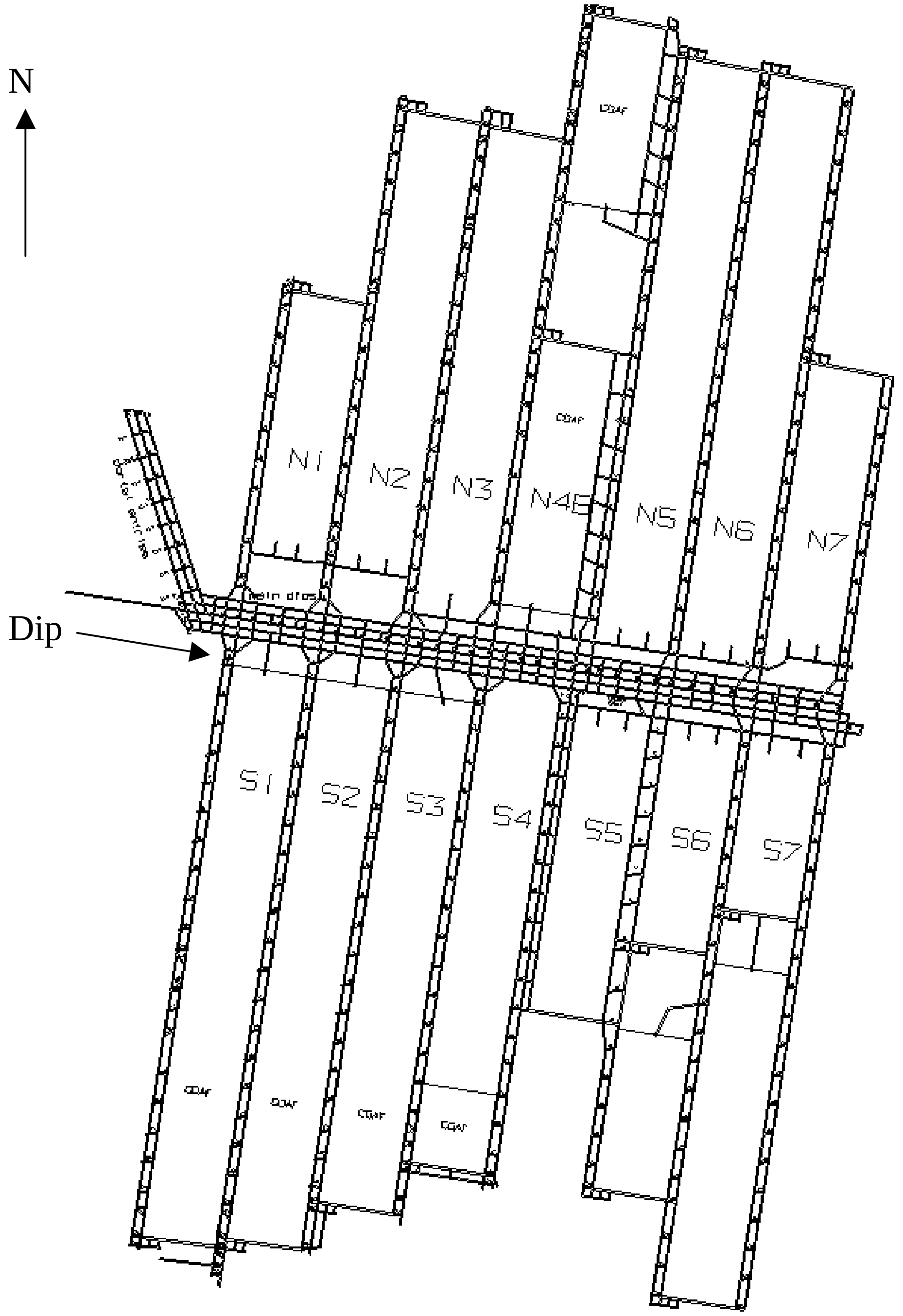

Figure 5.1 Mine layout at the field site, Newlands Colliery.

The mines primary ventilation circuit comprises two intake drifts from the highwall and a single exhaust/return airshaft. Two surface exhaust fans are used to supply about 240 m^3/s of airflow at 1.2 kPa pressure. During longwall panel extraction, approximately 50 m^3/s of airflow was supplied to the face through maingate and during face recovery operations, the airflow in the panel was gradually reduced to 10 m^3/s. As the longwall face retreats, seals were constructed in the maingate cut-throughs to isolate the goaf from the adjacent panel. A 20 point tube bundle monitoring system was installed at the mine for continuous environmental monitoring in the longwall panels.

The longwall panel extraction at this mine started with panel S4 on south side and continued towards S3, S2 and S1 panels. Similarly panel extraction on the north side started with N4 panel extraction. In view of this panel extraction, the bottom gateroad in the panels, which was located adjacent to the old goafs, was used as tailgate return airway. Top gateroads in the panel, which were located adjacent to the virgin blocks, were used as maingate intake airways.

In view of the perceived spontaneous combustion risk in the goafs and low goaf gas emissions, the mine employs inertisation during sealing-off of every longwall panel. The mine purchased a Tomlinson Boiler inert gas generator and maintains it on the surface for these routine inertisations and/or for any emergency purposes. The coal seam extraction thickness at this mine was about 4.8 m. It is to be noted that this high extraction thickness results in greater caving zone heights and more goaf volume. In order to estimate the inertisation time, the mine initially estimates the goaf void volume near the finish line and then calculates the volume of inert gas required to reduce the oxygen content below 8%. These calculations estimated the inertisation time in the range of 48 hours after panel sealing.

The original inertisation scheme was to introduce inert gas through the MG or TG seals immediately after sealing the panel. Improvements in the scheme included injection of inert gas from the TG for 2 to 3 days before panel sealing, with airflow short-circuited between the maingate and chute roadway. Over the years, Newlands has made significant improvement in the inertisation schemes and was able to reduce the goaf inertisation time down to 2 days, a good result compared with other mines. However, there was a need to optimise the inertisation operations to ensure complete inertisation of the goaf and to further reduce the inertisation period.

The aim of these inertisation studies was to further reduce this goaf inertisation time from 2 days to a few hours using optimum inertisation strategies. The details of the N4B longwall panel, monitoring plan and inertisation strategy are presented in the following section.

5.3 FIELD STUDIES - DETAILS

Field demonstration studies of the optimum inertisation strategy were conducted in N4B longwall panel of the Newlands Colliery. This panel was the first panel in the sequence of longwall extraction on the north side. The layout of the N4B panel and the ventilation system are presented in Figure 5.2. The orientation of the panel was such that the outbye tailgate corner was the point of lowest elevation in the panel. In this panel a “U” ventilation system was employed with the top maingate as intake and the bottom tailgate as return roadway. Goaf gas emission flow rate in the panel was about 300 l/s (0.3 m^3/s).

Approximately 50 m^3/s of airflow was supplied to the panel during panel extraction and the airflow was reduced to about 10 m^3/s during the face recovery operations. A chute-roadway was driven near the finish-line of the panel to simplify the chock withdrawal process. During face recovery operations this chute roadway was used as a return roadway after collapse of the face line near the TG. It is also to be noted that the face finish line was at 2 cut-through (c/t) in this panel.

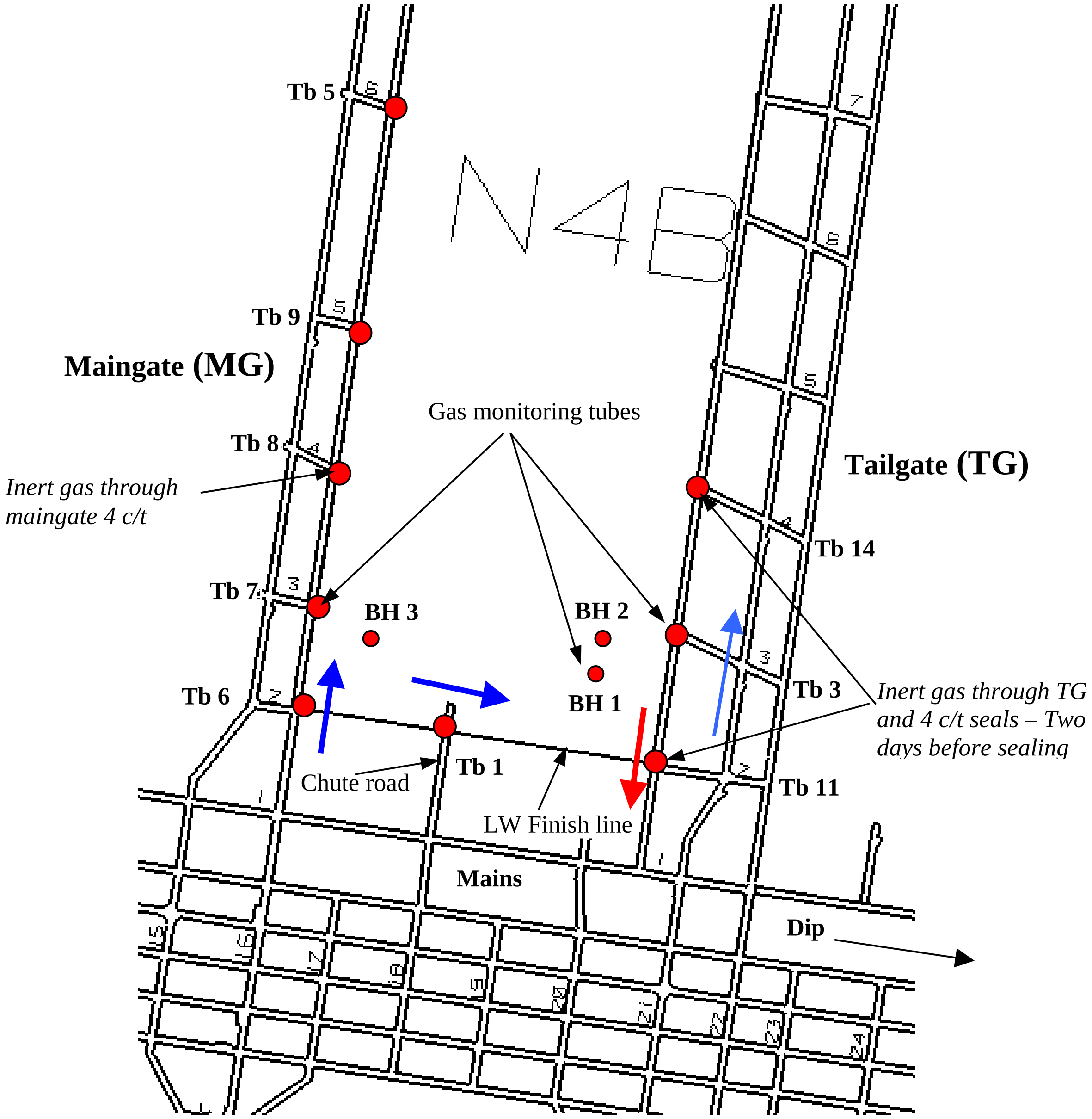

Figure 5.2 Longwall panel layout and location of gas monitoring tubes

As this panel was the first on the sequence of extraction on the north side, it provided a good opportunity for gas distribution monitoring on both sides of the goaf. Therefore, an extensive continuous gas monitoring system with 9 sampling tubes located on both sides of the goaf was implemented during the field demonstration studies. Newland's tube bundle monitoring system was used for these gas monitoring studies. Three surface boreholes were also drilled into the goaf near the finish line for additional goaf gas monitoring. SIMTARS mobile gas laboratory was utilised for gas monitoring from these surface goaf holes. Ten tube bundle points coupled with three surface boreholes covered a wide area of the goaf near the finish line. The location of sampling tubes and boreholes is shown in Figure 5.2.

The face recovery and panel sealing sequence employed in N4B panel was as follows:

(i) Chock recovery started from the TG side of the face. Ventilation at that stage was from maingate to tailgate.
(ii) After recovery of 50% of the chocks, the airflow was allowed to return through the chute roadway at the centre, as the take-off roadway collapsed near the tailgate area.
(iii) TG seal construction.
(iv) After completion of chock recovery, seals were constructed at the MG and chute roadways with small doors at the centre.
(v) Panel sealing by closing off the doors and completing the seals in that section.

For longwall goaf inertisation, a Tomlinson inert gas generator was set up on the surface and two 150 mm diameter boreholes were drilled from surface into the coal seam near the main entries for delivery of inert gas from the surface into the underground longwall goaf. Inert gas was injected into the longwall goaf at the rate of 0.5 m^3/s. The optimum inertisation strategy developed during the course of the project was implemented in N4B longwall panel during the field demonstration studies. This optimum inertisation strategy for Newlands Colliery involved the following stages:

(i) Inert gas injection through TG and tailgate 4 c/t seals for two days before panel sealing. (Inert gas was initially injected through the TG seal for one day to confirm its effects on goaf inertisation. The MG and chute road seals were being constructed during that inertisation process).
(ii) Inert gas injection through 4 c/t on the maingate side (@ 0.5 m^3/s) for one day with the door on the chute road seal still open. (4 c/t was located at 170 m behind the face finish line).
(iii) Panel sealing and continuation of inert gas injection through maingate 4 c/t until oxygen levels in the goaf reduced below 8%.

To assist in correct interpretation of the results presented in various figures, the timings of inertisation operations are presented below:

(i) Inert gas injection through the TG seal - started on 1-7-01 at 15:00 hours.
(ii) Inert gas injection through tailgate 4 c/t seal – started on 2-7-01 at 15:30 hours.
(iii) Inert gas injection through maingate 4 c/t seal – started on 3-7-01 at 08:30 hours.
(iv) Panel sealed – on 4-7-01 at 10:20 hours.

Goaf gas conditions were monitored continuously at 30 minute intervals during the field demonstration studies to study the changes in goaf gas distribution during the inertisation process. Tracer gas studies were also carried out during the inertisation field studies to map and confirm the inert gas dispersion patterns in the longwall goaf. Details and results of these tracer gas studies are presented in section 5.5. The effect of the optimum inertisation strategy on N4B panel goaf inertisation and other results of the field demonstration studies are presented in the following section.

5.4 INERTISATION - FIELD STUDIES – RESULTS AND ANALYSIS

(a) Gas concentration levels near the seals

Gas concentration changes at various sampling points around the longwall goaf are presented in Figures 5.3 to 5.11. Gas monitoring results from tube 11 (Figure 5.3) shows that gas composition behind the TG seal changed to inert gas composition immediately after introduction of boiler gas through this seal. Inert gas injection into this seal started at 15:00 hours on 1-7-01 and continued for one day. Gas monitoring results of tube 14 (Figure 5.4) shows that there was no major change in gas composition at 4 c/t location (on tailgate side) during inert gas injection through the TG seal.

Oxygen gas concentration reduction rate at 4 c/t location was very slow, with oxygen level reduced from 16% to only 15% in one day. At that stage, inert gas was injected from the tailgate 4 c/t seal also and gas readings behind the seal from that time onwards just showed the boiler gas composition. Inert gas injection into tailgate 4 c/t seal started at 15:30 hours on 2-7-01. Analysis of these results also confirmed that introduction of inert gas at 100 to 200 m behind the finish line results in better goaf inertisation compared with inert gas introduction through the TG or MG seals. Gas composition results obtained from tube 3 at tailgate 3 c/t seal showed that oxygen levels at this location also reduced rapidly to 3% within a few hours of inert gas introduction through 4 c/t seal.

