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Use of gas mixing equations and simulation approaches in the design of mine inertization systems

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ABSTRACT: The primary objective of the study is to examine gas mixing and dilution approaches to give a better understanding of how acceptable levels of contaminants within a mine atmosphere can be evaluated. As an example the interaction between gases from inertization systems and the underground mine atmosphere can be evaluated to assist in design of the mine inertization system. Inertization approaches include use of engine exhausts, nitrogen, carbon dioxide, and diesel fired boiler units. Inertization systems for handling underground fires, spontaneous combustion heatings and management of the potential explosibility of newly sealed goafs have been accepted as important safety approaches within the many parts of the international industry. Case studies of the designs and applications of inertization systems to assist in stabilising mine atmosphere situations are given.

1 Introduction

The use of various inertization systems for handling underground fires and management of the potential explosibility of newly sealed goafs have been accepted as important safety approaches within the many parts of the international industry. New approaches allowing improvement in understanding the use of inertization techniques have been examined. Case studies have been developed to examine available calculation or computer simulation approaches for predicting the induced inertization gas interaction with the mine ventilation system. Comparisons are made of the use of different approaches to estimate the time required to inert a sealed underground atmosphere. Available approaches include direct calculations and simulation exercises.

Two calculation approaches are:

- the application of “commonly accepted rules-of-thumb” for fluid dilution or flushing of a mined space with a minimum diluting gas requirement of for instance of three times the void volume, and
- the direct utilization of gas mixing and dilution equations (Hartman *et al.,* 1997).

Another approach involves the understanding of mixing through the use of advanced fire simulation network software for modelling a mine ventilation system. Simulation software has the great advantage that underground mine fire scenarios can be analyzed and visualized. The simulation approach allows thermodynamic effects of gas temperature changes as mixing occurs to be taken into account; changes that the calculation approaches can not readily take into account.

A number of fire simulation packages have been developed to allow numerical modelling of mine fires (such as Greuer, 1984; Stefanov *et al.*, 1984; Deliac *et al.*, 1985, Greuer, 1988; Dziurzyński *et al*., 1988). Details of the Ventgraph program have been described by Trutwin *et al*. (1992). The software provides a dynamic representation of a fire's progress in real time and utilizes a colour-graphic visualization of the spread of combustion products, oxygen and temperature throughout the ventilation system. During the simulation session the user can interact with the ventilation system such as open or close doors, breach stoppings, introduce inert gases and change fan characteristics. These changes can be simulated quickly allowing for the testing of various fire control and suppression strategies. Validation studies on Ventgraph have been performed using data gathered from a real mine fire as undertaken by Wala *et al*. (1995).

The primary objective of the study is to use these available approaches to gain a better understanding of how inertization delivered gases can interact with the underground mine atmosphere and to assist in the design of mine inertization systems. Inertization approaches include the use of engine exhausts, liquefied nitrogen, pressure swing adsorption and molecular sieve manufactured nitrogen, carbon dioxide, and diesel fired boiler units. Inertization systems for handling underground fires, spontaneous combustion heatings and management of the potential explosibility of newly sealed goafs have been accepted as important safety approaches within the many parts of the international industry. In this paper, case studies of the designs and applications of inertization systems to assist in stabilising mine atmosphere situations are given.

2 Inertization Systems

Inertization has been accepted to have an important place in Australian mining emergency preparedness. The two jet engine exhaust GAG units purchased from Poland by the Queensland government in the late 1990s for the Queensland Mines Rescue Service have been tested and developed and mines made ready for their use in emergency and training exercises. Their use in real and trial mine fire incidents has underlined the need for more information on their application (Gillies & Wu, 2006).

The NSW Mineshield (liquefied nitrogen) apparatus dates to the 1980s and has been actively used particularly in gob heating incidents. The diesel fired boiler has been purchased by a number of mines and is regularly used as a routine production tool to reduce the time in which a newly sealed gob has an atmosphere "within the explosive range" and for gob spontaneous combustion headings. Nitrogen Pressure Swing Adsorption units are available and in use both for reducing the time in which gobs are "within the explosive range" and for gob spontaneous combustion headings. Each of these facilities puts out very different flow rates of inert gases. Each is broadly designed for different applications although there is some overlap in potential usages.

