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DEVELOPMENTS IN THE MANAGEMENT OF SPONTANEOUS COMBUSTION IN AUSTRALIAN UNDERGROUND COAL MINES

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ABSTRACT: In 1996 the book Spontaneous Combustion in Australian Underground Coal Mines was first released (Cliff, *et al.*, 1996). Since that time it has been reprinted several times and minor updates have been made. A major overhaul of the book was commissioned by ACARP and this paper reports on some of the changes to spontaneous combustion management that have occurred over the past eighteen years. Our knowledge of the fundamental chemical processes that control spontaneous combustion has improved materially in that time. In addition preventive control measures such as good ventilation and proactive inertisation coupled with computer modelling of goaf behaviour have emerged, as well as improved reactive control measures including the use of foams and gels to control airflow into active goafs. Mine environment monitoring techniques and technology have also undergone major development with sophisticated automated continuous gas monitoring systems being the norm in our mines and ultrafast ultra sensitive gas chromatographs being widely used. Pressure and air flow measurements are also used routinely to monitor and predict airflows not only in roadways but across seals and through goafs.

INTRODUCTION

The last incident in Australia where lives were lost due to spontaneous combustion was the Moura No. 2 mine disaster in August 1994. Since that time no lives have been lost however, significant incidents have still occurred in underground mines requiring the evacuation of the mine and protracted remote treatment of the incident. The most recent major incident was at Carborough Downs mine in 2012. Spontaneous combustion continues to be a problem in some open cut mines as well, especially where they are mining through old underground workings, in stockpiles and waste heaps which have carbonaceous or pyritic waste material. It is thus still relevant to ensure that spontaneous combustion is given sufficient importance when considering potential hazards at our mines.

Over the years ACARP has expended many millions of dollars on research aimed at improving our knowledge and ability to manage spontaneous combustion and other types of mine fires. The fact that no lives have been lost since Moura must be in large part due to the outcomes of this research, which has pioneered such things as computerised fluid dynamic modelling of goafs and proactive inert gas injection. Other initiatives funded by ACARP included the use of gels and polymers to control air ingress into coal, laboratory studies to better understand the science of coal oxidation and the development of camera based borehole investigation systems to investigate goafs. At the same time major effort has gone into understanding spontaneous combustion in coal stockpiles and waste heaps, in part due to concerns over greenhouse emissions.

Over the years there have been a number of reviews of spontaneous combustion, (e.g. Cliff and Bofinger, 1998; Nalbandian, 2010). In addition the then New South Wales Department of Industry and Investment have released an updated Mine Design Guideline MDG-1006 Spontaneous Combustion Management Guideline supported by a comprehensive technical reference guide (NSW DII, 2011a and 2011b).

DEVELOPMENTS IN THE UNDERSTANDING OF THE OXIDATION PROCESS

Whilst it is reasonable to say that many of the factors that affect the ability of coal to exothermically oxidise and reach spontaneous combustion have been well known for many years (see for example Table 1 extracted from Cliff and Bofinger 1998), it is also reasonable to say that it is only in recent years that the significance of a number of these factors has been recognised and quantified.

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Table 1 - Factors affecting the oxidation of coal (extracted references cited in Cliff and Bofinger, 1998)

Intrinsic Factors	Extrinsic Factors
Low rank of coal	Faults
Low ash	Folds
High friability	Dykes
Weak caking properties	Weak and disturbed strata conditions
High reactivity	Seam thickness
High heat capacity	Steepness of seam
Low thermal conductivity	Shallow cover
High coefficient of oxygen absorption	Multi seams in close proximity
High proportion of oxygen functional groups	Porous petrographic structure
High volatile matter	Mining parameters that increase the amount of broken coal exposed to air for significant periods of time
Pyrites	Mine ambient temperature
Moisture content	
Particle size and surface area of coal	