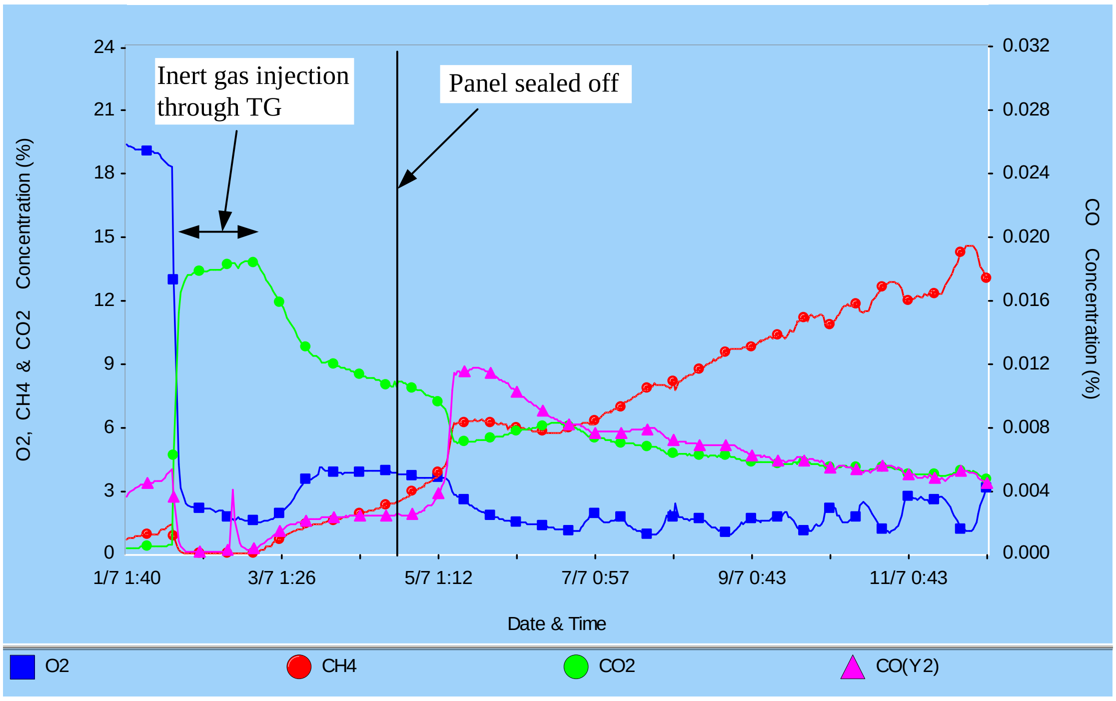

Figure 5.3 Gas concentration profiles at TG seal (Tube 11)

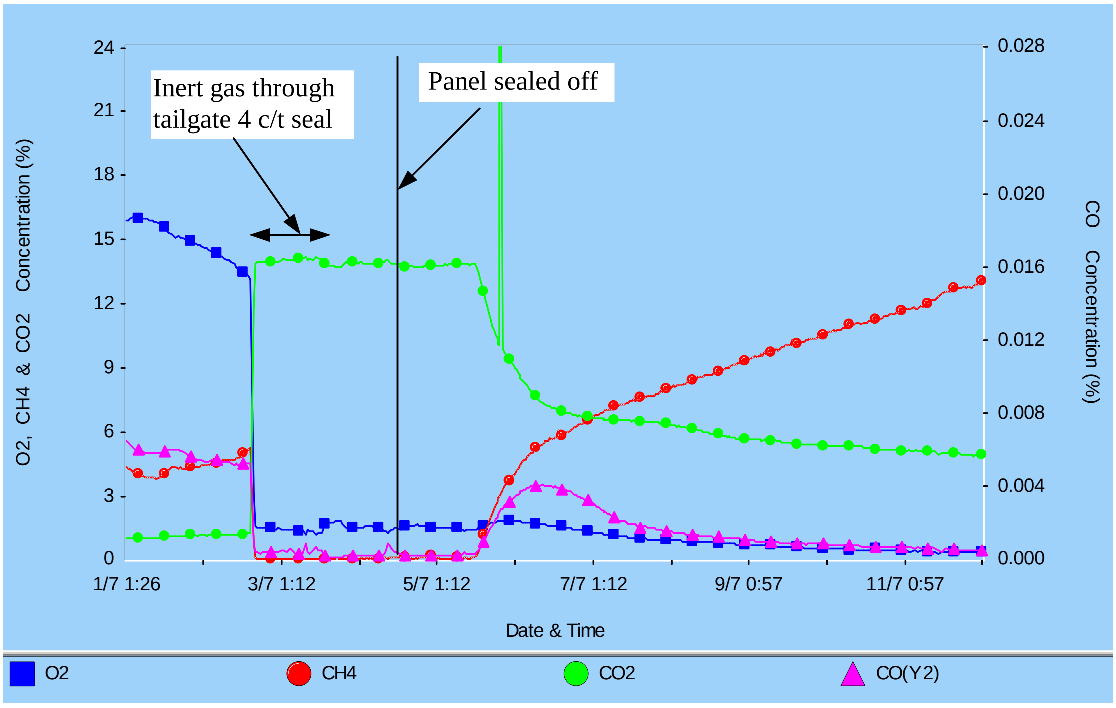

Figure 5.4 Gas concentration profiles at tailgate 4 c/t seal (Tube 14)

After two days of inert gas injection through the tailgate 4 c/t and TG seals, inert gas was injected through the 4 c/t seal on the maingate side with the door on the chute road seal still open. Inert gas injection into the maingate 4 c/t seal started at 08:00 hours on 3-7-01. Results from tube 8 are shown in Figure 5.5. This figure shows the gas composition changes behind the 4 c/t seal on maingate side. Results show that oxygen level at this location was above 12% before introduction of inert gas and confirms the need for introduction of inert gas through this seal rather than from the MG seal. Gas composition at this location changed to inert gas composition immediately after introduction of boiler gas through the seal.

Gas composition at the adjacent 3 c/t seal, as recorded by tube 7, before and after panel sealing for a 10 day period are shown in Figure 5.6. Gas concentration changes near the seal just during panel sealing off and inertisation period for 2 days are shown in an enlarged view in Figure 5.7. Results show a rapid reduction in oxygen gas concentration at the 3 c/t seal after introduction of inert gas through the inbye 4 c/t seal. Oxygen concentration level reduced to 8% within a few hours of inert gas introduction on inbye side of the goaf. The oxygen concentration at this location continued to reduce at a rapid rate and reached 2% by the time of panel sealing on 4-7-01. It is to be noted that when inert gas was injected through the MG seal in one of the review case studies, there was no significant change at this location even after one day of inert gas injection. Results at this location also confirm the effectiveness of the strategy of inert gas introduction through 4 c/t seal on the maingate side of the goaf.

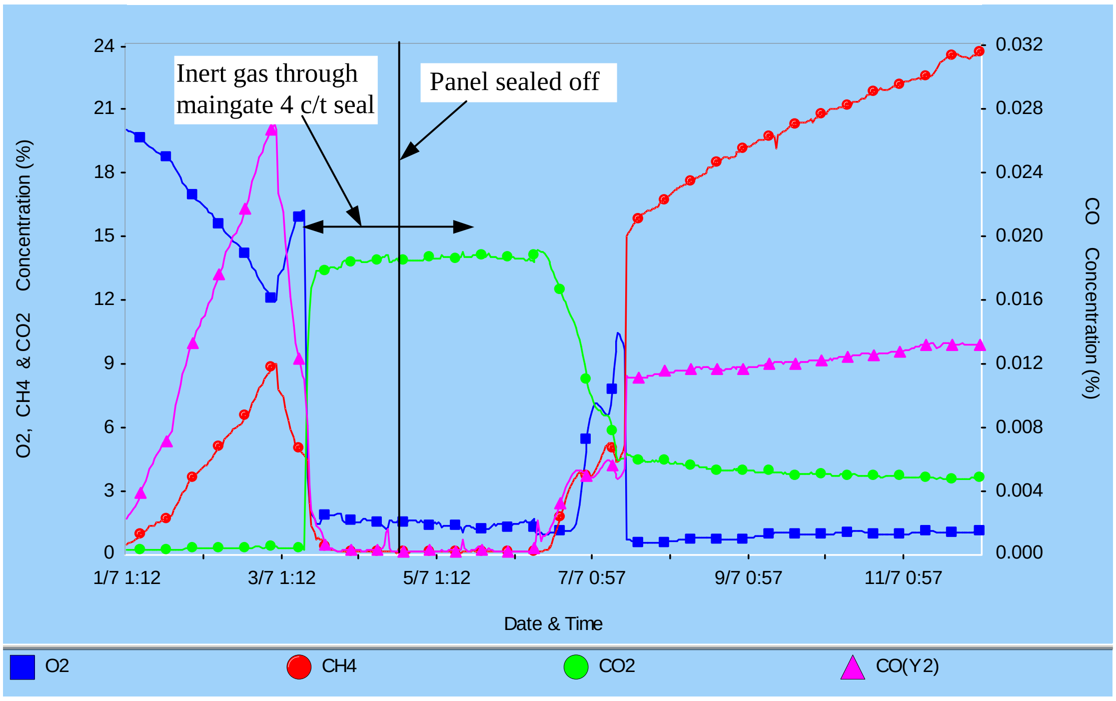

Figure 5.5 Gas Concentration profiles at maingate 4 c/t seal (Tube 8)

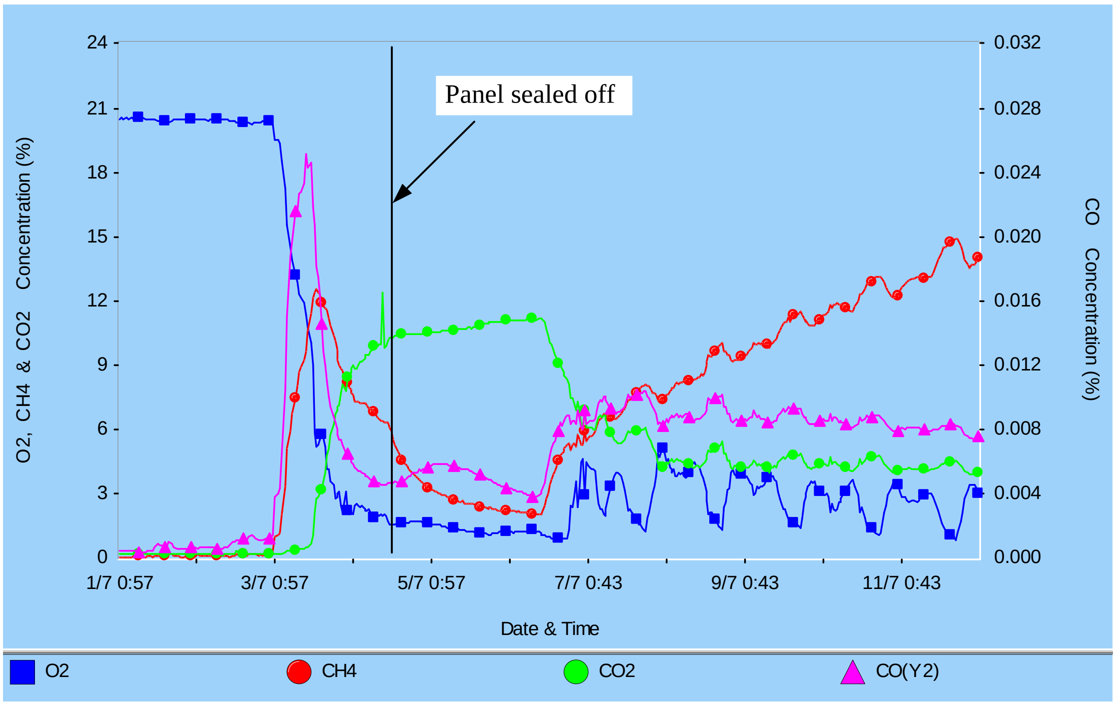

Figure 5.6 Gas Concentration profiles at maingate 3 c/t seal (Tube 7)

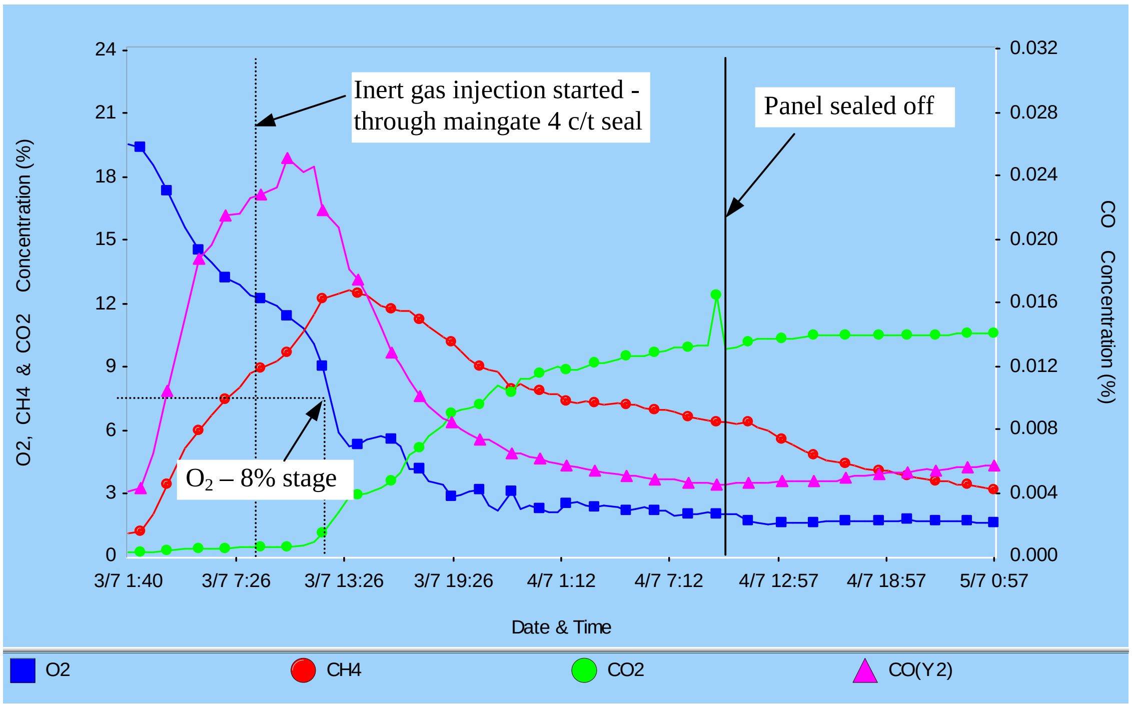

Figure 5.7 Gas Concentration profiles at maingate 3 c/t seal – during LW seal off and inertisation

Goaf gas composition results obtained from tubes 6 and 1 are shown in Figures 5.8 and 5.9. These results show the changes in gas concentration levels at MG seal and chute road seals respectively over a 10 day period. It is to be noted that inert gas was not injected through any of these seals. The sudden change in gas levels recorded by tube 6 on 3/7 was due to shifting of the tube from intake roadway to goaf side of the MG seal. Gas concentration changes near the chute road seal over a 2 day period just during panel sealing off and inertisation period are shown in Figure 5.10. Results show that the oxygen concentration level at both these locations also reduced rapidly to below 8% levels within a few hours of inert gas introduction. By the time the panel was sealed off at 10:20 hours on 4-7-01, the oxygen concentration level at both the MG and chute road seals was below 5%. In other words, the goaf was completely inert by the time panel was sealed off.

