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Spontaneous Combustion Management - Linking Experiment With Reality

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SPONTANEOUS COMBUSTION MANAGEMENT – LINKING EXPERIMENT WITH REALITY

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ABSTRACT: Despite the best efforts of researchers to try to understand spontaneous combustion it still affects many mines. Laboratory testing and modelling have been available for many years and yet they are still not able to reliably predict the propensity for a coal seam to spontaneously combust.

The complexities of the spontaneous combustion process are explored by delving into the chemistry of the oxidation process. It is able to demonstrate why the testing and modelling of spontaneous combustion can be of limited accuracy. Laboratory tests and simulations are carried out under conditions cannot reflect the full complexity of the underground environment. This does not mean that the experimental work is meaningless, but the results need to be included as part of a proper risk assessment that includes the contributions and influences of other parameters currently not able to be adequately modelled or simulated in the laboratory. In addition laboratory testing can offer insights into the influence of such things as water content, ash content and particle size.

It is recommended that the Trigger Action Response Plans (TARP) in place in underground coal mines go beyond detection of spontaneous combustion and include indicators that identify the increased likelihood of spontaneous combustion and allow for controls to be put in place in time to prevent spontaneous combustion from occurring.

INTRODUCTION

Researchers have been attempting to develop methods for predicting the likelihood of spontaneous combustion in coal mines for over 100 years (there are some records going back to the Middle Ages). Despite this, major spontaneous combustion events continue to occur in Australian Underground Coal Mines roughly once a year. These events have not caused any loss of life since Moura No.2 in 1994 but they still necessitate the evacuation of the mine and many days lost production, not to mention the costs of remediation. If the problems in coal stockpiles and open cut mines are added then the severity of the problem escalates significantly.

It is standard practice to establish a spontaneous combustion management plan supported by a risk assessment (RA). This RA is based at least upon prediction of the likelihood of the coal to spontaneously combust. The starting point for this prediction is laboratory testing sometimes coupled with computer modelling. Why are these predictions of limited accuracy?

Consider this example. A consultant provided an assessment of the spontaneous combustion potential of the roof coal above a longwall block for an underground coal mine. This assessment was based upon a combination of small scale laboratory testing of R_{70} indices for the various coal bands in the roof and computer model that attempted to simulate the goaf conditions. The conclusion from the study was that "there does not appear to be any spontaneous combustion potential associated with any of the bands tested". Within two years, for the first time in the history of the mine there was a major spontaneous combustion event that took nearly 12 months to control and cost many millions of dollars in lost production and direct control costs. Neither the mine nor the consultant have been identified, it is not the purpose of the paper to criticise them. There are many examples like this.

To understand why there is often a significant disparity between assessments and reality it is necessary to delve into the fundamental processes involved, appreciate the complexity of the spontaneous combustion process and recognise the multitude of influences and parameters.

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THE CHEMISTRY OF SPONTANEOUS COMBUSTION

The structure of coal

Conventionally spontaneous combustion is thought of as simply coal reacting with oxygen to form carbon dioxide and carbon monoxide. This reduces coal to a simple uniform molecule, which of course it is not. Coal is a macro-molecule which has many different components, each with their own reactivity. Figure one depicts a typical model structure. It shows that coal contains a wide range of functional groups including those containing purely carbon and hydrogen as well as many including oxygen, such as aldehyde, alcohol, ketone, ether, ester, carboxylic acid. These latter functional groups are much more reactive than the pure hydrocarbon groups (Kalema and Gavalas, 1987).