Laboratory testing at both the small and medium scale has added significantly to our understanding of the processes both chemical and physical that influence the ability of coal oxidation to become spontaneous combustion. The complex role of moisture has been demonstrated. Adsorption of moisture has been shown to increase the temperature of coal which causes the acceleration of the oxidation rate. Conversely coal with significant inherent moisture is appreciably inhibited as the coal has to dry out before oxidation can develop (Wang, *et al.*, 2003; Beamish and Beamish, 2012). Finally it has also been shown that there needs to be some moisture present for low temperature oxidation to occur (Wang, *et al*., 2003). Other studies have quantified parameters that have been demonstrated to enhance oxidation, e.g. pyrites, (Miron, *et al*., 1992)) or inhibit it, e.g. mineral matter (Beamish and Blazak, 2005)). These studies have also identified the key components of the odour generated during spontaneous combustion as well as confirming one significant non oxidation related source of hydrogen gas (H_2) (the reaction of acidified water on mild steel) (Hitchcock, *et al*., 2011). The odour associated with coal oxidation is typically due to the presence of aldehydes and other unsaturated oxygenated species, principally acetaldehyde and acrolein (Clarkson and Usher, 2008, Hitchcock, *et al*., 2011). Increasing ash content reduces the reactivity of the coal (Beamish and Arisoy, 2008). Laboratory tests have also confirmed the impact of weathering on deactivating coal to the oxidation process (Beamish, *et al*., 2000), through removing active reaction sites without retaining the heat of oxidation.

It is also worth stressing that laboratory testing is only one part of the process required to develop adequate control systems to manage spontaneous combustion. A number of recent incidents have occurred in coals that based upon laboratory testing would not be regarded as prone to spontaneous combustion. In those cases the propensity for spontaneous combustion was enhanced due to exposure of coal to air for much longer than normal due to mining difficulties and/or the coal temperature being lifted appreciably above ambient temperature. The ambient temperature has been shown to be a significant influence in determining whether or not spontaneous combustion will occur (Beamish and Beamish, 2012). An increase in coal temperature of less than 10 ^{o}C may be sufficient to change the balance between heat loss and heat generated from the oxidation process to promote spontaneous combustion.

Recently medium scale and large scale laboratory testing has been able to link the small scale testing to the reality of what may occur in coal mines (Hitchcock, 2013). Large scale testing can take many months and thus is not really a viable routine proactive testing process (Cliff, *et al.*, 2000b). Medium scale (70 kg) testing offers a viable way of including many of the conditions found in underground mines such as the particle size distribution, moisture content, and ash content and then exploring mechanisms for control. Large scale testing has confirmed that it is possible for a small mass of coal to reach flame temperature insulated by a much larger mass of cooler coal (Cliff, *et al.*, 2000a) (Figure 1). This underlines the difficulties in detecting spontaneous combustion at an early stage, and why some events have developed to an advanced stage before they were detected.

PROACTIVE CONTROLS

Probably the most important area of improvement in the control of spontaneous combustion in underground coal mines is the prevention of spontaneous combustion through appropriate design of mining operations. Computational fluid dynamic modelling, coupled with control over pressure differentials around goafs and proactive application of inertisation, has reduced the potential for oxidation to occur in sealed areas (Ren and Baluso, 2005; Balusu, *et al.*, 2010). Figure 2 demonstrates the application of CFD modelling to goaf gas flows.