These results show that the optimum inertisation strategy implemented at the field site was highly successful in converting goaf environment into an inert atmosphere within a few hours of panel sealing. Figures also show that oxygen levels in the goaf did not rise after stopping the inert gas injection, confirming the success of goaf inertisation.

Gas concentration levels recorded by tube 9 at one of the inbye locations at 5 c/t seal are shown in Figure 5.11. Results show that oxygen levels were below 8% even before the start of the inertisation operations. Analysis and comparison of the goaf gas composition during face retreat and recovery operations shows that moderate goaf gas emission rates in the panel and seam geometry contributed to this positive result of oxygen levels below 8% during sealing off operations.

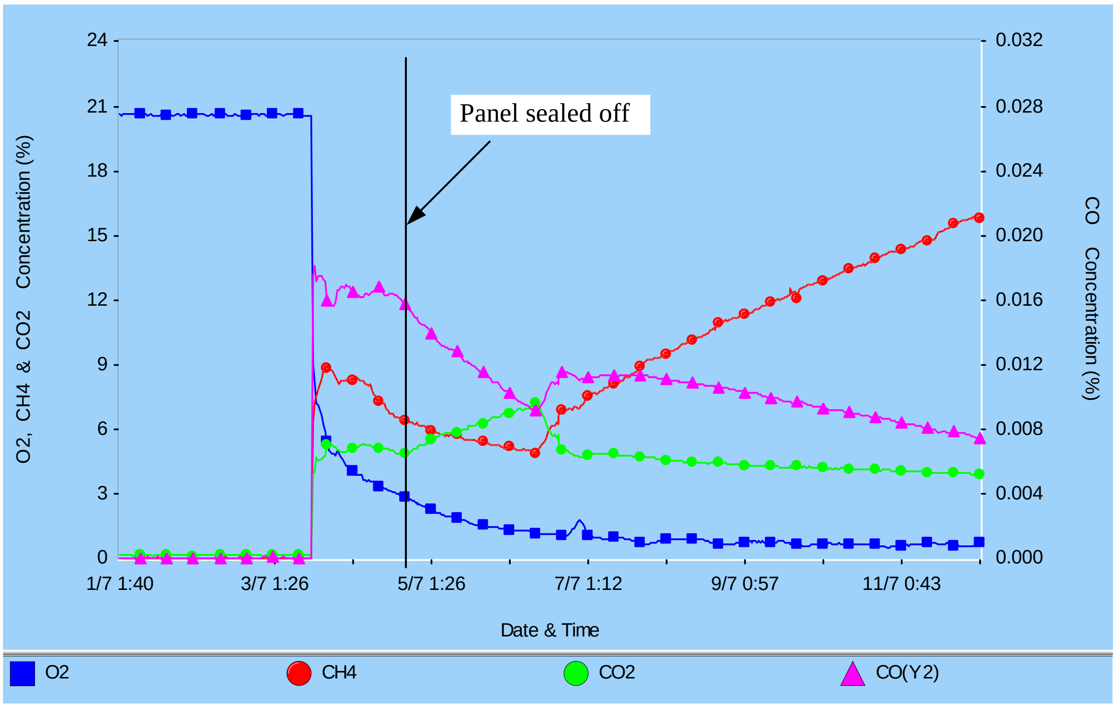

Figure 5.8 Gas concentration profile at MG seal (Tube 6)

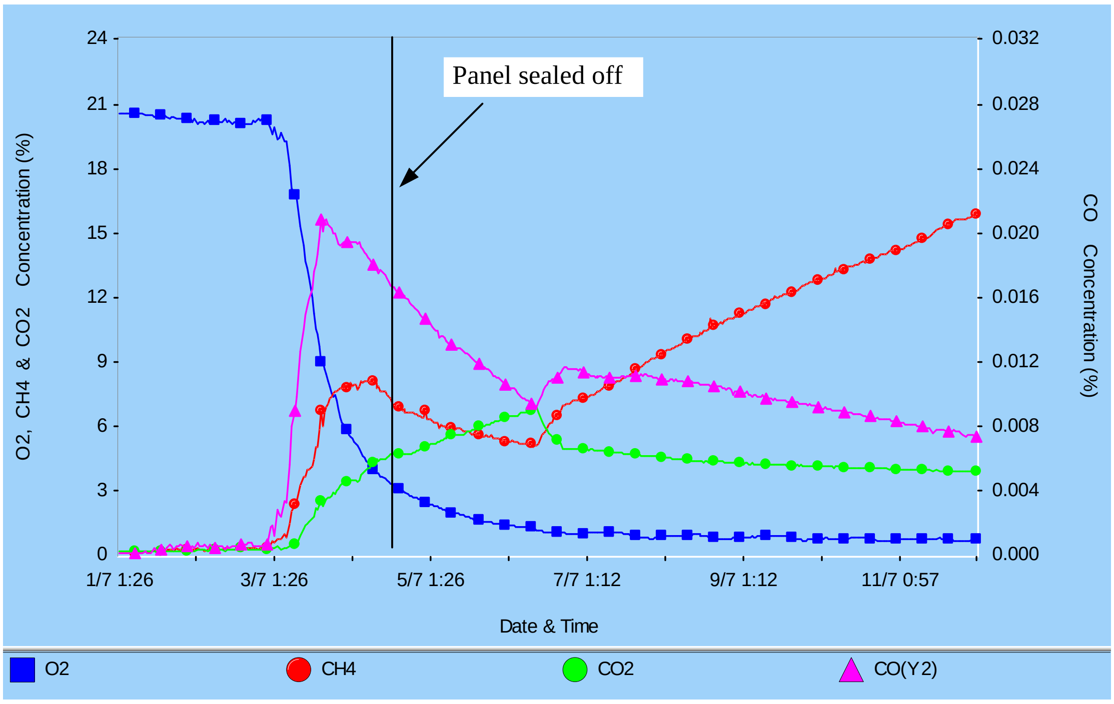

Figure 5.9 Gas concentration profiles at Chute road seal (Tube 1)

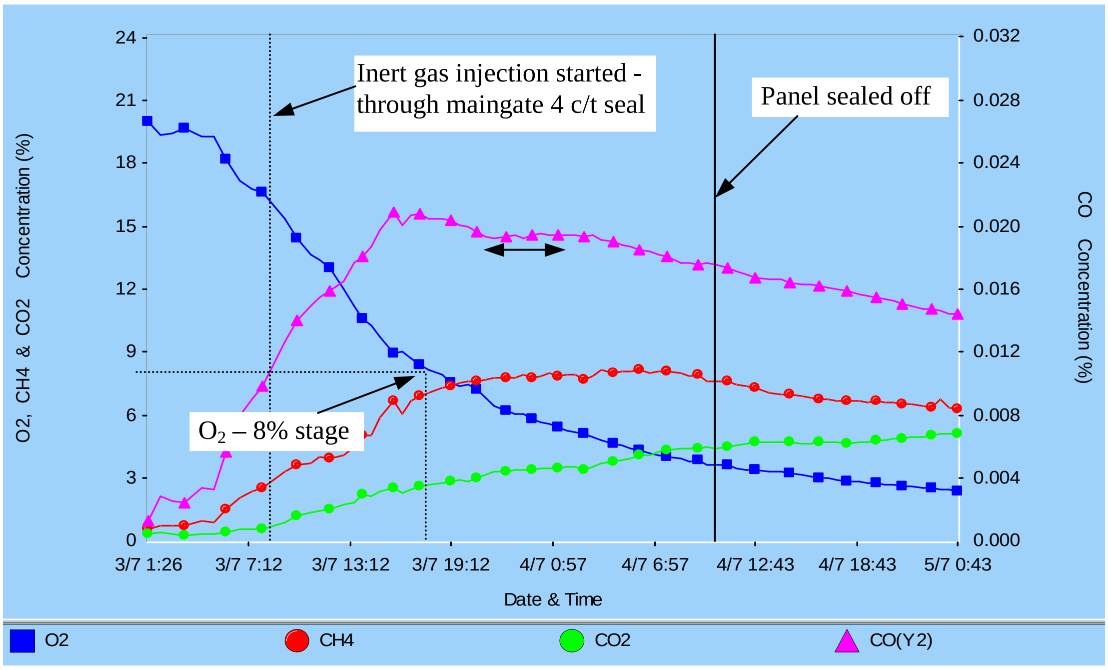

Figure 5.10 Gas Concentration profiles at Chute road seal – during LW seal off and inertisation

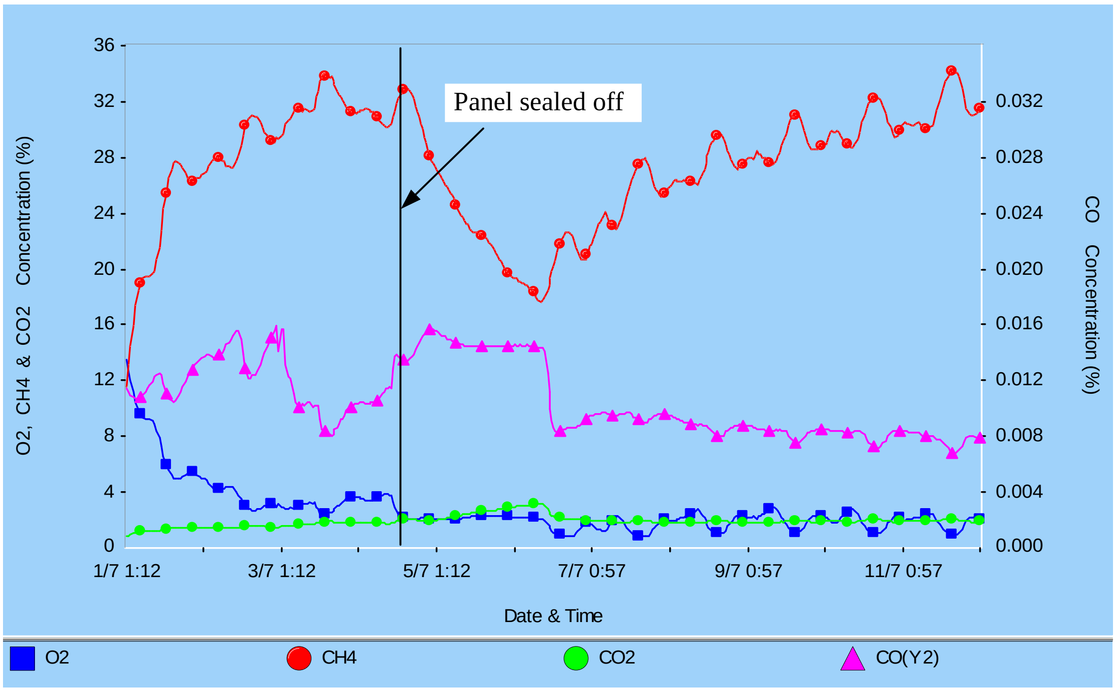

Figure 5.11 Gas concentration profiles at maingate 5 c/t seal (Tube 9)

(b) Gas concentration levels in surface boreholes

Three boreholes were drilled from the surface to the longwall goaf, to a level 20 to 60 m above the working section, to investigate the effect of goaf inertisation on gas distribution inside the collapsed goaf. The location of the surface goaf holes is shown in Figure 5.2, as BH1, BH2 and BH3. These holes were drilled at a distance of about 40 m from the gateroads and were located at about 60 to 80 m from the finish line. These three holes were also used as additional gas monitoring points for tracer gas studies. The SIMTARS mobile gas laboratory was positioned on the surface near these boreholes for continuous monitoring of gas conditions inside the longwall goaf, particularly at higher elevations.

Gas concentration levels detected at these locations prior to longwall sealing and the changes in gas levels during panel sealing-off and inertisation operations are presented in Figures 5.12 to 5.14. During chock recovery operations and just prior to panel seal-off, higher oxygen gas concentration levels were detected at the tailgate side boreholes (BH1 and BH2), although panel intake was from maingate side. These gas measurements confirm the results of CFD simulations presented in Figure 4.4 of chapter 4. Gas readings showed that methane gas concentration near the maingate side at higher elevations was around 95%, compared with 30 to 40% levels recorded at the working section level near the inbye seals. During longwall sealing off and inertisation periods, oxygen levels at these boreholes reduced down to 2% and confirmed the effectiveness of the optimum goaf inertisation strategy.

