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The application of nitrogen to control a spontaneous combustion event during a longwall face salvage

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ABSTRACT: In the UK, powered supports are normally salvaged from longwall faces on completion of production, for reuse on the next unit. Where a spare set of supports are held, the salvaged supports are often stored in underground roadways awaiting installation. One mine in the UK extracts a 5m section, and holds two sets of 2x950t powered supports, each weighing approx. 35t and having closed dimensions of 8m long, 2.5 high and 1.75m wide. As the first set would not be required for over 12 months, and because of space limitations below ground, it was decided that the supports would be left in situ, the district sealed, and reopened at a later date for support salvage. The paper described the decision making process, and the inertisation of the sealed district utilising nitrogen generated on the mine surface and piped to the point of use. The re-entry and re-ventilation of the district are also described. The paper then goes on to describe in more detail the discovery of a spontaneous combustion event that occurred in the waste behind the powered supports, and its treatment and control using extra nitrogen brought to the mine by tanker and introduced at strategic locations along the faceline via boreholes, leading to a successful salvage and re-sealing.

1 Introduction

Daw Mill Colliery is situated some 20 km (12 miles) north east of Birmingham. The mine opened in 1967 and is the most productive mine owned by UK Coal Mining Limited, with a workforce of around 500 and an annual output of 2.5 million tonnes. The seam worked is the Warwickshire Thick, which is a composite of a number of seams with a combined thickness of 7m. Current extraction is 5m, limited by equipment and by the need to maintain a coal roof to aid support of weak overlying strata.

The mine is served by two, 500m deep shafts, one downcast and the other upcast; and a surface drift which is utilised for materials and coal clearance as well as acting as a second intake. The current working area is approximately 6 km to the south west of the shafts. The working area is split into two sides, 300s to the east and 30s to the west, with one side producing while the other is developing.

The two working areas are ventilated antitropally with the working face supplied with a minimum air quantity of 24 m^3s^{-1}. A booster fan installation consisting of four, 112 kW fans in parallel is situated immediately outbye of the two working areas. This installation develops a pressure of 1.5 kPa and passes an air quantity of approximately 95 m^3s^{-1}. The ventilation strategy for the mine is high quantity at a low pressure to minimise the risk of spontaneous combustion.

The Warwickshire Thick seam has always been highly susceptible to spontaneous combustion. This has been supported analytically using the 'cross-over temperature test;' this is an empirical test which simulates the low temperature oxidation process involved in the spontaneous combustion of coal by heating a sample at a given rate and measuring the heat output of the sample as the oxidation process develops. The point at which the temperature of the sample begins to rise faster than the container temperature is known as the cross-over temperature, and indicates the point at which the oxidation process is self sustaining. A seam is classified as high risk if the cross-over temperature is below 200°C. The cross-over temperature for the Warwickshire Thick is 160°C.

2 Colliery Services

2.1 Tube Bundle Monitoring System

The mine was served by a network of 19 plastic tubes, each about 6mm (¼") internal diameter. These lead from a surface pump and analyser, initially in a bundle through the upcast shaft, gradually fanning out to various strategic locations in the mine. The system works by constantly drawing the ambient atmosphere into the tubes by the surface pump; the analyser then sampling each tube in turn.

Tubes will be sampled at typically 20-minute intervals, although the order of sampling can be adjusted to keep a closer eye on any particular location. Because the tubes are some km long, there is a delay between drawing the sample into the tube, and it arriving on the surface for analysis. In the case of 301s tailgate at the face finish position, the delay was 2.5 hours. Test samples introduced had sample recovery concentrations in excess of 95%.

2.2 Colliery Nitrogen System

The use of nitrogen at the colliery formed an integral part of the control measures in place to counter the risk of spontaneous combustion. This has resulted in a constant demand, which is met by the installation of two, Pressure Swing Absorption (PSA) Nitrogen plants on the Colliery surface. Each plant is capable of producing 20 m^3 per minute, of >98% purity nitrogen which is then delivered via dedicated pipe ranges to underground discharge points.