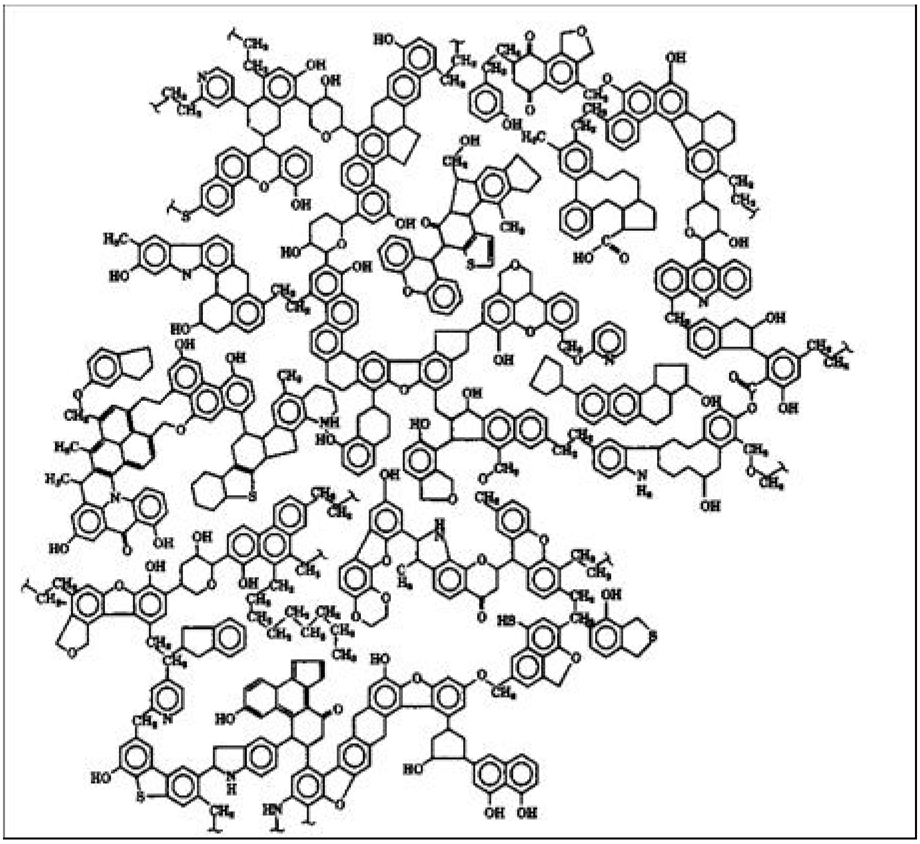

Figure 1 - Coal Model (Wells and Smoot 1991).

The oxidation process

Much can be learnt from mainstream organic chemistry. For example: consider the oxidation of methane to carbon dioxide (Chang, 1994).

$2CH_4 + O_2 =$	$2CH_3OH$	(1)
$CH3OH + O_2 =$	$CH_2O + H_2O$	(2)
$2CH_2O + O_2 =$	$2HCOOH$	(3)
$2HCOOH + O_2 =$	$2CO_2 + 2H_2O$	(4)

The activation energy of each reaction decreases from (1) to (4), this means that less energy is required to initiate reaction (4) than to initiate reaction (1). However the amount of energy released by reaction (4) is much less than if the oxidation process started at reaction (1) and ran through all four reactions. Relating this to coal suggests that coal with significant numbers of functional groups aligned to reactions (3) and (4) are likely to be more reactive than those without them. Conversely the latter coals will generate more heat when they do react with oxygen. The activation energy required to break aromatic hydrocarbon bonds is even higher than for aliphatic hydrocarbon bonds. Generally high rank coals are low in oxygen content and have few reactive functional groups, they are the most aromatic. Therefore generally they are not highly prone to spontaneous combustion and produce the most heat when burnt. Low rank coals, contain more oxygen than high rank coals, and have significant concentrations of oxygenated functional groups. These are generally more reactive and prone to spontaneous combustion but do not generate as much heat when burnt.