Mine fires lead to complex interrelationships with the airflow in the mine ventilation system (Gillies *et al*., 2004; Wala, 1996). Addition of the gas stream from an inertization unit adds another level of complexity to the underground atmosphere behaviour. Important questions include will buoyancy effects lead to airflow reversal and the drawing of combustion products or seam gases across a fire leading to an explosion?

Summary details on the operational characteristics of these and other inertization units are given in Table 1. Various types of inertization systems are currently available and in use in Australian coal mines for elimination of the potential explosibility of newly sealed gobs, for combating gob spontaneous combustion headings, for sealing of old mine workings or for stabilizing fires in high priority locations.

Table 1 Characteristics in simplified form of the outlet flow of the GAG-3A, Mineshield, Tomlinson boiler and Membrane Floxal inertization units.

	Flue Gas Generator (Tomlinson Boiler)	Mineshield Liquid Nitrogen System	GAG unit	Membrane System (AMSA Floxal Unit)
Inert Output Range, m^3/s	0.5	0.2 – 4.0	14 – 25	0.12 – 0.7
Default Quantity, m^3/s	0.5	2.0	20	0.5
Delivery Temperature, °C	54	Atmospheric	85	20
Oxygen, %	2	0	0.5	3
Nitrogen, %	81.5	100	80 – 85	97
Carbon Dioxide, %	15.3	-	13 – 16	-
Carbon Monoxide, ppm	0	-	3	-
Water Vapor, %	1.2	-	some	-
Water droplets			significant	

Sources: Tomlinson Boilers, 2004; MinesShield, 2002-3; Bell, 1997; AMSA Floxal Unit, 2006.

3 Case Study I: Nitrogen inertization

The purpose of this case study was to provide an estimation of the time required to inert a sealed single entry development at an Australian underground coal mine using a membrane nitrogen gas unit. Data supplied by the mine are as follows.

1) Diagram (Figure 1) of the sealed single entry development heading and inertization arrangement.
2) Parameters of the sealed single entry development roadway are:
   - Total length of sealed zone 280 m with brattice sail partition,
   - Dimension of the single entry roadway 2.6 m by 5.3 m., and
   - Gas make methane (CH_4) is 14 m^3/hr; carbon dioxide (CO_2) is 7.2 m^3/hr.
3) Parameters of the inertization system proposed,
   - A nitrogen gas inert unit with inert line into the sealed zone and an inert capacity of 1100 m^3/hr 0.316 m^3/s.
   - Inert gas output oxygen level of 0.01%.
   - Brattice sail partition starting from the seal and along the 280 m single entry roadway to the dead end. End of brattice sail is 3 m from the dead end.

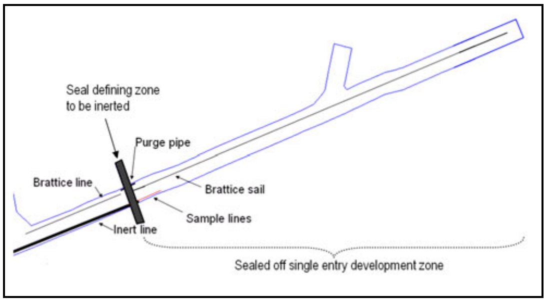

Figure 1 Layout of the seal and inertization arrangements

In order to estimate the time required to adequately inert the sealed single entry roadway, three approaches have been used. These are:

a) Dilution or flushing rule-of-thumb – time determined from inert gas flow rate and mined void volume:

$$\tau = C\frac{Y}{Q} \qquad (1)$$

b) Gas mixing and dilution Equation (Hartman *et al*., 1997):

$$\tau = \frac{Y}{Q}\ln\left(\frac{BQ + Q_g - (Q + Q_g)x_0}{BQ + Q_g - (Q + Q_g)x}\right) \qquad (2)$$

where
- Y is volume of working space in m^3,
- τ is time in seconds,
- x is concentration of contaminant in the mixture,
- x_0 is concentration of contaminant in the working space initially,

B is concentration of contaminant in normal intake air, and

C is a constant set at for instance 3**.**

c) Ventgraph fire simulation program and model.