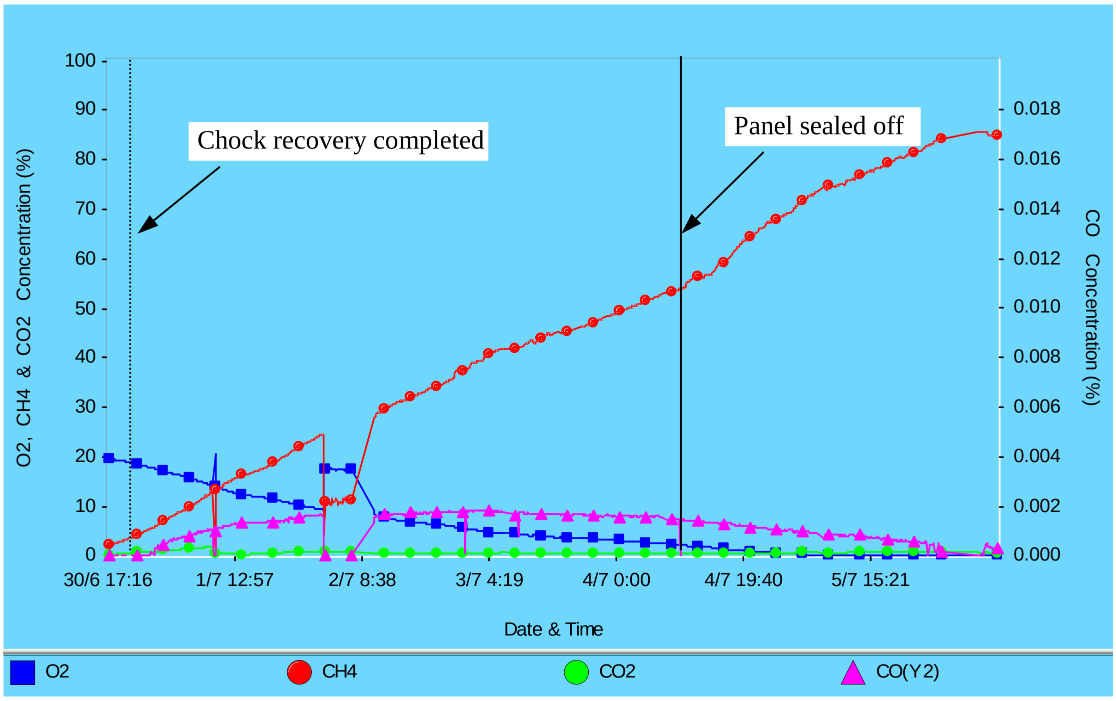

Figure 5.12 Gas concentration profiles in Borehole No.1

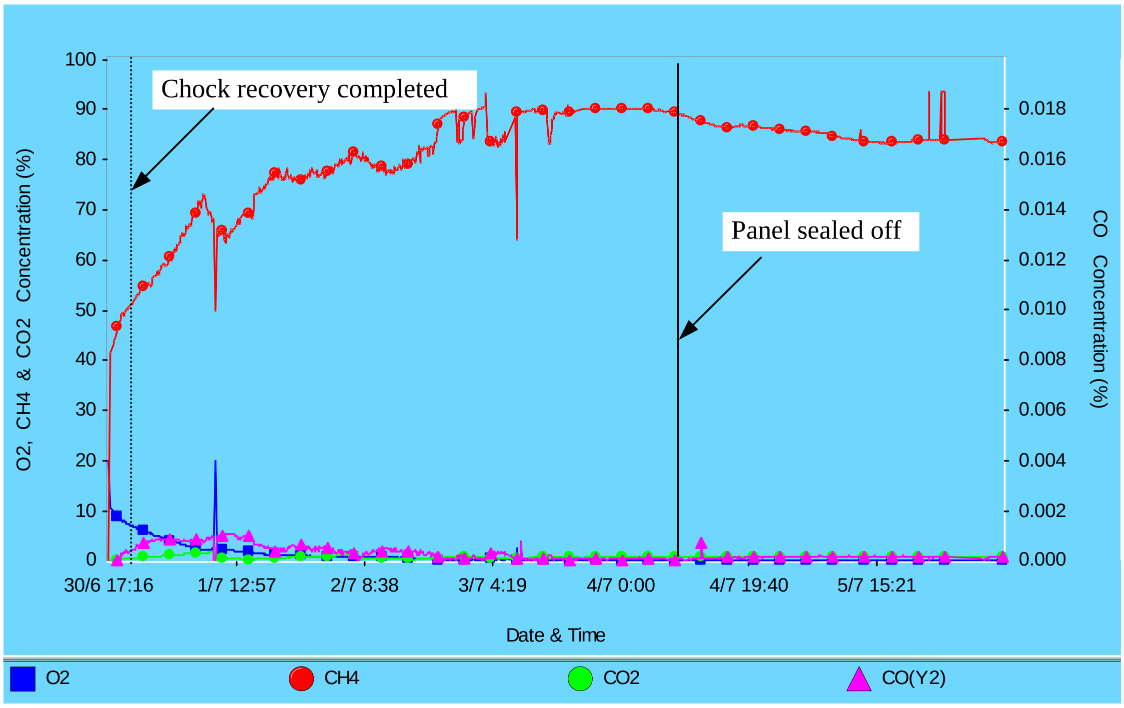

Figure 5.13 Gas concentration profiles in Borehole No.2

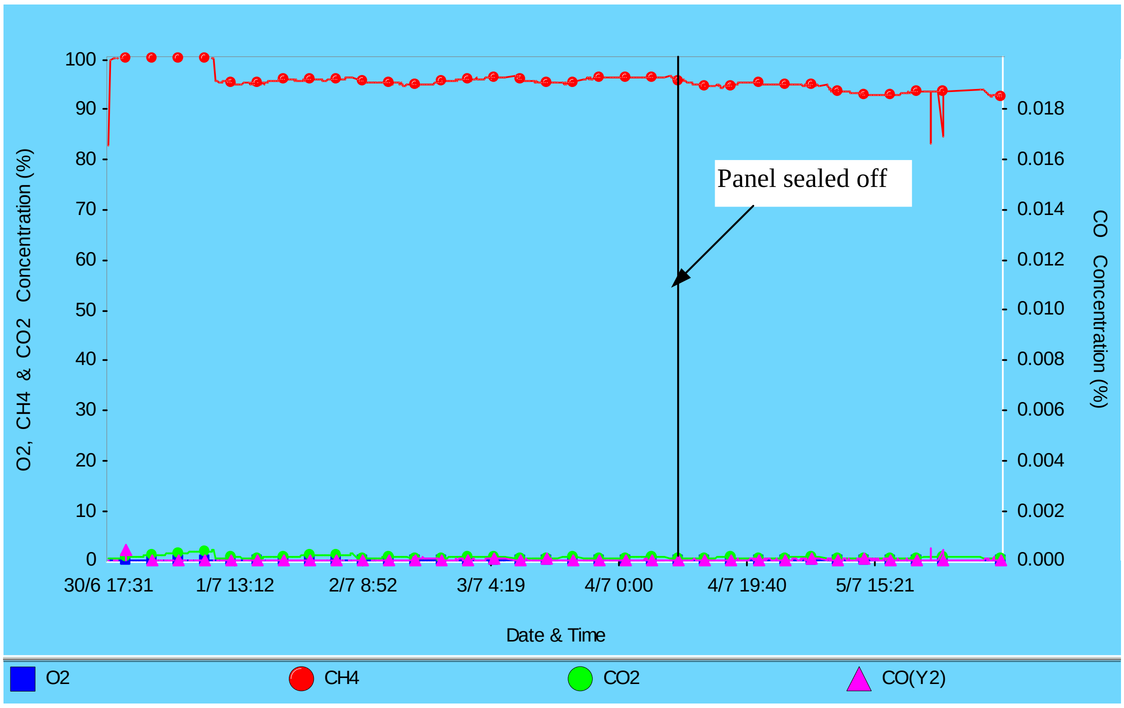

Figure 5.14 Gas concentration profiles in Borehole No.3

(c) Goaf gas distribution at working seam level

Gas distribution at various locations around the goaf in plan view is presented in Figures 5.15 to 5.22. These figures show the changes in gas composition at various locations around the goaf during longwall panel sealing-off and inertisation periods. Gas distribution in the longwall panel N4B goaf during the chock recovery process is shown in Figure 5.15. Results show that oxygen ingress distance on the maingate intake side was about 300 m and about 200 m on tailgate side. Readings indicate that gas distribution in the goaf during chock recovery stage still depended largely on the panel ventilation system. Conversely, the buoyancy effect of methane gas emissions in the goaf was not significant at the working seam level. The high oxygen concentration zone was spread over a wide area in the goaf.

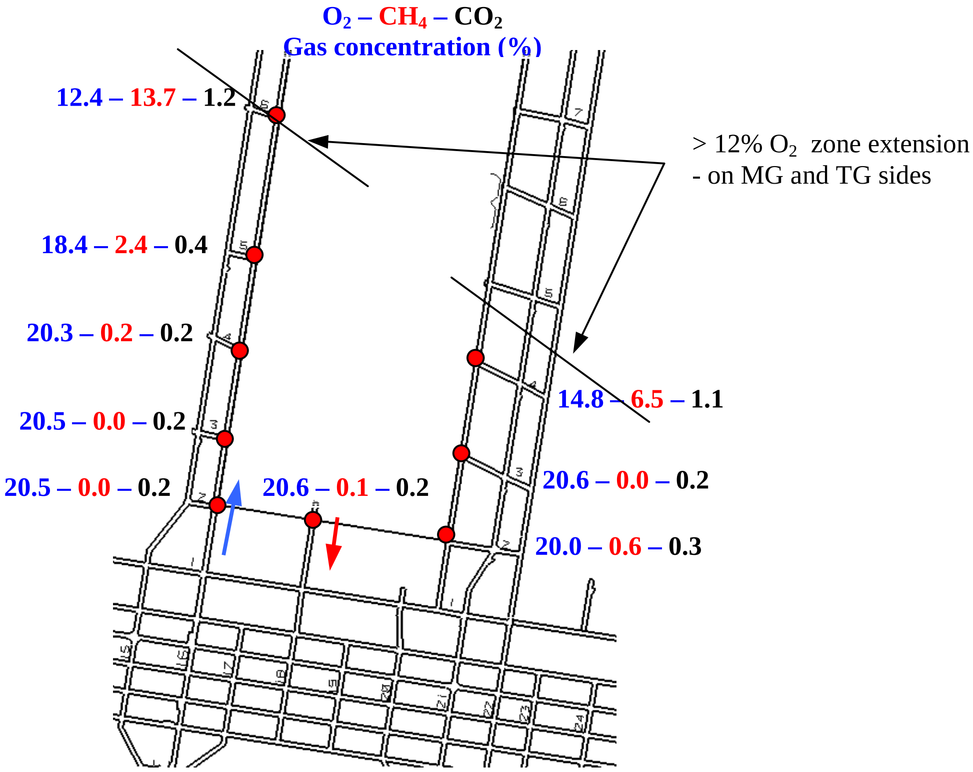

Figure 5.15 Gas distribution in the goaf – just after chocks recovery

Gas distribution in the goaf immediately before sealing off the tailgate roadway is shown in Figure 5.16. By that time airflow into the goaf was substantially reduced. Intake air ingress distance into the goaf on the intake side reduced from 300 m to 200 m, which was almost equal to the air ingress distance on tailgate return side of the goaf. Results indicated that methane gas buoyancy pressure started exerting more influence on goaf gas distribution at the working seam level. Methane gas concentration level at maingate 5 c/t seal increased from 2.4% to 26.6% within 24 hours. Oxygen concentration levels were still high at above 15% over a wide area on both sides of the goaf.

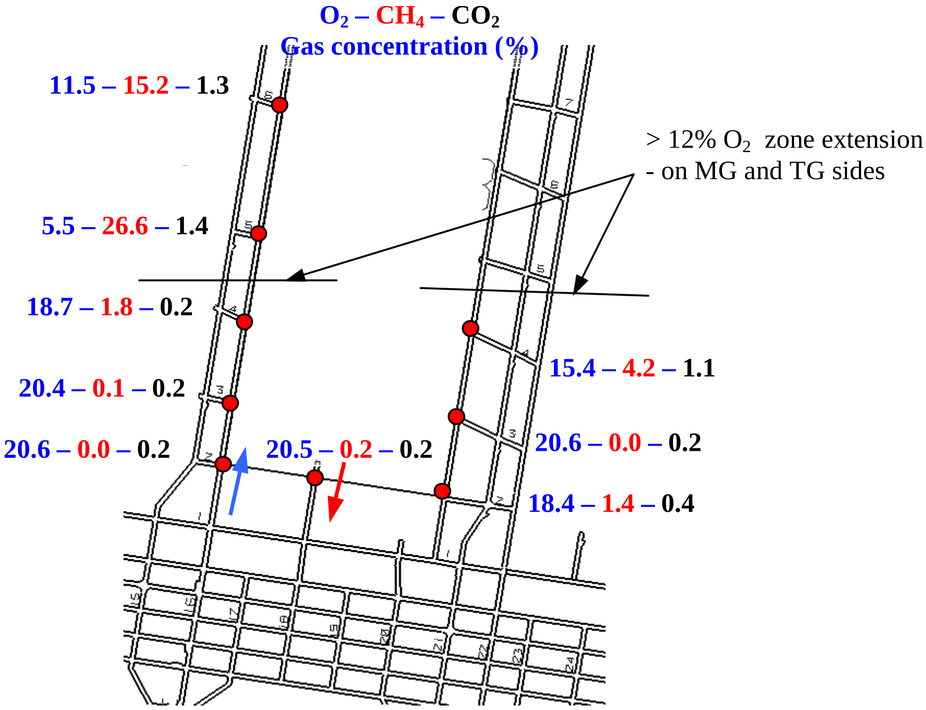

Figure 5.16 Gas distribution in the goaf – just before sealing TG

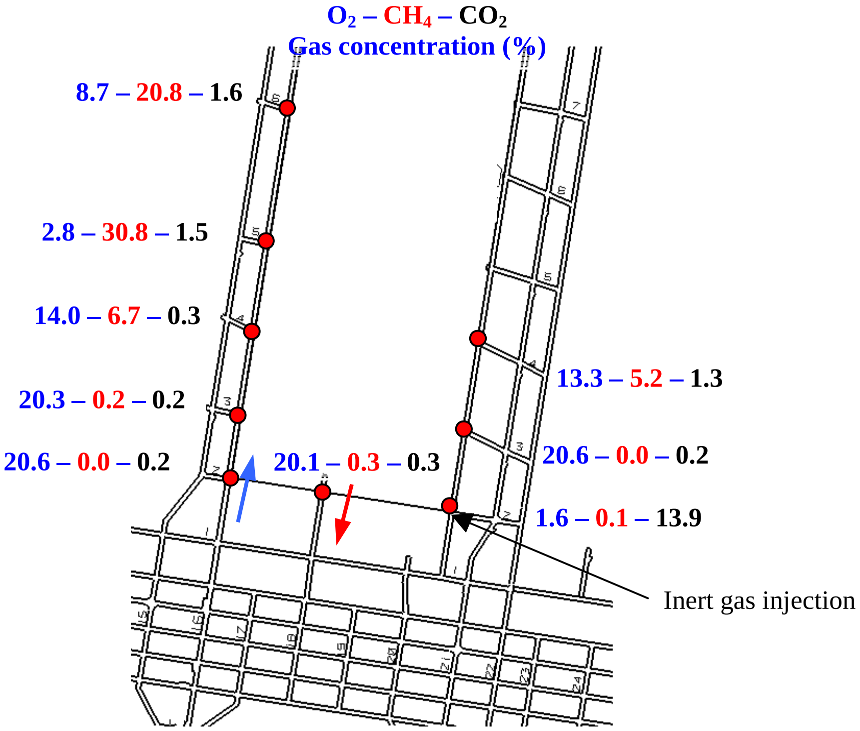

Figure 5.17 Gas distribution in the goaf – after 1 day of inert gas injection through TG seal

Longwall goaf gas distribution in the panel after one day of inert gas injection through the TG seal is shown in Figure 5.17. Inert gas was introduced into the panel at the rate of 0.5 m^3/s. On that day seals were being constructed at the maingate (MG) and chute roadways, i.e., MG and chute roadways were still open. Gas distribution presented in the Figure 5.17 shows that inert gas dispersion in the goaf was restricted to a small area near the TG seal only. There was no sign of inert gas composition even near the adjacent 3 c/t seal. Oxygen gas concentration level at 3 c/t seal on tailgate side was still around 20.6%.

Analysis of the results confirmed that inert gas injection into TG seal would not substantially alter the gas composition at inbye locations in the goaf within a short period. The results confirmed that the optimum location for inert gas injection into the goaf should be at 100 m to 200 m behind the finish line, depending on the goaf gas emission rates, goaf characteristics and gateroad conditions.

Inert gas was then introduced into the tailgate 4 c/t seal and the latest gas distribution in the goaf after 12 hours of inert gas injection into 4 c/t seal is shown in Figure 5.18. Results show that gas composition behind the 4 c/t seal was almost equivalent to injected boiler gas composition. Results also show that even at 3 c/t seal, the oxygen concentration level reduced to 2.0% within few hours of inert gas injection through 4 c/t seal. All the goaf area on tailgate side was inert by the time seals at the MG and chute roadways were ready to be closed.