The role of water

Of course for coal the oxidation process is a much more complicated chemical system than the simple one outlined above and would involve hundreds of interrelated chemical reactions. Each one has its own temperature and reactant concentration dependence. A further complication to the reaction scheme is the role of water. Water is often only included in spontaneous combustion for its heat transfer capacity – heat of vaporisation and heat of condensation. However it is now clear that water also can become involved in the chemical reactions. Water produces highly reactive free hydroxyl and hydroperoxy; radicals, HO and HO_2 (Ford, 1981). These radicals can act as catalysts in the oxidation process changing the balance between the various reaction paths and mechanisms. Stoichiometry or the ratio of fuel to oxygen also shifts the balance of the reactions.

Other influences

A further complication is that the reactions will occur in four dimensions – three orthogonal spatial dimensions and varying also with time as the nature of the coal changes with time. The concentrations of the reactants and products will vary in each of the dimensions and so for any simulation to be of value it must account for this.

Add to this a whole raft of intrinsic and extrinsic parameters that can influence the spontaneous combustibility of a coal sample. Examples are listed in table 1 below. These affect the ability of the coal to react with oxygen and for heat to be retained or removed.

Table 1 - Examples of intrinsic and extrinsic parameters (from Cliff and Bofinger 1998)

Intrinsic (Properties of the coal)	Extrinsic (external to the coal)
Friability	Thickness of coal seam
Caking property	Ventilation patterns
Heat capacity	Gas drainage
Thermal conductivity – coal and adjoining strata	Geological features – faults, folds and dykes, strata conditions
Coefficient of oxygen absorption	Seam dip
Surface area	Multiple seams
Gas content	Petrography

SMALL SCALE LABORATORY TESTING

Small scale oxidation tests remove most of these variables because the samples are:\

- crushed – removing the effect of surface area, and seam gases
- dried – removing the effect of moisture,
- subject to high air flows – reducing residence time and altering the chemical balance – this favours fast reactions and single stage chemistry
- reacted in uniform temperature environments – removing the effects of ranges in temperature

- taken to represent an entire coal seam – not allowing for natural variation in ash content and chemical composition within the seam (Cliff and Bofinger, 1998).

The oxidation occurs in a uniform environment and only single stage reactions are observed. Despite this there is a broad correlation between the reactivity determined by small scale testing and the historical occurrence of spontaneous combustion in coal mines. Small scale tests only attempt to identify the inherent reactivity of the coal sample. The measure of reactivity is generally relative to other coals with a known history of spontaneous combustion activity. In Australia the most common test is the R_{70} test which determines the rate of rise of temperature of a sample under control conditions between 40 and 70 ^{o} C. Details and critiques of this method can be found elsewhere. As such the determination is the starting point for any assessment of the propensity for spontaneous combustion, not the end point (see for example: Beamish and Arisoy, 2008).

MEDIUM SCALE LABORATORY TESTING

Medium scale tests attempt to bridge the gap between the small and the large scale testing, using larger sample sizes (70 kilograms vs 70 g) and some of the conditions found to stockpiles and goaves (samples not dried nor finely crushed). This method is showing promising results and correlation with events in stockpiles. Unfortunately even this degree of complication is demonstrating reaction processes that we are only starting to understand. This larger scale reactor does allow multi stage reactions to occur in a linear dimension. This allows the study of the interrelationship between the components, and the impacts of moisture, and ash. By understanding these factors the correlation between testing and reality can be improved (Hitchcock and Beamish, 2008).

LARGE SCALE LABORATORY TESTING

Large scale tests use run of mine coal samples of up to 16 tonnes and allow more complex conditions closer to the mine environment to be established but suffer from the time it takes for spontaneous combustion to occur and presupposes that the conditions used in the test simulate the goaf of a coal mine. The large scale reactor tests demonstrate how complex the oxidation process is as it allows for the three spatial dimensions as well as variability in gas concentrations and moisture in each of the dimensions (Clarkson, Beamish and Cliff, 2005).