3 301s District

3.1 Layout

301s retreat face was the first production unit in 300's area of coal and had a retreat length of approximately 3000m and a panel width of 300m. The panel lay at a depth of approximately 900m and retreated slightly to the rise. Coalface support was by Joy 2x950 IFS Powered Roof Supports (PRS), with support of the gate roads by rockbolting. Coal was cut by an Eickhoff SL 500 double ending ranging drum shearer, fitted with 2.75 m diameter x 1m web drums.

Production commenced in April 2002 and was completed in May 2005 producing some 5.69 million tonnes of coal from the panel. The first year was dogged by unforeseen geological problems but the district achieved an average weekly production over the life of the district of 50 000 tonnes and a peak weekly output of 90 000 tonnes.

3.2 Treatment Post-Production

When 301's was replaced as the production unit at the colliery by 31's, this face was equipped with a second set of powered supports, the consequence of which was that the powered supports on 301's would not be required on the subsequent 302's face for about 18 months. Sufficient storage room was not available in the underground roadways to accommodate storage of this number and physical size of powered support, nor was it feasible to dismantle the powered supports for return to and storage on the surface. Following the exploration of various potential courses of action and in consultation with various specialists it was decided that the safest way forward would be to seal the district with the powered supports in-situ and then to re-enter the district nearer the time when 302s was available to accept them. This was always subject to there being no spontaneous combustion activity present prior to sealing.

This course of action was quite innovative for this purpose although two districts at another of the company's mines had been sealed with all the mining equipment in-situ and inertised with nitrogen to prevent spontaneous combustion whilst the workforce at the mine was on strike. As Daw Mill had its inherent problems of spontaneous combustion, wider views and opinions from outside the company were sought, including HSE's Mines Inspectorate for legal and mining engineering input, and TES Bretby (UK Coals scientific services provider) for mine air analysis and interpretation. UK Coal's Insurers were also consulted regarding cover during the sealing in and recovery of the powered roof supports.

It was decided to prepare the faceline for salvage, then to seal off the district with the supports in-situ. The onset of spontaneous combustion would be prevented by inertising the district by flooding it with nitrogen, fed from the surface. The atmosphere within the district would be monitored to ensure that it was maintained in an inert state.

3.3 Sealing

The intake face end had been identified as the most significant air leakage path into the waste and thus the most likely causal trigger of any spontaneous combustion event. To help seal the waste at the intake end, during the final cuts of the working face, a ventilation seal had been constructed immediately behind the face at the intake end.

To help seal the waste at the tailgate end, a ventilation seal was constructed across the tailgate, immediately behind the return end of the face. This ventilation seal incorporated a deep waste sampling pipe which was extended the length of the tailgate and into the main return, thus allowing samples to be collected from this point either by the Tube Bundle system or by traditional hand sampling methods. In addition, three pipes were left through this seal, to points 40, 15 and 7m into the waste for possible future sampling. One of these later proved invaluable. (Figure 1).

The district was sealed in August 2005 at the outbye ends of each gate, by the construction of 5m long explosion proof stoppings. To permit injection of nitrogen for inertisation purposes, pipes were laid through the intake stopping. One was to a point 30m into the waste behind the face at the intake end of the face: as was standard practice at the colliery, nitrogen from the surface plant was already being discharged into the waste at this point. The second was to a point immediately inbye the intake stopping. A third nitrogen injection pipe was left through the tailgate stopping should the need subsequently arise for introduction of nitrogen to this side of the district.

All ventilation regulators on 300's return between the gates were removed to minimise the pressure drop across the district.

3.4 Inertisation

The flow of Nitrogen delivered to the point 30m into the waste at the intake end was determined by an orifice measuring device sited at the inbye end of the coal gate

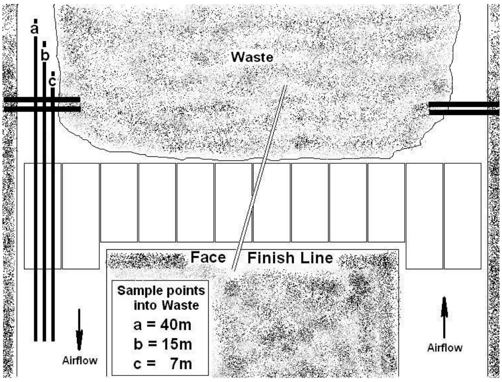

Figure 1. Face end seals and sample pipe configuration

and was routinely measured around $2m^3$ per minute. A total of about 7 m^3 per minute were delivered to the district in total, and quickly replaced the existing atmosphere within the district.