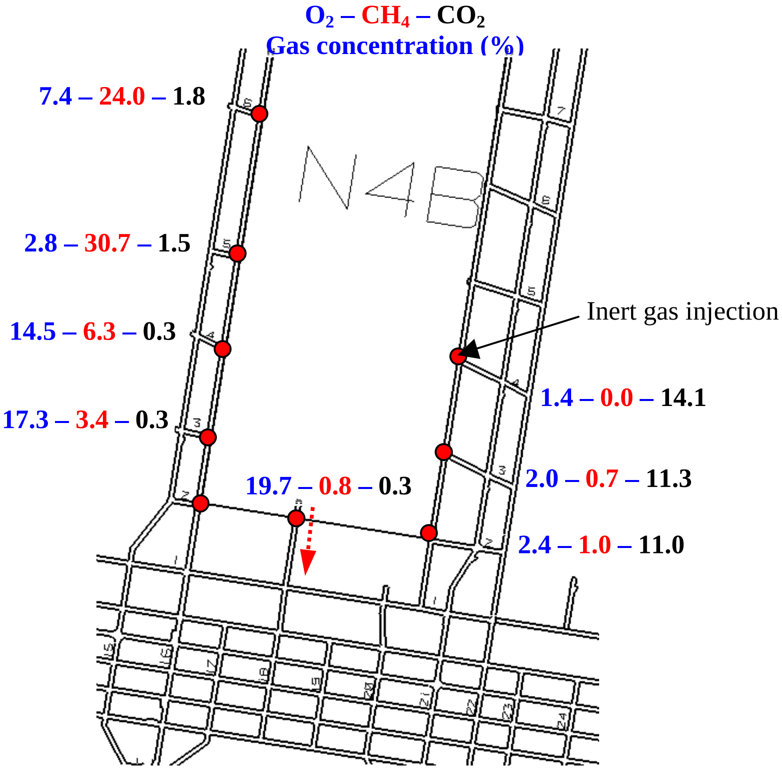

Figure 5.18 Gas distribution in the goaf – 12 hours after inert gas through tailgate 4c/t

In line with the designed optimum inertisation strategy, inert gas injection into maingate 4 c/t seal started at 08:30 on 3-7-01, with the door on the chute road seal still open. As per the designed strategy, inert gas was injected through this seal for one day. Gas distribution in the goaf after 4 hours of inert gas injection into 4 c/t seal is shown in Figure 5.19. Results show that within that four hours of inert gas injection, oxygen concentration in the goaf was below 12% at all locations around the goaf. Oxygen concentration at the critical 3 c/t and MG seal locations reduced to 5.9% and 9.1% respectively within 4 hours of inert gas injection through 4 c/t seal.

An interesting point to note is that methane gas concentration at the adjacent 3 c/t seal increased to 12.4% while CO_2 concentration was only around 2.1%. These results indicate that in the case of the optimum inertisation strategy, inert gas works *in combination* with goaf gas emissions and would achieve faster goaf inertisation. This is in contrast to the results presented in review case studies with the standard inertisation practice of inert gas injection through the MG seal. Case 5 results presented in chapter 2 shows that after 12 hours of inert gas injection through MG seal, methane gas concentration at 3 c/t seal remained at 0.1% while CO_2 concentration increased slowly to 5.0%, with a slight reduction in oxygen gas concentration. Results indicate that in the case of the standard inertisation system, inert gas works *against* goaf gas emissions and hence takes a longer time for inertising the goaf.

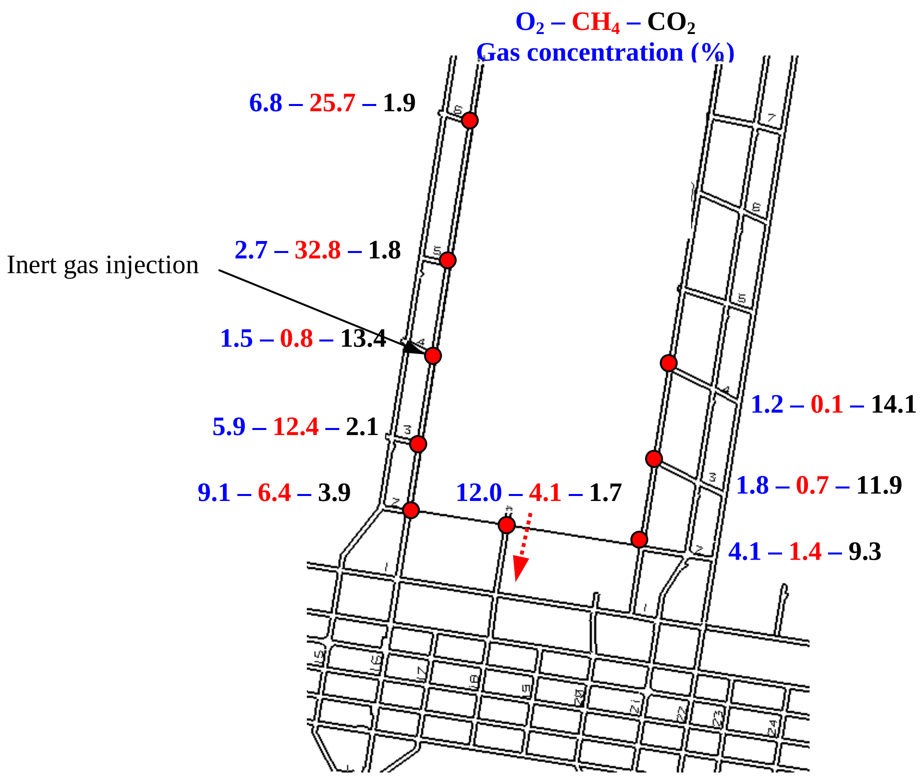

Figure 5.19 Goaf gas distribution – within 4 hours of inert gas injection through maingate 4 c/t

Gas concentration distribution in the goaf after 9 hours of inert gas injection into 4 c/t seal is shown in Figure 5.20. Results show that oxygen concentration reduced to 8.1% within 9 hours of inert gas injection. Oxygen gas concentration at the critical 3 c/t and MG seal locations reduced to 3.6% and 5.1 % respectively. Methane gas concentration at these locations was 10.9% and 8.8% respectively.

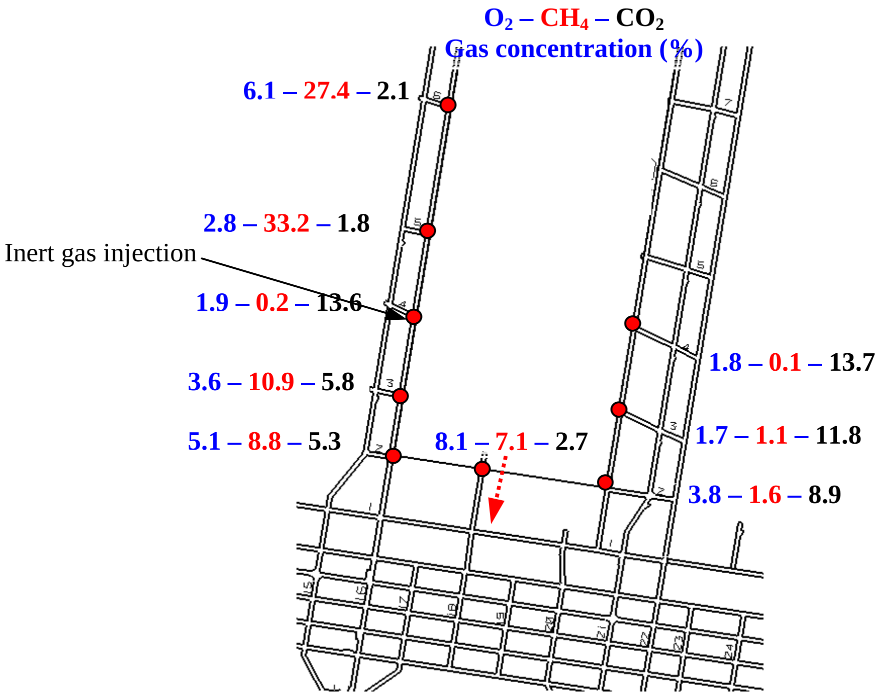

Figure 5.20 Goaf gas distribution – within 9 hours of inert gas injection through maingate 4 c/t

Gas distribution in the longwall goaf just before sealing off the panel on 4-7-01 is shown in Figure 5.21. Gas readings show that oxygen gas concentration was below 5% at all locations in the panel. In other words, goaf atmosphere was completely inert and safe by the time of panel sealing. Gas distribution in the goaf one hour after panel sealing is shown in Figure 5.22. Results show that oxygen concentration levels continued to fall and there were no signs of high oxygen concentration zones in the goaf. Gas levels across the goaf were continuously monitored for another one week to check the effectiveness of goaf inertisation. Results showed that oxygen gas levels remained low at around 2 to 3% and the goaf was completely inert.

Analysis of the results shows that the optimum inertisation developed during the course of the project was highly successful in longwall goaf inertisation during the sealing off period. During these demonstration studies, results show that the goaf atmosphere was completely inert with oxygen concentration below 5.0% at all locations in the goaf by the time of closing the doors on the final seals. Analysis of the results also indicate that boiler gas dispersion in the goaf was not just confined to a narrow zone in the collapsed maingate, but extended to a wider area in the goaf and resulted in faster and complete goaf inertisation.

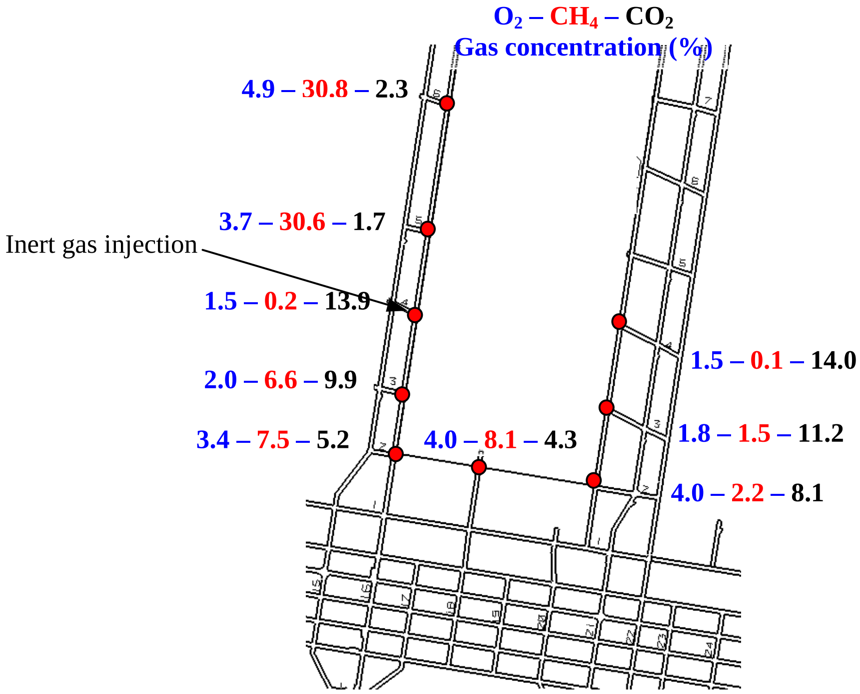

Figure 5.21 Gas distribution in the goaf – Just before sealing off the longwall panel N4B

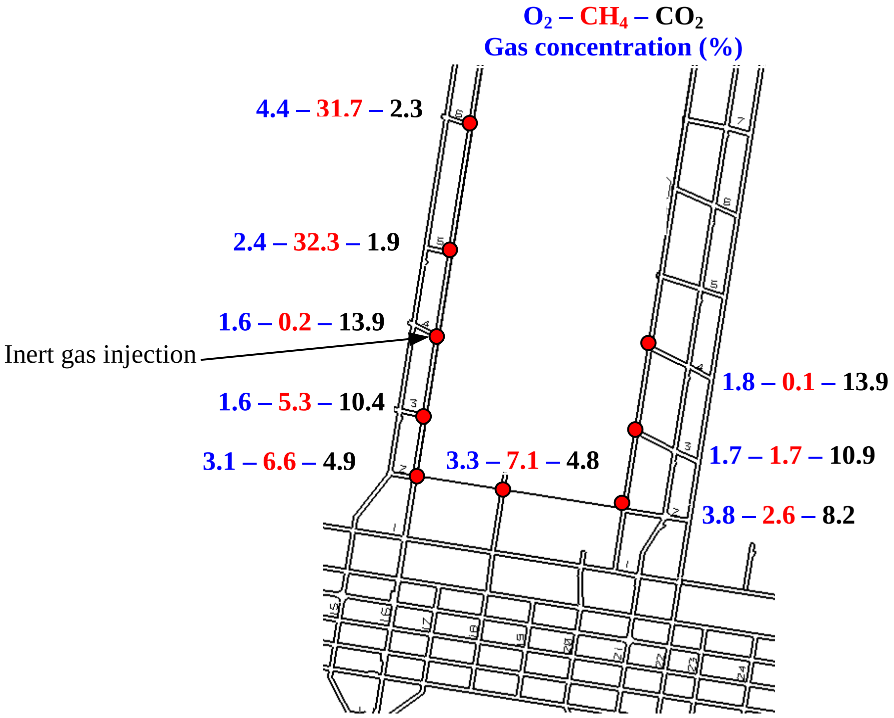

Figure 5.22 Gas distribution in the goaf – within 1 hour of N4B panel sealing

5.5 TRACER GAS STUDIES – RESULTS AND ANALYSIS

Tracer gas studies were also conducted during the inertisation field demonstration studies to improve our understanding of the inert gas flow and dispersion patterns in the longwall goafs. Sulphur Hexafluoride (SF_6) gas was used as tracer gas in the field studies. The studies basically involved release of tracer gas at designated locations into the goaf and collection of gas samples at various locations in and around the longwall goaf. The tracer gas flow paths and velocities in the goaf are then interpreted based on the tracer gas travel time to various locations and the magnitude of tracer gas concentration detected at various monitoring points.

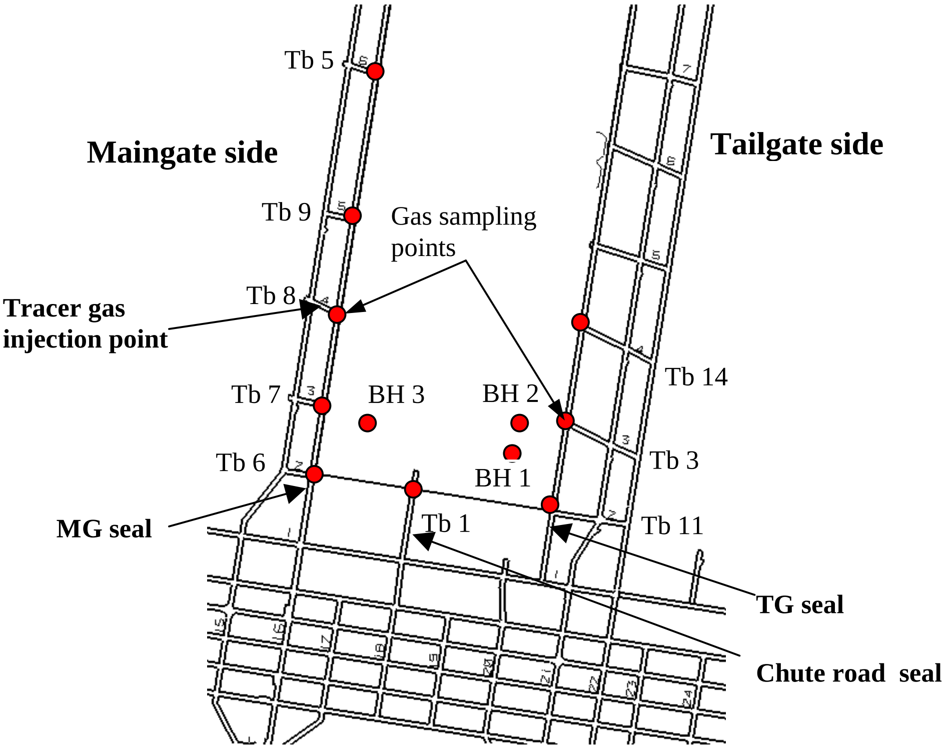

Figure 5.23 Tracer gas studies – sampling tubes location in the longwall panel

The tracer gas release point and the location of various monitoring points in the N4B longwall goaf is shown in Figure 5.23. Three surface boreholes were drilled into the goaf to investigate the effect of goaf inertisation on gas distribution deep inside the goaf, particularly at higher elevations. These three holes were also used as additional gas monitoring points for tracer gas studies. In total, 12 monitoring points were used in the tracer gas studies.