COMPUTER MODELS

Current computer models are still in their infancy and do not allow for the complexities outlined above. Indeed it is hard to model all the processes involved in spontaneous combustion as some are still unknown. There have been some attempts to allow for the conditions found in a goaf but as described above they can give the wrong answer. Attempts to calibrate the models against experiments have met with limited success (Humphreys, 2008).

DISCUSSION

Laboratory testing should not be abandoned. Testing is providing valuable information on the effects of ash content and other coal composition variables. The medium and large scale tests will give insights into the effects of the other parameters and allow for adequate computer models to be developed. Any assessment of spontaneous combustibility must recognise the limitations of the process used and embody processes to monitor and identify factors that will alter the validity of the assessment.

It is very naïve to expect one single test or calculation to give a universally applicable outcome. When a NERRDC funded study (McGowan, 1987) on thick seam mining was carried out at Ulan Colliery in the late 1980's over 60 R_{70} tests were carried out on the working seam over its 10 m height. Approximately 20 % of the tests were classified as highly prone to spontaneous combustion. The vast majority of samples were determined to have low to moderate reactivity. If only one sample was taken then depending on where it was taken from the reactivity would have been assessed as anything from negligible to highly prone. Testing is the starting point, once this assessment is done then the influence of the extrinsic factors needs to be applied, by experienced mine site personnel, as part of the risk assessment process. This process that should be ongoing, being modified as parameters change or new information comes to hand.

For example: in the case study above, it became evident after mining that unlike previous goaves, the atmosphere in the goaf was remaining close to fresh air, and not going inert. With hindsight this was an indicator that something was different. No indicators of active spontaneous combustion were observed in the goaf for many months after mining, which reinforced the unlikelihood of an event occurring. The assumptions about spontaneous combustibility for this coal are hedged around the atmosphere going inert within a relatively short period of time. The laboratory tests did indicate that the roof coal had a high propensity for spontaneous combustion ($R_{70} > 1$). Historically this had been offset by the inert goaf atmosphere.

Laboratory experiments and models can also give an indication of control measure effectiveness, eg inertisation, or replacing the water content. In addition they can give an estimate of the significance of a change in a key parameter, such as seam thickness, gas drainage or ventilation patterns.

Testing is also giving us insights into the fundamental processes of spontaneous combustion. For example: Recent work by Hitchcock et al has shed new light onto the complex formation process of hydrogen during coal oxidation. This suggests that there is at least two different formation paths for hydrogen during coal oxidation, one relating to the direct oxidation process and the other relating to an anaerobic reaction process downstream of the oxidation zone, at lower temperature, where the coal is still drying out and may contain oxygen absorbed onto the surface of the coal (Hitchcock, Cliff and Beamish, 2008).

TRIGGER ACTION RESPONSE PLANS (TARPS)

Testing and modelling can provide the triggers for detecting abnormality prior to excess oxidation occurring. Triggers do not need to be just the products of oxidation, rather they could include:

- the presence of oxygen where it should not be
- unexpected geology – eg increased seam thickness
- changes to mining method – reduced retreat rate or increased retreat rate
- strata issues that impact upon ventilation of the goaf or mining method
- ventilation changes that affect the flow of gases in the goaf
- changes in coal quality

From geology and core samples zones of higher propensity can be identified, where additional care should be taken. This can include areas where mining may be slow due to difficult terrain, or where extra coal is left in the goaf due to faulting or folding.

Characterisation of the gas atmosphere throughout the goaf that should exist and being able to determine deviation from this early, will enable proactive controls to be put in place. It is better to monitor too much than not enough.

CONCLUSION

Spontaneous combustion management is a complex process and should not be oversimplified. Placing too much reliance on small numbers of tests or computer simulations should be avoided. They provide vital information to assist in the assessment of spontaneous combustion risk. The results of such studies should be included in the overall assessment process, along with knowledge of local conditions and intrinsic and extrinsic factors. More research and testing under controlled conditions is required to allow for the refinement of models and to identify all the factors that can influence spontaneous combustion. Management is an ongoing process.

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