3.1 Dilution or flushing rule-of-thumb

The time required for the nitrogen unit to adequately seal a single entry heading using the dilution or flushing rule-of-thumb can be calculated by knowing the volume of the sealed area (4,000 m^3) and the inert flow rate (0.316 m^3/s). For instance, 10.5 hrs is required for the nitrogen unit to fully inert the sealed area if three time rule is acceptable from Equation 1**.** The following table shows various estimated times required with various constant values used.

Table 2 Times required for inerting the sealed area with various constant values used

Constant Values Used	Time Required for the Inert system to achieve (hrs)
1	3.5
2	7.0
3	10.5
4	14.0
5	17.5
6	21.0

3.2 Gas mixing and dilution Equation

A spreadsheet was constructed from Equation 2 for gas mixing and dilution to calculate the time required for the gas output from the membrane nitrogen unit to inert a sealed single entry heading. Parameters used are listed as Table 3.

Table 3 Parameters for Example 1 exercise

Length	290 m	Sealed roadway length
Area	13.78 m^2	Cross-sectional area
Volume, Y	3996.2 m^3	
Inert Gas Q	0.3159 m^3/s	
CH_4	0.0039 m^3/s	CH_4 Gas make: 14 m^3/hour
CO_2	0.0020 m^3/s	CO_2 Gas make: 7.2 m^3/hour
$O_{2\ Initial}$	20.7 %	Initial O_2 content
$O_{2\ Membrane}$	0.01 %	Membrane unit output

Calculation showed to achieve an oxygen level of 1.0% in the sealed area it would take the proposed inertization system about 10.7 hrs. Times required for the inert system to achieve various other oxygen levels within the sealed area are shown in the Table 4.

From the use of Tables 2 and 4 it is possible to back calculate the resulting oxygen levels for various constant values used in the dilution or flushing rule-of-thumb calculation for the time required for the inert system to inert the sealed area. A correlation is derived between the constant values used and the resulting oxygen levels and is described in the Figure 2. Table 5 shows the resulting oxygen levels for the constant values used in Table 2.

Table 4 Times required for the inert system to achieve various resulting oxygen levels in the sealed area

Resulting oxygen Level in the Sealed area (%)	Time Required for the Inert system to achieve (hrs)
8.0	3.3
6.0	4.4
4.0	5.8
2.0	8.2
1.0	10.7
0.5	13.2
0.1	19.1

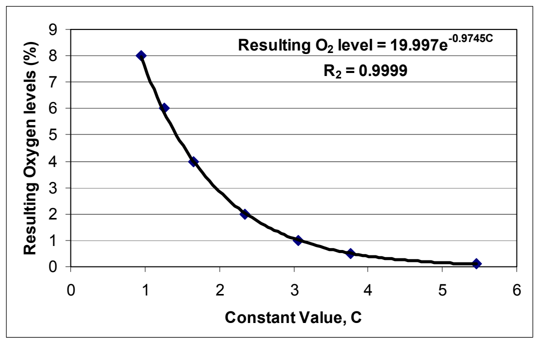

Figure 2 Correlation between constant vales, C and the resulting oxygen levels for dilution or flushing rule-of-thumb.

Table 5 Times required for the inert system to achieve various resulting oxygen levels in the sealed area

Constant Values Used	Time Required for the Inert system to achieve(hours)	Resulting oxygen Level (%)
1	3.5	7.6
2	7.0	2.9
3	10.5	1.1
4	14.0	0.4
5	17.5	0.2
6	21.0	0.1

Table 5 can be used to establish safe or acceptable times to achieve a desirable oxygen levels in the sealed single entry development drive. For instance if desired oxygen level is 3.0% then a time just less than 7 hrs is required and if 1.0% is required then a little over 10.5 hrs is necessary. In these cases achieving 3.0% requires a minimum dilution or flushing constant value of about 2 while achievement of 1.0% requires flushing constant of about 3. It is generally accepted that in a fire situation a two percent oxygen atmosphere will be sufficient to inert burning or smouldering coal as long as this minimum level is held for a considerable time.