Tube Bundle sampling points had been left within the district to monitor the effects of the inertisation, these were located at the inbye and outbye end of the tailgate, with a third sample point 30m down the face line from the tailgate end. This third sample point was discontinued following re-entry to the district.

During the time that the district was sealed, analysis of the tube bundle samples confirmed that there was no indication of any spontaneous combustion activity. Table 1 shows a typical analysis.

Table 1. Typical analysis from behind the tailgate stopping.

Gas	Analysis %
Methane	50.0
Oxygen	1.58
Nitrogen	44.71
Carbon Dioxide	3.7
Carbon Monoxide	0.0017
Hydrogen	0.001

It is interesting to note that despite the fact that nitrogen was constantly being injected, during the whole of the time the district was sealed excess nitrogen was never seen at the sampling point at the outbye end of the tailgate. This sampling point essentially only saw displaced waste gas, which consisted of high concentrations of methane and carbon dioxide. This is influenced by the gradients within the district, which because of faulting encountered, meant that the tailgate was much higher than the intake and faceline, thus allowing the more buoyant waste gasses to migrate there. The analysis from behind the intake gate stopping showed > 90% nitrogen and < 2% oxygen reflecting the fact that nitrogen was being injected directly behind this stopping near to the sample point.

4 Recovery

4.1 Re-entry

Planning the re-entry required a multi disciplined approach, involving staff from the Colliery, the Mines Rescue Service and Company specialist personnel. In April 2006 the district was degassed, re-ventilated and the stoppings breached. It was planned to ventilate the district within the range 5 – 7 m^3s^{-1} to minimise the introduction of oxygen into the waste.

Following the establishment of an air circuit, the intake stopping was then demolished to permit vehicular access for the necessary roadway refurbishment and subsequent equipment removal. As 302s was behind schedule, no urgency was placed on 301s salvage and progress was slow.

4.2 Start of Salvage

Salvage on the faceline commenced with the AFC working from the intake gate end up the face. By December 2006 all the AFC had been removed work was concentrating on commissioning of the Petito Mule, to be used on the face line for pulling the PRS out of rank, and the Eimco 942 transporters which would be used to remove them from the district. Work was suspended over the Christmas period. From the initial re-entry right up to this point environmental results continued to show that there was no spontaneous combustion activity: Figure 2 showing between 7 and 9 ppm generally during the early part of December 2006.

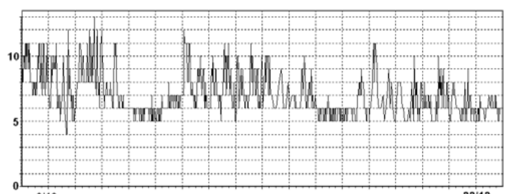

Figure 2. District CO level 5th December to 22nd December 2006.

4.3 Detection of Spontaneous Combustion Event

On the morning of Christmas Eve, CO levels were at their normal level of 6/7 ppm. However CO levels on the district started to rise and by noon on Christmas Day the CO level at the outbye end of the tailgate was 10ppm, and by midnight 14ppm. On Boxing Day morning the inspecting official identified what he thought was the source of an incipient heating with an increased CO pick up in the roof at around 150 PRS. This CO rise is shown by figure 3.

On Boxing Day, members of the colliery management team went underground to appraise the developing situation, and formulate a plan of action. The following day a significant number of staff was assembled at the colliery and dedicated to the incident. An Incident Committee was formed prior to going underground for an

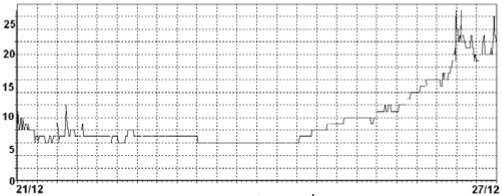

Figure 3. District CO level 21st to 27th December 2006

inspection: the Committee included Mine Management, Headquarters Senior Mining Directors along with Safety/Environment staff and Technical Advisors from TES Bretby.