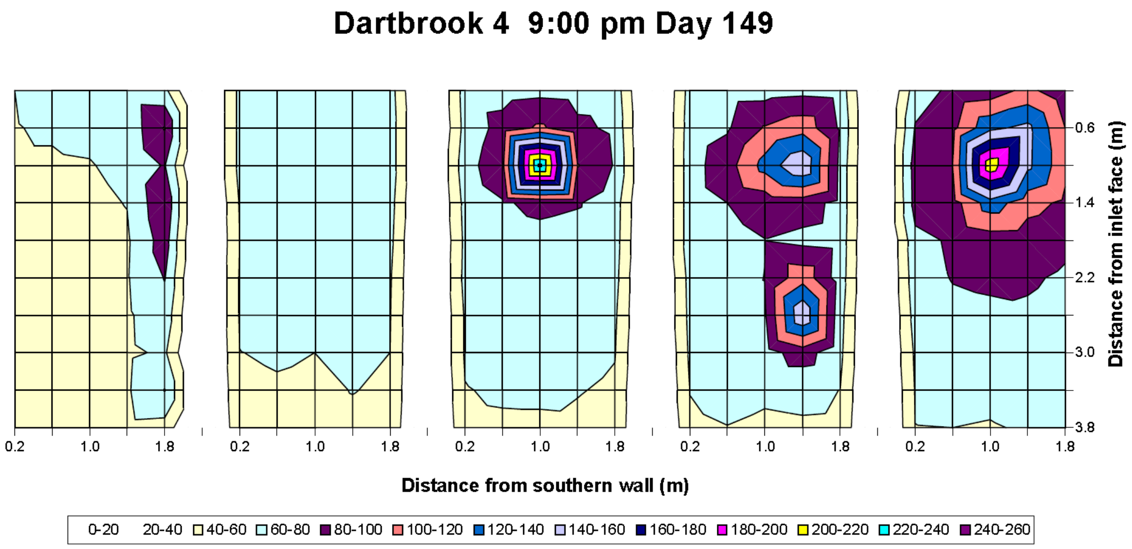

Figure 1 - Hot spot development in 16 tonne reactor (Cliff, *et al*., 2000a)

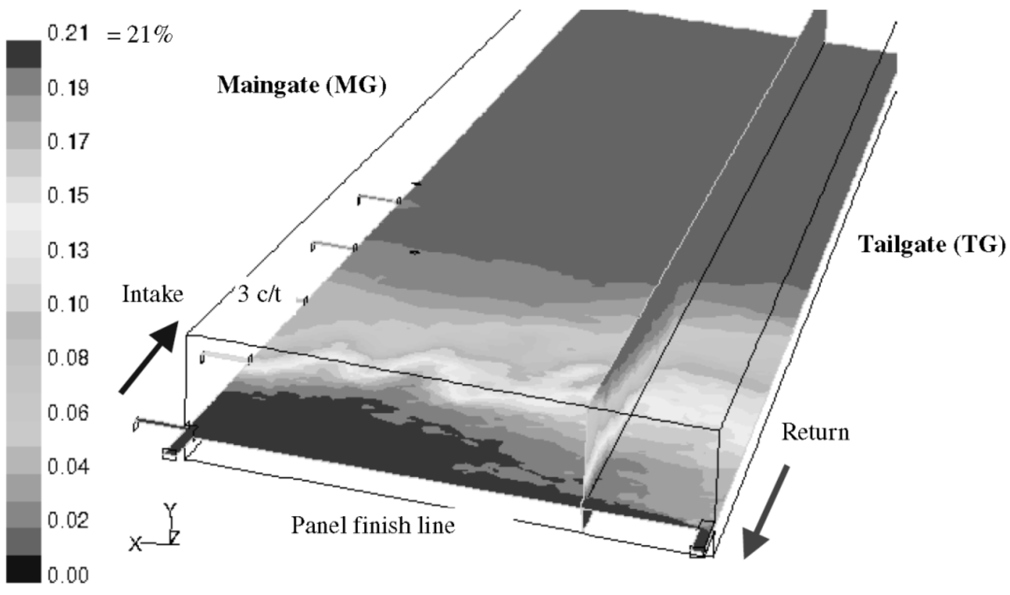

Figure 2 - Oxygen gas distribution in the longwall goaf near the finish line – with 50 m^3/s airflow (Balusu, *et al*., 2002)

These techniques are assuming increasing importance as longwall panels become wider and longer and thicker seams are mined.

Modelling has also enabled the potential impacts of goaf gas drainage on the distribution of gases in the goaf to be evaluated, as well as scouring of the goaf due to high face ventilation quantities and pressure differences (Ren, *et al*., 2005; Balusu, *et al.*, 2010).

Ventilation models are able to evaluate the pressure changes around mining panels under various configurations, including two or three gate roads and bleeder roadways. The modelling has been validated using tracer gas studies (Luxbacher and Jong, 2013).