3.3 Ventgraph fire simulation program and model

A Ventgraph simulation based on the Figure 1 and Table 3 mine data shows that it takes about 10.2 hrs for the membrane nitrogen unit inerting system to reduce the oxygen level in the sealed area down to about 1.1% as shown in the Figure 3. The model created here assumes some leakage from the wide side of the heading to the narrow side behind the brattice by use of modelled leakage paths every 50 m along the length.

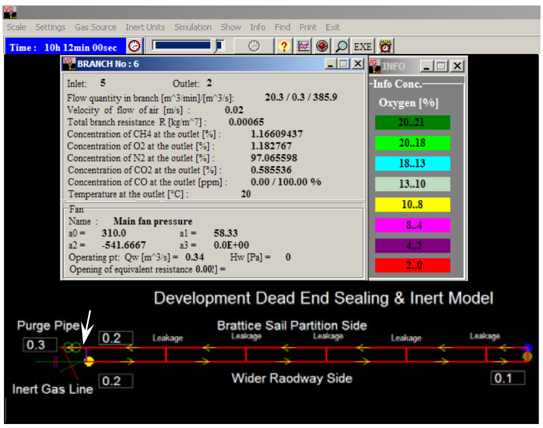

Figure 3 Snapshot from Ventgraph simulation after 10.2 hrs with oxygen level at about 1.1%.

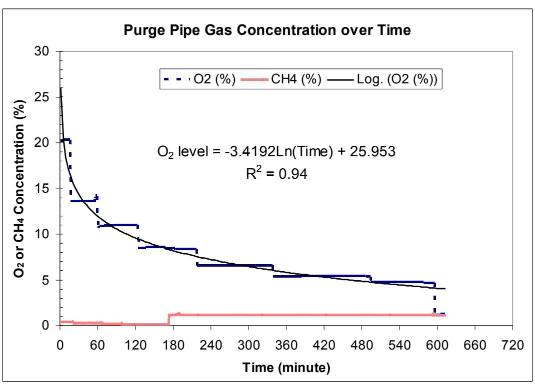

Figure 4 Predicted Gas Concentration in the Purge Pipe over time from Ventgraph simulation outputs.

Figure 4 shows Ventgraph model simulations for oxygen and methane levels over time in the atmosphere leaving the face heading through the purge pipe. The Ventgraph model has taken into account the effects of seam gases CH_4 and CO_2 and leakages between the two sides of the brattice sail along the single entry roadway on the inerted atmosphere.

It is essential to ensure the inert gas travels along the wider side of the brattice sail to the end of the roadway and then travels back down the narrow side of the brattice sail to the purge pipe. The brattice sail should start immediately from the seal and be well installed to avoid leakage. A tight fit of the line brattice to the seal is very important.

3.4 Summary

Based on the simple gas dilution or flushing rule-of-thumb with three times volume requirement, it was found that it will take the membrane nitrogen inerting system about 10.5 hrs to fully inert the sealed area with an oxygen level down to about 1.1%. A time of between 8 and 9 hrs would have inerted the void to about 2% oxygen level. When applying the gas mixing and dilution equation calculation, it was found that it would take the membrane nitrogen inertization system about 10.7 hrs to achieve an oxygen level of 1.0% for example in the sealed area. Times required for the inert system to achieve various resulting oxygen levels in the sealed area were also given.

From Ventgraph simulations it is shown to take about 10.2 hrs for the membrane nitrogen inerting system to reduce the oxygen level in the sealed area down to 1.1% with the assumptions of some leakage from the wide side of the heading to the narrow side behind the brattice by use of modelled leakage paths every 50 m along the length.

In summary, it was found that all three approaches are indicating that it will take around 10 hrs to fully inert the sealed single entry development with a resulting oxygen level of about 1%. A slightly shorter time may apply sufficient inerting of 2% oxygen level and so this determination is conservative.