The on site inspection could not identify any obvious signs of an inward leakage path at the intake end of the face, but it was thought probable that there was some significant leakage around the intake ventilation seal.

4.4 Evaluation

Table 2 shows the gas concentrations between 29/12/06 and 01/01/07 from the control sample pipe 'B,' 15m behind the face line at the tailgate end of the face. Over this period physical signs of increased activity of the heating were observed with smoke and glowing embers reported between 154 and 155 PRS on the night of 30/12/06.

Interpretation of the analysis was complicated by the fluctuating presence of waste gas and the possibility that injected nitrogen had reached the sample point. However it was believed that at this stage of the incident nitrogen injection rates were not of sufficient volume to drive nitrogen to the sample point. Figure 4 shows the CO concentration in the tailgate during this period.

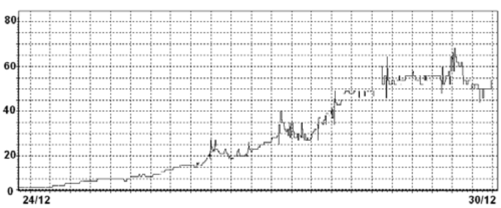

Figure 4. District CO levels from 24th to 30th December 2006.

Table 2. Gas Concentration from Control Sample Pipe B.

	29.12.06	31.12.06	1.1.07
CH_4 %	12.80	13.60	12.80
O_2 %	3.05	4.12	4.77
N_2 %	80.29	78.34	78.6
CO_2 %	3.85	3.90	3.70
CO %	0.0057	0.0210	0.0650
H_2 %	0.0065	0.0160	0.0630
Graham Ratio	0.03	0.13	0.41
CO:H_2 ratio	0.9	1.3	1.0

Hunneyball (2000), recognises and describes three key indicators in assessing whether a heating is progressing: the carbon monoxide concentration, the Graham Ratio and the carbon monoxide: hydrogen ratio. In this particular incident, the carbon monoxide concentration showed a sharp increase over the period coupled with a similar increase in the Graham Ratio. The value of the latter on 01/01/07 indicated a heating temperature below 100°C. However the carbon monoxide: hydrogen ratio of approximately 1.0 indicated a well established heating with a temperature in excess of 100°C. The assessment taking into account all three indicators concluded that the Graham Ratio result should be used with caution because of the nitrogen injection, although the trend was valid. The most useful indicator was considered to be the carbon monoxide to hydrogen ratio which, coupled with the sharp increase in the carbon monoxide concentration, indicated a well established heating that was increasing in activity.

4.5 Control of the Heating

A major difficulty in attempting to control the heating was the number of variable or unknown factors related to its location and its source of oxygen. The Incident Committee considered that the heating was probably located no more than a few metres behind the powered support line, more towards the tailgate rather than the intake gate as incandescent material and smoke were later observed around the bases of 154 and 155 powered roof support on the night of 30th December. It was suspected that air leakage paths existed from the intake gate end of the face into the waste but their routes behind the powered roof supports was unknown. It was assumed that there was a leakage path immediately behind the powered roof supports for much of the length of the face. Tube samples and laboratory analysis showed that products of combustion were being detected at the tailgate end of the face through the sample pipe 15m behind the face end seal. This sample pipe gave a good indication and most reliable information of changes in analysis due to the heating's development and changing barometric pressure.

It was decided that the primary method of controlling the heating should be to inject nitrogen into the main leakage path that was feeding oxygen, such that the leakage air would carry the nitrogen direct to the heating. To this end a second pipe was installed through the intake face end seal to deliver nitrogen closer to the waste edge behind the face. The seal was also reinforced at this time. These measures had no beneficial effect on the heating, so it was then decided to inject nitrogen into the waste in an attempt to intercept one of the leakage paths at the back of the roof supports. This involved drilling holes into the strata over the powered roof supports - a course of action not without risk as it could provide more leakage paths for oxygen to reach the heating.

Each hole had to be carefully drilled, sealed and plugged when completed prior to connection to the nitrogen range. Attempts were made to seal other leakage paths by systematically drilling and injecting cementitious material into the waste to a depth of three metres, every five PRS along the coal face and by spray sealing the waste edge at the back of the powered supports with phenolic foam.