Two tracer gas tests were carried out during the field demonstration studies. The objective of the first test was to study the inert gas dispersions patterns in the goaf before the longwall sealing off period. In the first test, tracer gas released into the longwall goaf through maingate 4 c/t at the start of inert gas injection through this seal on 3-7-01 at 08:30 hours. At that time the door on the chute road seal was still open. The objective of the second tracer gas test was to study the gas flow patterns in the goaf immediately after sealing off of the longwall panel. For the second test, inert gas was injected into the same maingate 4 c/t seal on 4-7-01 at 10:30 hours immediately after panel sealing. During each of the tests, about 9 kg of SF_6 tracer gas was injected into the goaf through the pipes installed in the 4 c/t seal. The duration of the tracer gas release was about 20 minutes.

Gas samples were collected from the monitoring points at the designed time intervals, which varied from 10 minutes to few hours during various stages of the studies. Tracer gas sampling was continued for three days up to 6-7-01. Tracer gas samples collected from various monitoring points during the field test were analysed at SIMTARS laboratory using a gas chromatograph (GC) with an electron capture detector. The detection limit on this ECD GC was about 1 ppb. SIMTARS (Safety in Mines Testing and Research Station) staff carried out all the gas analysis required for the investigations.

Results of the tracer gas tests are presented in Table 5.1, which shows tracer gas magnitude detected at various locations during the test period. In presentation of the results, the first tracer gas release time is taken as reference point, i.e. “0” hours. The second test started at 26 hours in the time scale shown in the results table and various figures. Results presented here have been corrected against the tube delay times at various sampling locations. Tracer gas concentration measured behind the maingate 4 c/t seal is shown in Figure 5.24. The two peaks in the figure show the tracer gas release periods for the two tests. The figure shows that SF_6 concentration at the seal reduced steeply to minimum levels within a few minutes of tracer gas release. These results indicates that tracer gas released at the seal was quickly dispersed away into the goaf.

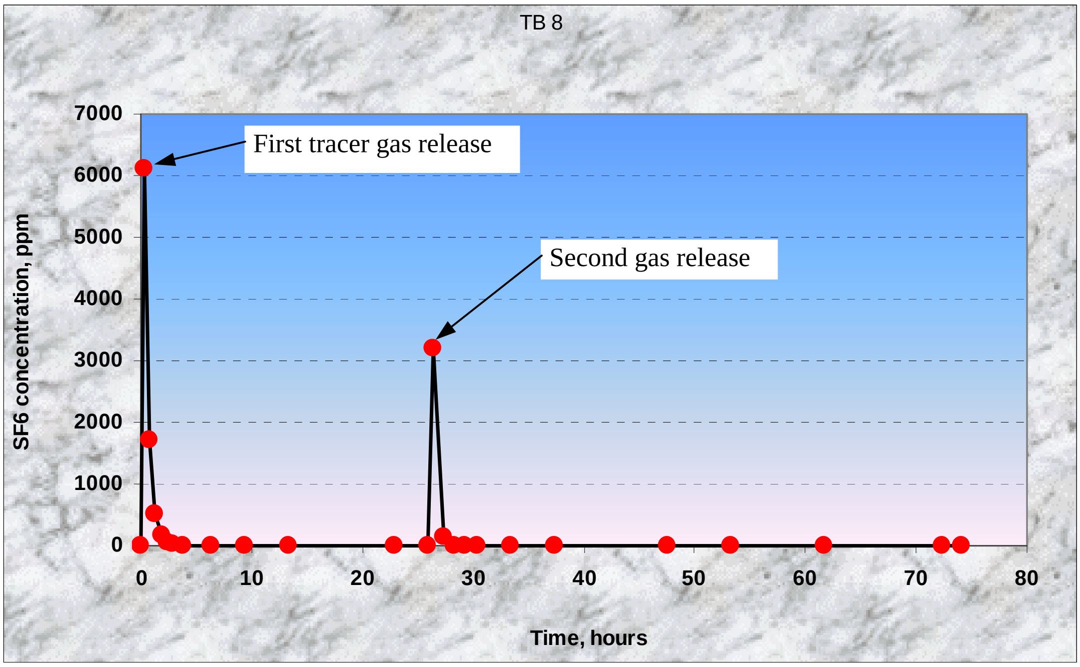

Figure 5.24 Tracer gas concentration at maingate 4 c/t seal (Tube 8) – tracer gas release point

Table 5.1 Tracer gas concentration measured at various sampling points around the goaf

T1		T3		T5		T6		T7		T8	
time, hr	SF6,ppm	time, hr	SF6,ppm	time, hr	SF6,ppm	time, hr	SF6,ppm	time, hr	SF6,ppm	time, hr	SF6,ppm
0	0	0	0	0	0	0	0	0	0	0	0
0.8	0.04	1.5	0.00	1.6	0.00	0.4	0.11	0.4	0.74	0.3	6100.00
1.3	0.03	2.0	0.01	2.1	0.00	0.9	0.06	0.9	0.23	0.8	1700.00
1.7	0.07	4.0	0.01	4.1	0.00	1.9	0.01	1.9	6.00	1.3	515.00
1.9	0.01	6.5	0.00	4.6	0.00	4.3	25.40	3.9	151.00	1.8	182.00
2.4	0.05	9.5	0	9.6	0	6.4	52.30	6.4	99.80	2.3	58.20
2.9	0.11	23.1	0	23.2	0	9.4	50.20	9.4	39.90	2.8	21.60
3.9	1.10	25.5	0	25.6	0	13.4	35.80	13.4	22.80	3.8	7.60
4.8	8.70	28.5	0	28.6	0	23.0	22.50	23.0	7.40	6.3	2.50
6.4	20.60	30.5	0	30.6	0	25.4	33.70	26.4	6.50	9.3	0.59
9.4	28.70	33.5	0	33.6	0	27.4	17.10	27.4	246.00	13.3	0.13
13.5	32.00	47.7	0.04	47.7	0.19	28.4	22.20	28.4	310.00	22.9	0.04
23.0	24.50	53.6	0.3	53.8	2.9	29.4	26.80	29.4	358.00	26.0	0.03
25.4	31.50	60.0	1.9	62.1	10.7	30.4	38.80	30.4	218.00	26.3	3200.00
27.4	16.50	72.2	8	72.3	17.5	33.4	26.90	33.4	38.00	27.3	150.00
28.4	16.80	74.4	10.2	74.5	20	47.6	28.00	37.4	14.50	28.3	8.00
29.4	19.90					53.4	24.20	47.5	9.70	29.3	1.70
30.4	23.80					61.8	18.00	53.4	9.60	30.3	0.93
33.4	30.50					72.3	14.30	61.8	8.20	33.3	0.25
47.6	26.50					74.2	14.00	72.4	4.70	37.3	0.12
53.5	25.70							74.1	4.50	47.5	0.04
61.9	20.30									53.3	1.70
72.2	14.80									61.8	0.06
74.2	14.50									72.4	0.03

T9		T11		T14		BH1		BH2		BH3	
time, hr	SF6,ppm	time, hr	SF6,ppm	time, hr	SF6,ppm	time, hr	SF6,ppm	time, hr	SF6,ppm	time, hr	SF6,ppm
0	0	0	0	0	0	0	0	0	0	0	0
1.6	0.01	2.0	0.00	1.6	0.00	1.8	0	1.9	0	1.3	0
2.1	0.01	2.5	0.00	2.1	0.00	3.3	0	3.4	0	2.0	0
4.1	0.01	4.0	0.00	4.1	0.00	6.3	0	6.4	0	3.5	0
6.6	0.00	6.5	0.00	6.6	0.00	9.3	0	9.4	0	6.5	0
9.6	0.00	9.5	0.00	9.6	0.00	13.6	0	13.7	0	9.5	0
23.2	0.00	23.1	0.00	23.2	0.00	22.8	0	22.9	0	13.7	0
25.6	8.90	25.5	0.25	25.5	0.00	27.3	0	28.4	0	23.0	0
28.6	0.22	28.5	0.00	26.6	0.06	30.4	0	30.5	0	27.4	0
30.6	1.60	30.5	0.00	28.6	0.00	33.3	0	33.4	0	30.5	0
33.6	4.20	33.5	0.02	31.6	0.00	37.6	0	37.6	0	33.5	0
47.8	30.70	47.6	23.50	47.8	0.01	47	0	47.1	0	37.7	0
53.7	29.90	53.6	24.90	53.7	0.13	53.3	0	53.4	0	47.1	0
62.1	32.50	62.0	23.60	62.0	8.80	62	0	62.0	0	53.4	0
72.5	32.00	72.1	18.70	72.5	16.20	71.1	0	71.1	0	62.1	0
74.5	28.40	74.3	15.60	74.4	16.30	74.5	0	74.6	0	74.6	0

Tracer gas (SF_6) profiles measured at various critical locations are presented in Figures 5.25 to 5.29. Figure 5.25 shows the gas profile measured at the adjacent 3 c/t seal location. This figure also shows two peaks within few hours of tracer gas release. Comparison of the two tracer gas concentration peaks at the two adjacent 4 c/t and 3 c/t seals (Figures 5.24 and 5.25) indicate a major difference in inert gas dispersion patterns under open goaf and sealed goaf conditions. Results indicate that under open goaf conditions with the optimum inertisation strategy, inert gas disperses deep into the critical areas of the collapsed area of the goaf and would improve the effectiveness of goaf inertisation operation. Tracer gas profiles at the chute road seal location are presented in Figure 5.26. Results show that although tracer gas concentration magnitude was the same during both tests, there was a significant difference in travel times, indicating a difference in tracer gas travel paths during the two tests.

Gas profiles on the tailgate side of the goaf at TG seal and 4 c/t seal are presented in Figures 5.27 and 5.28 respectively. Both figures indicate that the tracer gas travelled towards the tailgate side only after sealing of the longwall panel. Significant tracer gas concentration was first detected at the TG seal 20 hours after panel sealing. Tracer gas was detected at tailgate 4 c/t seal 36 hours after panel sealing. Results show a very slow rate of inert gas dispersion on the tailgate side after panel sealing. The tracer gas profile at inbye 6 c/t seal on the maingate side is presented in Figure 5.29. Tracer gas was first detected at this location 21 hours after panel sealing. Analysis of the gas samples collected from the boreholes shows that tracer gas was not detected at any of the boreholes. It is to be noted that boreholes were located at 30 m above the working section in the goaf. Results show that the heavier tracer gas did not disperse to any of these higher elevations in the goaf, which confirm the buoyancy effects in the goafs.

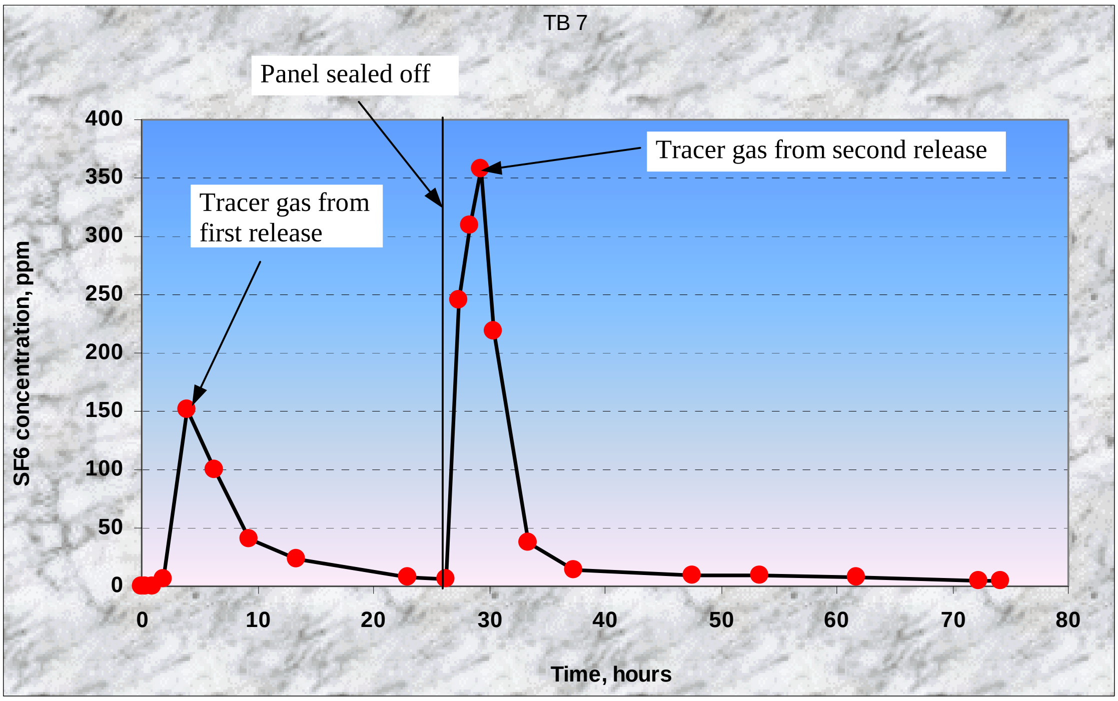

Figure 5.25 Tracer gas concentration profile at maingate 3 c/t seal (Tube 7)

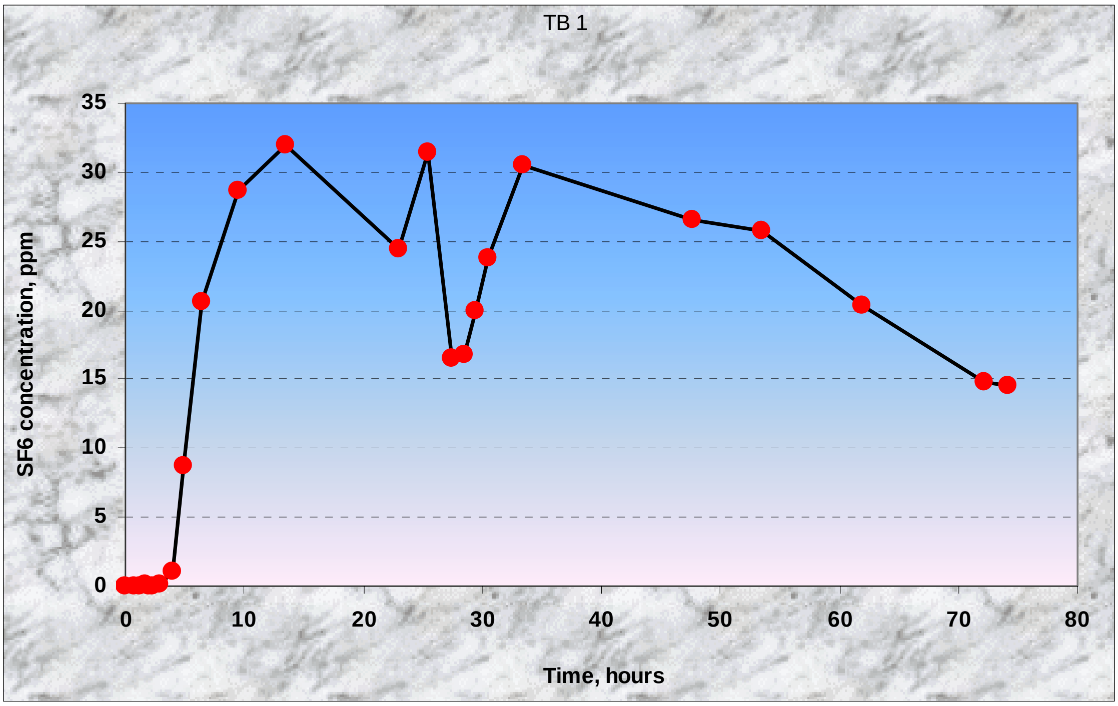

Figure 5.26 Tracer gas concentration profile at Chute road seal (Tube 1)