It should be noted that all three approaches have not taken into consideration the climatic pressure effect on the sealed area caused by the magnitude of the diurnal pressure changes over time and the time of day. It would be wise to act on the conservative side and allow a safety factor in calculating the time necessary for inertization of the dead end heading.

4 Case Study II: Diesel Fired Boiler Inertization

The purpose of this case study is to provide an estimation of the time required to inert a sealed coal Mains development in case of emergency using a diesel fired boiler inertization unit. This is part of the requirement for a mine in preparation of their mine emergency management plan. Data supplied by the mine are as follows.

1) Diagram of the sealed Mains development areas and inertization arrangement as shown in Figure 5.
2) Parameters of the sealed Mains development roadways,
    - 66 roadways with a total length of 2,273 m.
    - Dimension of the roadway 2.7 m by 5.0 m.
3) Parameters of the inertization system proposed,

- Three inertization boreholes, one 0.76 mØ and two in 0.56 mØ are located at 4 ct between B and C Headings.
- The boreholes are 54 m in length with a surface steel manifold structure to connect the boreholes to the inertization unit as shown in the Figure 6. The manifold is designed and manufactured to be a docking portal for the GAG jet engine inertization unit owned by the Queensland Mine.
- Rescue services and this is a statutory requirement in Queensland underground coal mines.
- To inert the Mains area, all intake portals will be sealed and the main exhausting fan stopped but with fan louver doors left open for venting.

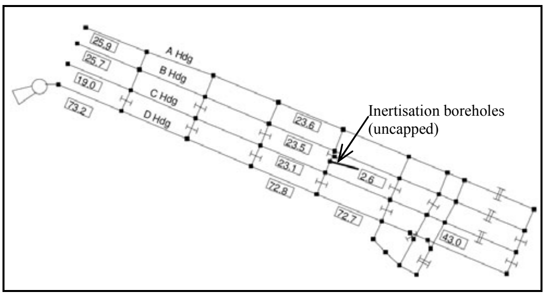

Figure 5 Layout of the Mains development area and inert boreholes arrangements

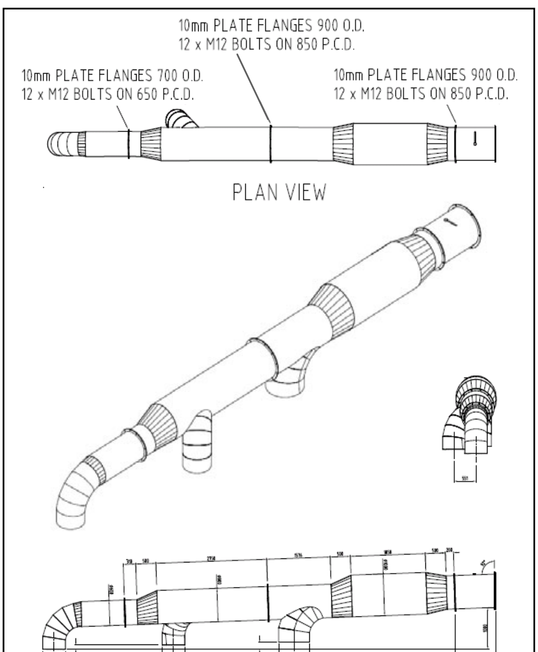

Figure 6 Schematic diagram of surface steel manifold structure for inertization

The same three approaches as described in Case Study I have been used to estimate the time required to inert the sealed Mains development roadways.

a) Dilution or flushing rule-of-thumb – three times volume requirement
b) Gas mixing and dilution equation
c) Ventgraph fire simulation program and model

4.1 Dilution or flushing rule-of-thumb

For the time required for the diesel boiler unit to inert the sealed Mains development area using the dilution or flushing rule-of-thumb was calculated by knowing the volume of the sealed area (30,685 m^3) and the flow rate of inert (0.51 m^3/s). Table 6 shows the resulting oxygen levels for various constant values used in the dilution or flushing rule-of-thumb calculations. An estimate of 50.1 hrs is required for the diesel boiler unit to fully inert the sealed area to an oxygen level of 2.9%.