Numerous nitrogen injection points, at various depths and inclinations were drilled into the waste area and their respective impact measured in an attempt to identify the most suitable injection point(s). The success of nitrogen injection and the sealing of air leakage paths was determined by observing a change in the carbon monoxide and hydrogen concentrations at the tailgate sample pipe B.

4.6 Barometric Effects

Monitoring the beneficial effects of the above remedial measures by analysis of the combustion products was complicated by the effects of the barometric pressure which fluctuated widely and sometimes rapidly during the whole incident. This had the effect of drawing waste gas towards, and at other times away from, the sample pipes and either contaminating or diluting the control analysis from these sample pipes. The effect can clearly been seen on Figures 5 to 8, which show that CO, CH_4 and O_2 all varied in line with the barometer, either directly or inversely. A clear understanding of the effects of changing barometric pressure on the control analysis was established and used to inform decision making to avoid erroneous conclusions being drawn from the control analysis.

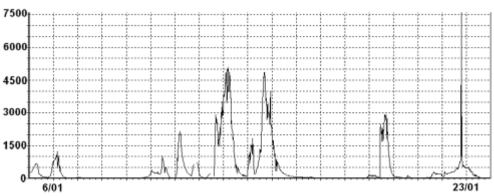

Figure 5. CO level from Sample Pipe B under varying Barometric pressures.

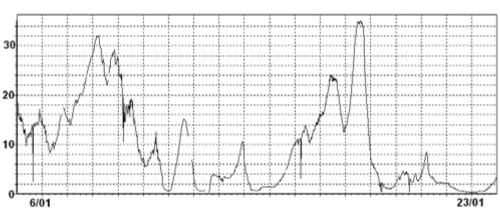

Figure 6. Methane level from Sample Pipe B under varying Barometric pressures.

5 Salvage of the Powered Supports

5.1 Maintenance of Adequate Faceline Ventilation

Various factors had to be taken into consideration to ensure control of the situation was maintained. Previous salvages at the Colliery had always resulted in serious spontaneous combustion problems: an exacerbating factor being the

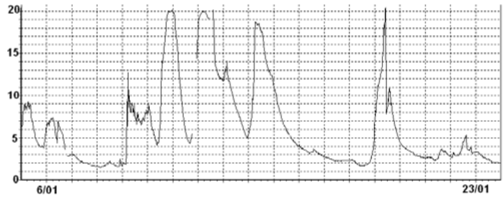

Figure 7. Oxygen level from Sample Pipe B under varying Barometric pressures.

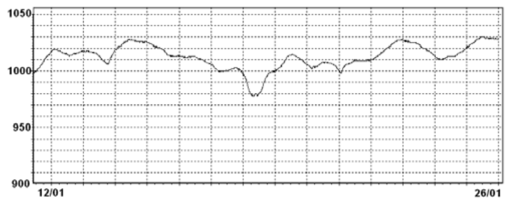

Figure 8. Variation in Barometric Pressure over the sampled period.

support system previously adopted which while adequate for the immediate support situation was inadequate to maintain the salvaged portion of the face line open as an airway for the duration of the salvage operation. The result of this was increased ventilation resistance on the face line and air being forced into the waste, thus increasing the likelihood of a heating. It was imperative that 301's salvaged face line was maintained with an effective cross sectional area, to eliminate any pressure drive into the waste edge.

5.2 Prevention of Oxygen Ingress into Waste

During salvage of the powered roof supports it was essential that local air leakage paths were not set up which could have resulted in leakage of oxygen into the waste. These could feed the heating, encourage it to move or even change the flow of the nitrogen and possibly change the route of the combustion products away from the sample pipes. In addition to the programme of sealing the waste behind the PRS discussed above, further sealing was carried out with phenolic foam behind the PRS themselves.

5.3 Salvage Rate of The PRS

A PRS salvage rate of four per day was considered to be the optimum achievable. This salvage rate included drawing the PRS from rank by the Petito Mule and transporting it off the district using the Eimco 942 transporters. Wooden cribs could then be built to support the newly exposed roof, to maintain a stable airway through the salvaged part of the faceline. In addition, further phenolic foam treatment of the waste edge was undertaken as soon as the PRS had been removed and support set, to maintain the seal at the waste edge.