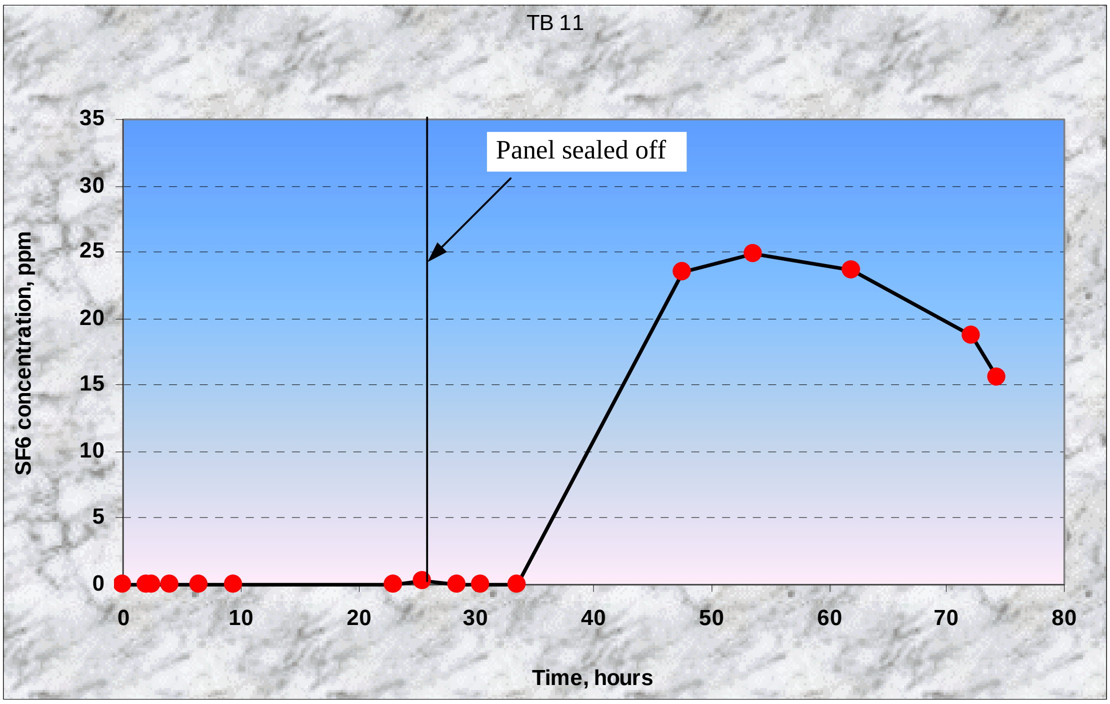

Figure 5.27 Tracer gas concentration profile at TG seal (Tube 11)

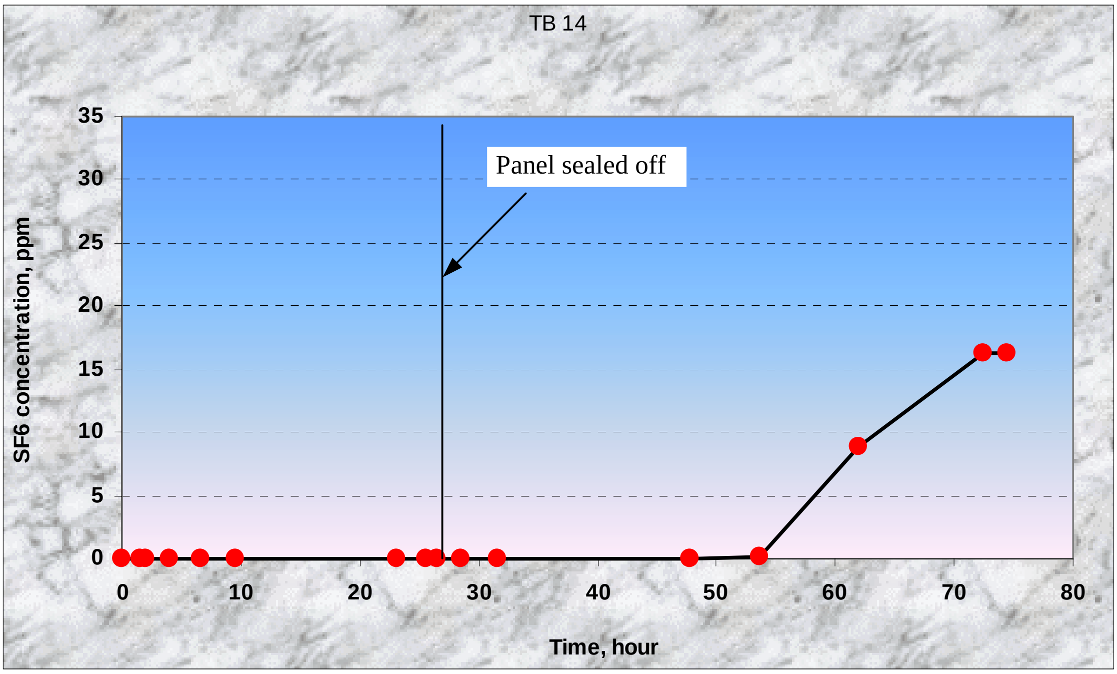

Figure 5.28 Tracer gas concentration profile at tailgate 4 c/t seal (Tube 14)

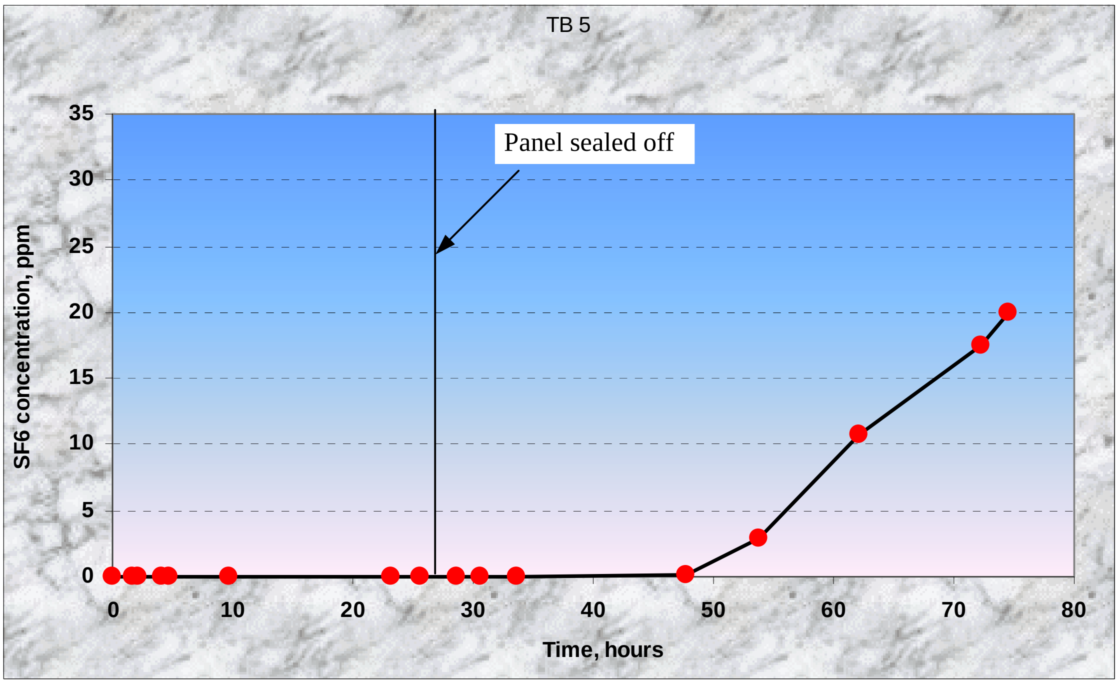

Figure 5.29 Tracer gas concentration profile at maingate 6 c/t seal (Tube 5) – inbye side of the tracer gas release point

Tracer gas concentration levels at various locations around the goaf at 4 hours after the first tracer gas release are shown in Figure 5.30. Results show that peak tracer gas concentration detected at the maingate 3 c/t was only about 151 ppm, as against the 6,100 ppm level detected at the adjacent 4 c/t seal at the time of release. Tracer gas levels detected in the goaf at 4 hours after the second release are shown in Figure 5.31. SF_6 gas concentration detected at maingate 3 c/t seal was about 358 ppm, which was significantly higher compared with gas levels detected after the first release. Tracer gas distribution in the goaf 48 hours after the second release is shown in Figure 5.32. Results showed that a significant amount of tracer gas was dispersed to inbye locations on the maingate side and to locations on tailgate side of the goaf after panel sealing.

Analyses of the results indicate that tracer gas dispersion patterns in the goaf were significantly different under open goaf and sealed goaf conditions. These results indicate that the inert gas injected into the goaf prior to sealing would disperse over a wider area in the goaf, including the critical high oxygen areas inside the goaf. Inert gas injected into the goaf after panel sealing would probably travel more along the collapsed gateroads and may not be very effective on high oxygen concentration areas inside the goaf.

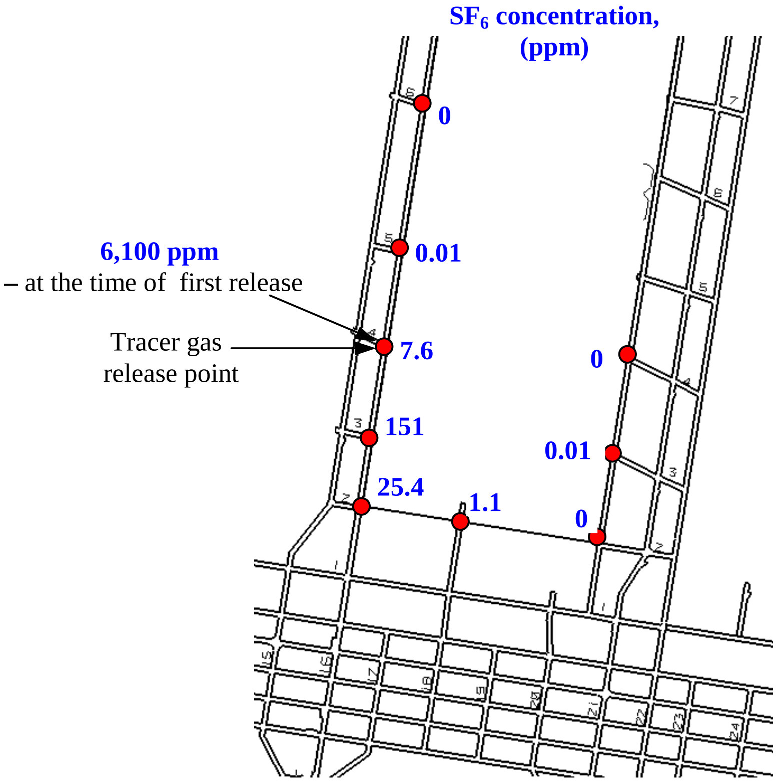

Figure 5.30 Tracer gas (SF_6) concentration distribution in the goaf – 4 hours after first release.

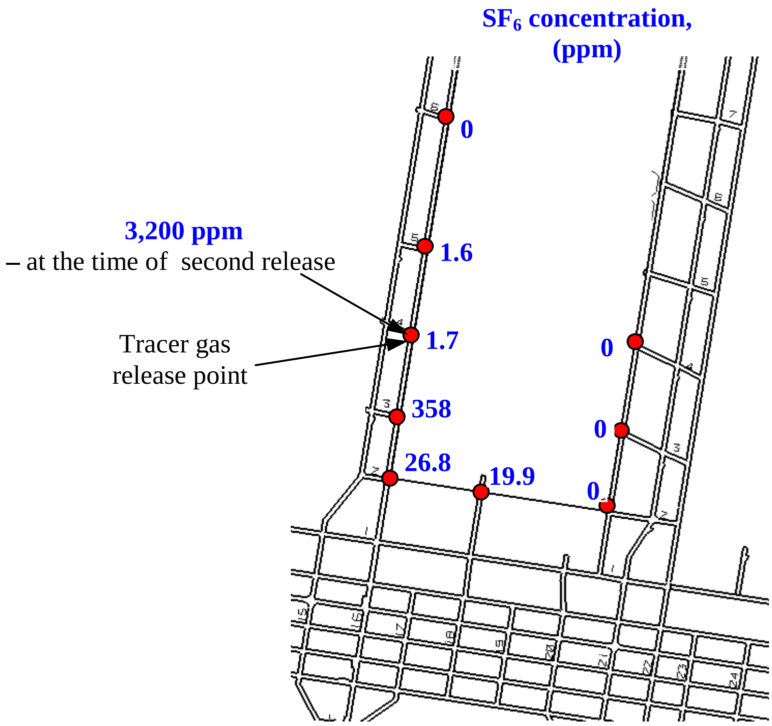

Figure 5.31 Tracer gas (SF_6) distribution in the goaf – 4 hours after second release.

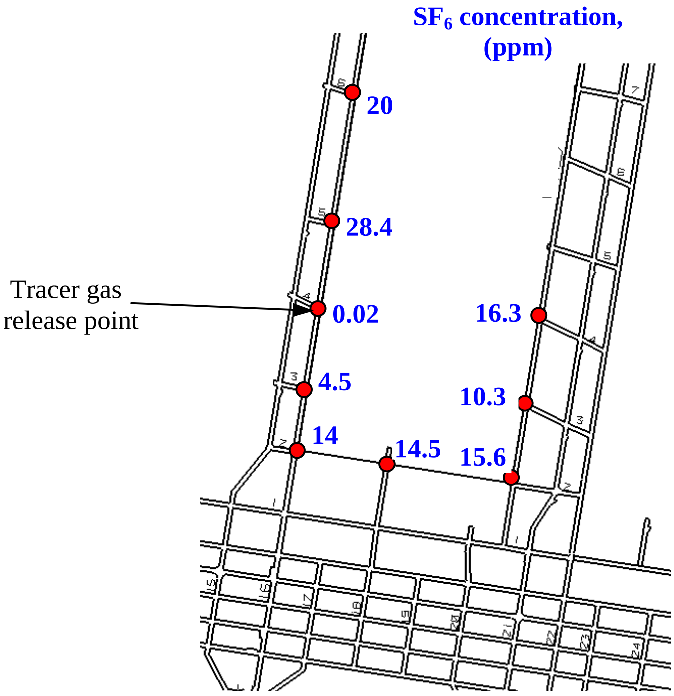

Figure 5.32 Tracer gas concentration distribution in the goaf – 48 hours after second release.