A number of mines now minimise air ingress into active longwall goafs by constructing pressure balancing chambers in gate-road seals. These chambers can be linked to remove any pressure differential between seals, or they can be pressurised with inert gas to prevent air ingress (Brady, *et al.*, 2008).

REACTIVE CONTROLS

Gas monitoring has also developed enormously over the past seventeen years. Much more comprehensive monitoring is undertaken with continuous monitoring systems being installed routinely. Monitoring also extends to bag sampling through seals. Detection systems have also increased their sensitivity and the range of gases that can be monitored. Four gas systems are the norm- methane (CH_4), oxygen (O_2), carbon monoxide (CO) and carbon dioxide (CO_2). Gas chromatographs have made the biggest improvements. The time taken to analyse a sample has shrunk from over thirty minutes to under one minute and the sensitivity for key gases such as CO and H_2 have improved from 10 ppm for CO to less than 1 ppm and from 50 ppm to 1 ppm for H_2 (Brady, 2008a).

This monitoring is supported by much better computer based data collection and analysis systems. Indeed now it is often difficult to identify which indicators are best suited to monitor for spontaneous combustion (Toth, 2005). The limitations of the various detection systems and associated analysis techniques are also much better understood (Brady, 2008b; and Cliff, 2005), including detection limits and the impact of inert gas on gas concentration based ratios. It is clear that detection should not rely on just one system or one indicator rather a range of indicators that give independent evaluation of the mine atmosphere (Cliff, 2005).

One of the more novel techniques that have been trialled in Australia is the use of radon detection on the surface above heating events; this technique is widely used in China (Xue and Cui, 2004).

Inertisation and ventilation controls are also applied to control advanced oxidation, particularly high volume techniques such as the GAG jet engine and the MINESHIELD liquid nitrogen vaporisation system. Gillies and Wu (2008) have provided an excellent comparison of the various inertisation techniques available as well as applying mine ventilation software to identify the optimum location to apply the inert gas to control an active mine fire under various scenarios.

The use of fillers and sealants to exclude oxygen from a heating has also been extensively studied (Humphreys, 2013). Guar gum based gels were found to exhibit the most suitable properties to minimise air ingress into goafs as well as offer quenching of any hot spots. Formulations were found to last up to twelve months (Miron, 1995). Others have demonstrated the value of applying water based fogs to mitigate the potential for spontaneous combustion, these fogs may contain additives to retard any combustion or improve their retention properties (Tripathi, 2008). High pressure foam plugs, generated using air, nitrogen or carbon dioxide have successfully been used to control spontaneous combustion (Ray and Singh, 2007).

HAZARD MANAGEMENT PLANS

A consequence of the Moura No.2 mine disaster was the reform of the coal mining safety and health legislation in NSW and Queensland to include the requirement for principal/major hazard management plans to control the risk due to spontaneous combustion. This facilitated a more systematic control approach whereby risk management principles were applied and mines had to demonstrate that they had assessed the potential for spontaneous combustion, identified the controls required. These plans must then outline the details of how the controls would be implemented and how their effectiveness would be monitored. Consistent with AS4804:2001, Occupational Health and Safety Management Systems – General Guidelines on principles, systems and supporting techniques, the plans must then identify key responsibilities, resourcing requirements and training needs.

To provide guidance in developing these plans the then NSW Department of Industry and Innovation, issued a revised Mine Design Guideline MDG1006 with an accompanying technical reference guide (TRG) (NSW DII, 2011a and b). The TRG is an excellent and detailed technical reference document, and includes details of 23 incidents that have occurred since 1970. The table of contents for MDG1006 provides a skeleton for the development of Spontaneous Combustion Management Plans:

1. Introduction – including overview, scope and policy
2. Consultation
3. Risk identification
4. Risk analysis and evaluation
5. Risk management controls
6. Monitoring - including inspections, gas monitoring and Trigger Action Response Plans (TARPS)
7. Information – documents that support the plan
8. Training
9. Roles and responsibilities
10. Supervisors
11. Audit
12. Review
13. References
14. Appendices