PRS salvage commenced at the tailgate end and progressed towards the intake gate, the first two normal supports were turned and used as soldier supports, behind which could be built the cribs to support the face line from where the powered supports had been removed.

5.4 Maintenance of Inert Waste

During the salvage operation it was vitally important to maintain or improve the flow of nitrogen at the injection points on the face to maintain the inert state of the waste generally, and to maintain the flow of nitrogen towards and over the heating site. It was also important to maintain the control gas sampling points at the tailgate end of the face.

A hole was drilled at the back of number 1 and 2 PRS and coupled to the Nitrogen range. A series of longer length 75mm (3”) diameter holes were also drilled to enable nitrogen to be injected deeper into the waste in further attempts to locate and intercept the main leakage paths. These holes were drilled on the intake side of the considered location of the heating, and are detailed in Table 3.

Table 3. Detail of Additional Nitrogen Injection Holes, 5 March 2007.

Location	Flow, m^3 / minute
Into the Mine	19.68
Intake face end seal	1.64
3 – 4 PRS	2.15
3-4 PRS low	0.00
13 PRS	0.00
17 PRS	0.00
53 PRS	0.00
80 PRS	9.19
102 PRS	1.30
121 PRS	0.71
131 PRS	0.00
147 PRS	-0.00

5.5 Maintenance of Nitrogen Flow

With the increasing number of discharge points, the amount of nitrogen provided by the colliery’s plant needed to be increased. To this end a commercial suppler was contracted to supply nitrogen by road tanker to supplement the existing plant.

As more holes were drilled in the waste, the system had to be adjusted to maintain nitrogen to the waste holes as well as nitrogen into the waste at the intake face end. Orifice measurements taken initially indicated that there was 11.07 m^3 per minute being pumped onto the district, which split 2.79 m^3 per minute into the waste at the intake end and 9.72 m^3 per minute going on to the face line holes. Fortunately the first of the 75mm (3”) diameter holes bored at number 80 PRS, (approximately in the middle of the face), hit significant breaks and allowed nitrogen to be pumped into it at flow rates ranging from 3.92 to 9.92 m^3 per minute. As more holes were bored into the waste, nitrogen flow was increased to a maximum of 22.00 m^3 per minute to the district.

5.6 Final Sealing

All the powered roof supports were salvaged by the 23rd March and the district was finally sealed by 5m explosion proof stoppings. Inertisation was achieved by the 29th March 2007. (Figure 9).

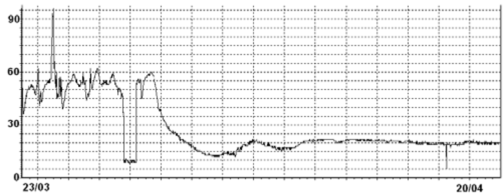

Figure 9. CO at sample point B during sealing / inertisation.

6 Conclusions

- The objectives of storing the PRS by leaving them in-situ and sealing them into 301’s district in an inertised atmosphere; and to later re-enter the district and salvage the face equipment, were all successfully achieved, so demonstrating the practicality of this method.
- A spontaneous combustion was allowed to develop on the district, influenced primarily by the extended time taken to perform the salvage after the initial re-entry. This reinforces the need to complete salvage operations within the recognised 13-week incubation period of these coals.
- Providing that no spontaneous combustion event is evident prior to initial sealing, it would be possible to use part of the normal 13-week period to salvage ancillary equipment, e.g. the AFC. Following re-entry, a further 13-week period should then be available to complete the works.
- The event was quickly identified, and then controlled over an extended period of time while all the PRS were removed from the face. This control was enabled by the collection of sound monitoring information, and its expert analysis and interpretation, taking into account both the effects of fluctuating barometer and the effects of nitrogen injection.
- Phenolic foam was used extensively in sealing around and behind the PRS during the salvage operation. The medium provided and maintained a good seal behind the PRS even after each respective PRS was removed from its face position, so minimizing the formation of additional leakage paths into the waste.

Reference

Hunneyball, S R, 2000. The Science of Spontaneous Combustion. *International Mining and Minerals*, 3(32): 205-210