5.6 SUMMARY AND CONCLUSIONS

Field demonstration studies were carried out at Newlands Colliery during panel sealing off operations. An optimum inertisation strategy developed during the course of the project has been implemented at N4B panel of Newlands Colliery for the field demonstration studies. Tracer gas studies were also carried out during the field studies to map the inert gas dispersion patterns in the longwal goaf. An extensive underground gas monitoring system was installed around the N4B panel involving 9 moniting tubes installed on both sides of the goaf. Three surface boreholes were also drilled into the goaf specifically for these demonstration studies to monitor the gas concentration levels deep inside the goaf during sealing off and inertisation operations.

The optimum inertisation strategy developed for Newlands Colliery as a demonstration field study involved:

(i) inert gas injection through tailgate 4 c/t and TG seals for 2 days before sealing
(ii) boiler gas flow rate at 0.5 m^3/s
(ii) inert gas through maingate 4 c/t for 1 day with door on chute road seal open
(iii) panel sealing and continuation of inert gas injection through maingate 4 c/t until oxygen levels in the goaf reduced below 8%.

Analysis of the results during inert gas injection though the tailgate side seals confirmed that introduction of inert gas at 100 to 200 m behind the face finish line results in better goaf inertisation compared with inert gas injection through TG or MG seals. Gas distribution in the goaf during inert gas injection through maingate 4 c/t showed that boiler gas dispersion was not just confined to a narrow zone in the collapsed maingate, but extended to a wider area in the goaf and resulted in better and faster goaf inertisation. These results indicate that for N4B longwall geometry and conditions, inert gas injection on the maingate side results in goaf inertisation over a wider area compared with inert gas injection on the tailgate side.

Results show that within four hours of inert gas injection through maingate 4 c/t seal, oxygen concentration in the goaf was below 12% at all locations around the goaf. Oxygen concentration at the critical 3 c/t and MG seal reduced to 5.9% and 9.1% respectively. Gas distribution in the goaf also indicated that with implementation of optimum inertisation strategy, inert gas worked in combination with goaf gas emissions and achieved faster goaf inertisation. It should be noted here that in the case of standard inertisation schemes involving inert gas injection through MG, inert gas normally works against goaf gas emissions and would take a longer time for goaf inertisation.

Goaf gas monitoring showed that oxygen levels in the goaf did not rise after stopping the inert gas injection, confirming the success of goaf inertisation. It may be recalled that in some of the review case studies, oxygen levels increased steeply after stopping inert gas injection into the goaf, which indicates insufficient goaf inertisation. Figures also showed that even CO levels did not increase at any of the seals during or after the inertisation process, confirming the success of the inertisation operations.

Tracer gas study results presented the gas dispersion patterns during longwall sealing off and inertisation operations. Results indicated a significant difference in tracer gas flow paths under open goaf and sealed goaf conditions. Tracer gas studies also indicated that with the optimum inertisation strategy implemented at the site, inert gas also dispersed towards high oxygen concentration areas inside the goaf and greatly improved the effectiveness of goaf inertisation operation.

The demonstration study results showed that the optimum inertisation strategy implemented at the field site was highly successful in converting goaf environment into an inert atmosphere within a few hours of panel sealing. In fact during these field demonstration studies, the goaf atmosphere was completely inert with oxygen concentration below 5% by the time of closing the doors on the final seals. This represents a major improvement to mine safety compared to typical inertisation practices that were able to achieve goaf inertisation within 2 to 4 days after sealing.

Chief Inspector of Mines, Mr Peter Minahan; Deputy Chief Inspector of Mines (Coal), Mr Brian Lyon and Senior Inspector of Mines, Mr Tim Jackson have visited the mine at the time of sealing to witness the effect of the new inertisation practices. The new inertisation techniques developed during the course of the project greatly reduced the risk and delays associated with panel sealing operations. Application of these optimised intertisation strategies and guidelines will significantly enhance the safety of coal mines.

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CHAPTER 6

CONCLUSIONS

6.1 CONCLUSIONS AND RECOMMENDATIONS

The aim of this ACARP research project was to develop and demonstrate optimum strategies for goaf inertisation during longwall sealing operations. The project has combined the detailed analysis of field trials of various inertisation schemes together with extensive computational fluid dynamic (CFD) modelling of different inertisation options to develop the optimum inertisation strategies. Technology transfer to the industry through field demonstration of the effectiveness of optimum inertisation strategies was also one of the main objectives of the project work. The main conclusions and recommendations from the research work are presented in the following sections.

(a) Goaf gas distribution

(1) During longwall retreat operations, the panel ventilation system and goaf gas emission flow rates would have a major influence on goaf gas distribution at working seam level when compared with the effects of goaf gas buoyancy pressures.

(2) During panel sealing off operations, when panel airflows are restricted, goaf gas composition and buoyancy forces play a major role on gas distribution in the goaf, even at working seam levels.

(3) Coal seam structure and gradient play a significant role in goaf gas distribution and needs to be considered during development of inertisation operations.

(4) Longwall goaf geometry, caving characteristics, chock withdrawal and panel sealing sequence would also have a significant influence on goaf gas distribution.

(5) Gas flow patterns in the longwall goaf would be significantly different under open goaf (during face recovery operations) and sealed goaf conditions.

(b) Design of inertisation operations

(6) Development of an inertisation strategy should take into consideration the effect of all the above site parameters on goaf gas distribution. The most important design parameters for goaf inertisation during longwall sealing operations are (in the order of influence):

   a. location of inert gas injection points;
   b. inertisation strategy – leakage paths, timing, etc.;
   c. flow rate of inert gas injection; and
   d. inert gas composition.

(7) There was no major difference in effectiveness of boiler gas and nitrogen inert gases on goaf inertisation under the modelled conditions.

(c) Effect of inertisation on heatings

(8) Rapid inertisation, i.e. inert gas injection at higher flow rates for a few hours, to control goaf heatings results in only a marginal decrease in peak temperatures.

(9) Studies indicate that rapid inertisation may not be an appropriate strategy to control all heatings in the longwall goafs, and needs to be investigated further to analyze its effects under different conditions.

(10) Introduction of fresh air into the goaf immediately after rapid inertisation results in revival of heatings in the longwall goafs and therefore should be avoided.

(11) Heatings in the goaf can survive for long periods even at 5 to 7% oxygen levels. Therefore, it is very important to prevent even small air leakages into goafs, as it can keep undetected heatings active for very long periods.

(12) Inert gas injection at low flow rates for longer periods (for example, at about 1.0 m^3/s for 1 week) at the appropriate location is the best strategy for control of heatings in longwall goafs. However, optimum design for any heating incident depends on the location and size of the heating and surrounding goaf and ventilation conditions.

(d) Optimisation of inertisation operations

(13) In many cases, the standard practice of inert gas injection through MG or TG seals immediately after panel sealing would not be effective for goaf inertisation. In addition, it may increase the inertisation time because it acts against the goaf gas emissions. The optimum inertisation strategy should work in combination with goaf gas emissions to achieve faster goaf inertisation

(14) Inert gas injection through 2nd or 3rd cut throughs behind the face, i.e. at 100 to 200 m behind the face finish line, would result in better goaf inertisation, compared with inert gas injection through MG or TG seals.

(15) During longwall retreat operations, injection of inert gas at low flow rates from 50 to 200 m behind the face on the intake side reduces the spontaneous combustion risk in the active goafs.

(16) Inert gas flow rate of 1.0 m^3/s is recommended under less gassy conditions. Inert gas flow rate of 0.5 m^3/s would be sufficient under moderately gassy conditions, if optimum inertisation strategies are implemented.

(17) Under the field site conditions, inert gas injection through cut-throughs on the maingate side results in effective goaf inertisation compared with inert gas injection through the tailgate side seals.

(18) It is critical to begin inert gas injection operations prior to final panel sealing to achieve faster goaf inertisation.

(19) The optimum inertisation strategy developed during the course of the project for the Newlands longwall panel geometry and site conditions is:

  i) inert gas injection through the tailgate 4 c/t seal for 2 days before sealing
  ii) inert gas through maingate 4 c/t for 1 day with door on chute road seal open
  iii) panel sealing and continuation of inert gas injection until oxygen levels in the goaf reduced below 8%.

(20) The recommended guidelines for optimum inertisation strategy are:

- i) inert gas should be injected into the goaf at 200 m behind the face finish line, i.e. at an inbye location with respect to explosive fringe in the goaf.
- ii) inert gas should be injected on the intake side of the goaf OR on both sides of the goaf, if possible.
- iii) inert gas injection should start at least 1 or 2 days before panel sealing, with minimum ventilation flow and doors on the return seal still open.
- iv) inert gas flow rate of 0.5 to 1.0 m^3/s is recommended, subject to implementation of all these optimum strategies.
- v) inert gas injection to be continued after sealing until O_2 levels are below 8%.

The field demonstration study results showed that the optimum inertisation strategy implemented at the mine was highly successful in converting goaf environment into inert atmosphere within a few hours of panel sealing. In fact, during these field demonstration studies, the goaf atmosphere was completely inert with oxygen concentration below 5% by the time of closing the doors on the final seals. Goaf gas monitoring showed that oxygen levels in the goaf did not rise after stopping the inert gas injection, confirming the success of goaf inertisation.

The project studies have greatly improved the fundamental understanding of the various site parameters and inertisation schemes on goaf inertisation. This new understanding has been used to develop the optimum inertisation strategies for site conditions, which have proved to be highly successful in goaf inertisation.

This project demonstrated that it is feasible to completely inertise the longwall goafs within a few hours of sealing the panel by implementing optimum inertisation strategies. Similar optimum inertisation strategies can be developed for other site conditions. The fundamental understanding of inert gas flow patterns and optimum inertisation guidelines developed during the course of the project greatly enhance the safety of coal mines.

6.2 FUTURE RESEARCH

The following issues may be addressed in the future research projects to further improve the fundamental understanding of the inert gas flow dynamics and advance inertisation technology for application in all coal mines.

- A greater understanding of the effect of inert gas injection into old bord and pillar workings of open cut mines.

  Advances in opencut mining technology have greatly increased the stripping ratio limits and applicability of opencut mining to extract coal from greater depths. A number of coal mining areas around the world that were developed and extracted partially by bord and pillar mining methods a few decades ago are now more suitable for opencut mining. In this type of opencut mines, fires in and around the old bord and pillar workings are a major problem. Inertisation operations were not successful on a number of occasions at these mines. Further research to obtain a greater understanding of the effect of various inertisation strategies under these conditions helps in developing effective fire control methods.

- Effect of low flow inertisation during chock recovery operations to control spontaneous combustion in the goaf.

  In a number of mines, spontaneous combustion rate in the goaf increases during face recovery operations. During that period, face is stationary and airflow into the goaf is reduced. Both these operational conditions create favourable atmosphere for spontaneous combustion development in the goaf. One potential way to control this situation is to introduce inert gas into the goaf at low flow rates. Further research is needed to develop appropriate designs and strategies for application of low flow inertisation technology during chock recovery operations.

- Low flow inertisation to minimise the risk of goaf heatings during a longwall face stoppage near geologically disturbed areas.

  Spontaneous combustion risk in the longwall goafs is higher near the geologically disturbed areas. Previous research on gas control (Balusu et al. 2001) also showed that goaf gas flow mechanics near the geologically disturbed areas are significantly different from the typical gas flow patterns. If the longwall face needs to be stopped or slowed down near these faulted areas due to geotechnical problems, it is better to inject inert gas at lower flow rates to prevent the development of heatings in the goaf. Further research in this area helps in developing effective designs and strategies for these conditions.

- Inertisation techniques for bord and pillar mines.

  Spontaneous combustion risk is normally higher in bord and pillar workings due to the complex nature of ventilation in the extraction panel goafs. Ventilation flow patterns in a bord and pillar goaf are very complex due to the coal stooks left in the goaf and pressure distribution in and around the goaf. Further research is recommended to investigate the inert gas flow patterns in bord and pillar extraction panels.

- Inert gas flow dynamics under various geological and mining conditions.

  Further research may be carried out to investigate the inert gas flow dynamics in longwall goafs under different geological, mining and operational conditions.

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REFERENCES

Balusu, R., Deguchi, G., Holland, R., Moreby, R., Xue, S., Wendt, M. & Mallett, C. (2001). Goaf gas flow mechanics and development of gas and sponcom control strategies at a highly gassy coal mine. *Australia-Japan Technology Exchange Workshop, 3-4 December 2001.* Hunter Valley, Australia. 18 pp.

Bell, S., Humphreys, D., Harrison, P., Hester, C. & Torlach, J. (1997). Demonstration of the GAG-3A inertisation device at the Collinsville No 2 coal mine. ***ACARP Report Number C6019****, April 1997.* Australian Coal Association Research Program. 48 pp.

Brady, J. (1997a). Sealing, monitoring and low flow inertisation of a goaf. ***ACARP Report Number C6002****, July 1997.* Australian Coal Association Research Program. 103 pp.

Brady, J. (1997b). Tomlinson Boiler, inert gas generator field trials. *Queensland Mining Industry Health and Safety Conference, 1997.* Australia. pp 152-157.

Brunner, D.J., Miclea, P.C., McKinney, D. & Mathur, S. (1995). Examples of the application of computational fluid dynamics simulation to mine and tunnel ventilation. *Proc. of the 7th U.S. Mine Ventilation Symposium.* Chapter 73. pp 479-484.

Cliff, D., Clarkson, F., Davis, R., Bennett, T. & Smalley, M. (2000a). Better indicators of spontaneous combustion. ***ACARP Report Number C5031****, October 2000.* Australian Coal Association Research Program. 134 pp.

Cliff, D., Clarkson, F., Davis, R. & Bennett, T. (2000b). The implications of large scale tests for the detection and monitoring of spontaneous combustion in underground coal. *Queensland Mining Industry Health and Safety Conference,* Australia. 8 pp.

Moloney, K.W., Hargreaves, D.M., Lowndes, I.S. & Pearce, W. (1999). Validation of computational models of auxiliary ventilation systems with experimental data. *Proc. of the 8th U.S. Mine Ventilation Symposium.* pp 551-557.

Pokryszka, Z., Tauziede, C., Carrau, A., Bouet, R & Saraux, E. (1997). Application of numerical gas flows modelling to optimisation of nitrogen injections in the goaf. *27th Int. Conf. of Safety in Mines Research Institute, 1997.* New Delhi, India. pp 411-420.

Srinivasa Rao, B., Baafi, E.Y., Aziz, N.I. & Singh, R.N. (1993). Three dimensional numerical modelling of air velocities and dust control techniques in a longwall face. *Proc. of the 6th U.S. Mine Ventilation Symposium.* Chapter 43. pp 287-292.

Sullivan, P. & Van Heerden, J. (1993). The simulation of environmental conditions in continuous miner developments using computational fluid dynamics. *Journal of the Mine Ventilation Society of South Africa, January, 1993.* 10 pp.

McKinney, R., Crocco, W., Tortorea, J., Wirth, G., Weaver, C., Urosek, J., Beiter, D. and Stephan, C. (2001). Report of investigation underground coal mine explosions July31 – August 1, 2000. *Mine Safety and Health Administration, Virginia, USA, July, 45 pp.*

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