TARP's are key elements of the plan that provide triggers for mine personnel to react to abnormal conditions. They should provide a graded response depending upon the severity of the situation. At the lower levels it is intended that change from normal is recognised in sufficient time to apply corrective actions before people are placed at risk. At the highest level the trigger is to allow people to evacuate from the mine or workplace before there is significant risk to life. TARP's should be set particular to individual areas in the mine, eg sealed goaf, active goaf and development headings. In addition they should be reviewed regularly and updated if conditions change or information becomes available that modifies any of the underlying parameters. TARP's should not just relate to gas concentrations or derived indicators but also to deviations from normal mining conditions or other operating parameters such as ventilation change or seal damage (Cliff, 2009).

TRAINING

Another major initiative that has occurred over the past twenty years is the development of industry-wide competency standards regarding spontaneous combustion management forstatutory positions. In addition the position of ventilation officer has been recognised as being important and is supported by formal competency requirements. Training to achieve these competencies must be undertaken by suitably qualified personnel from registered training organisations. In addition awareness training in spontaneous combustion has been included in induction training for workers.

OPEN CUT MINING

Spontaneous combustion is also an issue for open cut mining. Research in recent years has highlighted the processes that promote spontaneous combustion in stockpiles and waste heaps. This has allowed improved controls to be implemented to reduce the risks.

Day (2008) published a comprehensive handbook of spontaneous combustion in open cut coal mines. This summarises the essential information from earlier research (Carras, *et al*., (1994), Carras *et al*. (1998), Carras *et al*. (1999) Carras (2005) and Haneman and Roberts (1998), not only in terms of the causes of and major factors affecting spontaneous combustion in open cut coal mines, but also the potential contribution to greenhouse gas emissions and other forms of pollution. It also describes the management practices for avoiding and controlling spontaneous combustion. The problems associated with the emissions from spontaneous combustion can pose a significant issue not only to workers attempting to control a heating but also to the wider community. Of particular concern are the large quantities of carbonaceous waste that can be produced at open cut coal mines, rejects from the coal processing plants and overburden containing coal seams that are not economic to mine.

The focus of the handbook is on stockpiles and spoil-piles rather than *in situ* heatings. Figure 3 summarises the key factors the handbook identified as contributing to self-heating. It discusses the effects of the usual parameters in terms of the environment of the open cut. The report discusses modelling stockpiles and spoil piles and identifies the difficulties in undertaking such modelling, due to the necessary complexity of the models and the need to make assumptions and simplifications to make the problem manageable. Day suggested that the value of modelling is in making comparisons between various spoil pile configurations (Day 2008).

A number of researchers have undertaken computer modelling of stockpiles. Akgun and Essenhigh (2001) modelled the impacts of a number of factors such as pile height, slope angle, particle diameter of the coal and coal moisture. Their research indicated that there was a critical pile height above which spontaneous combustion becomes likely given sufficient time.

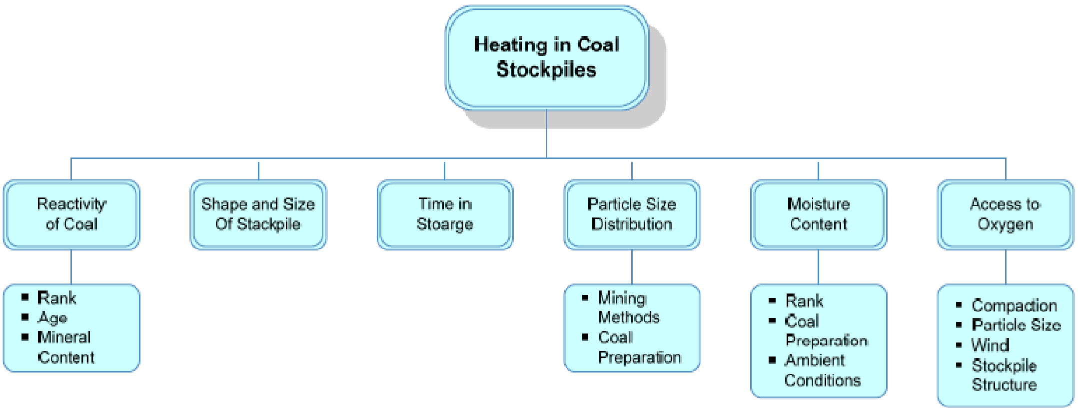

Figure 3 - Contributing factors to coal stockpile heatings (Day, 2008)