Table 6 Times required for the inert system to achieve various resulting oxygen levels in the sealed area

Constant Values Used	Time Required for the Inert system to achieve(hrs)	Resulting oxygen Level (%)
1.0	16.7	7.8
1.5	25.1	6.1
2.0	33.4	4.8
2.5	41.8	3.7
3.0	50.1	2.9
3.5	58.5	2.3
4.0	66.9	1.8
4.5	75.2	1.4

Table 7 Parameters for Example 2 exercise

Length	2,273 m	Sealed roadway length
Area	13.5 m^2	Cross-sectional area
Volume, Y	30,685 m^3	
Inert Gas Q	0.51 m^3/s	
$O_{2\ Initial}$	20.7 %	Initial O_2 content
$O_{2\ Diesel\ Boiler}$	2.0 %	Diesel boiler output

4.2 Gas mixing and dilution Equation

A spreadsheet was constructed to use the gas mixing and dilution equation to calculate the time required for the output from a diesel boiler unit to inert a sealed multi-entries Mains area of a coal mine. Parameters used in the spreadsheet are listed in Table 7.

For the gas mixing and dilution equation calculation, it was found that to achieve an oxygen level of 3.0% for example in the sealed area, it would take the proposed inertization system about 49.0 hrs to do so. Times required for the inert system to achieve various resulting oxygen levels in the sealed area are shown in the Table 8.

Table 8 Times required for the inert system to achieve various resulting oxygen levels in the sealed area

Resulting oxygen Level in the Sealed area (%)	Time Required for the Inert system to achieve (hours)
8.0	19.0
7.0	22.1
6.0	25.8
5.0	30.6
4.0	37.4
3.5	42.2
3.0	49.0
2.5	60.5

4.3 Ventgraph fire simulation program and model

From Ventgraph simulation it is shown to take about 50.5 hrs for the diesel boiler inerting system to reduce the oxygen level in the sealed area to 3.0% as shown in Figure 7 and with the assumptions of resistance values for the portal seals at 1,000 Ns^2/m^8. The model created here uses one borehole branch with equivalent cross-sectional area and resistance to represent the three surface boreholes and is based on assumptions of resistance values for the portal seals ranging from 100 to 10,000 Ns^2/m^8.

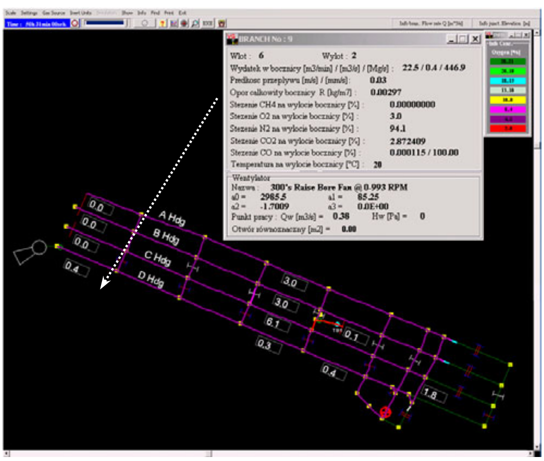

Figure 7 Snapshots from Ventgraph simulation after 50.5 hrs with oxygen level in the seal area at about 3.0% with Portal seals, R=1,000 Ns^2/m^8.

Figure 8 shows the oxygen levels over the time in the exhaust fan outlet from sensor outputs in the Ventgraph model simulation. It should be noted that the Ventgraph model is able to take into account of the effects of leakages in the seals installed at the Mains portal entries. It also simulated the inertization without the assumption of prefect mixing as applied in the calculations for dilution or flushing rule-of-thumb and gas mixing and dilution Equation. 1.

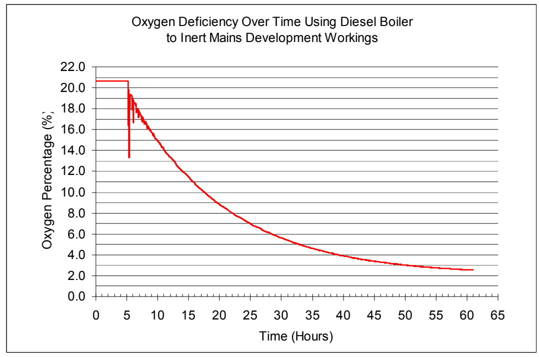

Figure 8 Predicted oxygen levels over time from Ventgraph outputs (Portal seals, R=1,000 Ns^2/m^8).

The times required to achieve the desirable oxygen levels in the sealed area will vary depending on the resistance values used for portal seals. Table 9 shows times required for the inert system to achieve various resulting oxygen levels in the sealed area based on three resistance values applied to the portal seals.

Table 9 Times required for the inert system to achieve various resulting oxygen levels in the sealed area

Resulting oxygen level (%)	Time required to achieve inert level in hours for varying seal resistances		
	R=100 Ns^2/m^8	R=1,000 Ns^2/m^8	R=10,000 Ns^2/m^8
8.0	24.9	22.0	18.1
7.0	27.9	24.9	20.5
6.0	31.5	28.4	23.7
5.0	36.1	33.0	27.3
4.0	42.3	39.2	32.6
3.5	46.5	43.7	36.9
3.0	53.5	50.5	42.6
2.5	66.0	62.3	53.6

4.4 Summary

In summary, it was found that based on the simple gas dilution or flushing rule-of-thumb with three times volume requirement, it will take the diesel boiler inerting system about 50.1 hrs to fully inert the sealed Mains area. When applying the gas mixing and dilution equation calculation, it was found that it would take the diesel boiler inertization system about 49.0 hrs to achieve an oxygen level of 3.0% for example in the sealed Mains area.

From Ventgraph simulation it is shown to take between 42.6 to 53.5 hrs for the diesel boiler inerting system to reduce the oxygen level in the sealed Mains area down to 3.0% with assumptions of resistance values for the portal seals ranging from 100 to 10,000 Ns^2/m^8.

However, as mentioned previously all three approaches have not taken into consideration the climatic pressure effect on the sealed area caused by the magnitude of the diurnal pressure changes over time and the time of day. It would be wise to act on the conservative side and allow a safety factor in the prediction of times required for inertization of the sealed Mains area.

5 Conclusions

Mine fires are recognized across the world as a major hazard issue. New approaches allowing improvement in understanding their use of inertization techniques have been examined. The outcome of the project is that the mining industry is in an improved position in their understanding of mine fires, use of inertization and the use of modern advances to pre-plan for the handling of possible emergency incidents.

The primary objective of the study has been to use various available approaches to gain better understanding of how inertization delivered gases can interact with the complex ventilation behaviour underground during a potential fire. Case studies have been developed to examine usage of induced inertization tools available to the Australian coal mining industry. Comparisons are made of estimations of the time required to inert include:

- the application of "commonly accepted rules-of-thumb" for fluid dilution or flushing with minimum three times quantity of inert gas requirements,
- the utilization of gas mixing and dilution equations, and
- the use of advanced fire simulation network software for and modelling of the mine ventilation system.

It was found that in general, these three approaches all give reasonable estimation of the times required to inert a sealed area. However, the simple gas dilution or flushing rule-of-thumb and the gas mixing and dilution equation do not take into consideration leakages presented in mine ventilation systems and assume a prefect gas mixing scenario in their estimations. Use of the Ventgraph fire simulation program is able to take these into account but need careful modelling to reflect the behaviour of the mine ventilation network under consideration.

It should be noted that all three approaches have not taken into consideration the climatic pressure effect on the sealed area caused by the magnitude of the diurnal pressure changes over time and the time of day. It would be wise to act on the conservative side and allow a safety factor in the time required for inertization of the area.

It could be concluded that fire simulation modelling for these problems most fully takes into account the mine ventilation situation and so allows the most accurate estimation of time for inerting to take place. The direct calculations are simpler and more approximate but do not require the effort to set up the fire simulation model.

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