Carras *et al*. (1994) as described in Day (2008) depicts a typical spoil pile as reproduced in Figure 4. Not surprisingly the carbon content of the spoil pile is directly related to the likelihood of spontaneous combustion. Heatings tend to be quite localised and can be buried quite deep into the pile if there are cracks or fissures that allow air to travel into the pile.

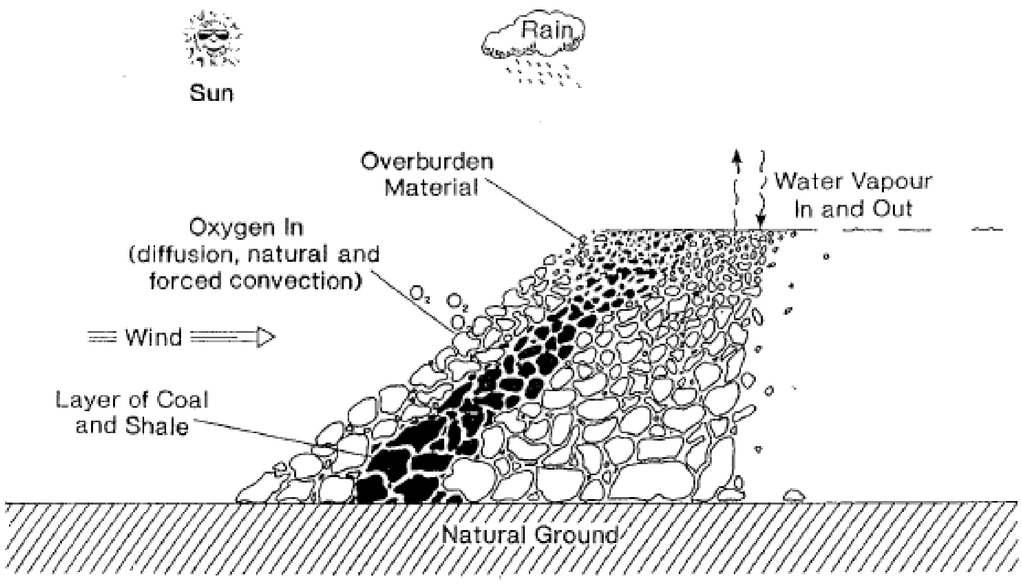

Figure 4 - Schematic representation of a spoil pile (from Carras, *et al.*, 1994) as reported in Day (2008)

Control is usually best achieved by prevention of air ingress using the techniques for coal stockpiles. Spoil piles can be covered more thickly than stockpiles as they are not required for transport elsewhere and it does not matter if the cover material mixes with the pile material. The covering material should be appropriately moist as this greatly reduces the voids in the cover and hence reduces the potential for air inflows. Clay rich materials with high water retention capacity can form effective barriers when 1-2 m thick. Sandstones which have lower water retention capacity have been found to need to be much thicker (5-10 m). The covering material must also be resistant to erosion and geotechnical instability.

Eroglu (2005) described the difficulties in open cut mining of old underground coal mines in South Africa. During surface mining air enters through cracks into the old underground workings causing spontaneous combustion. Where the old mines are close to the surface it is also possible for collapse of ground above the old bords, mainly at intersections, allowing air into the old workings. Eroglu discusses the effectiveness of a range of control measures including:

- cooling agents. High pressure water is used to cool hot spots. It can be difficult to get the water to the hot spot which may be buried deep within a pile or maze of underground workings.
- sealing agents. These combine an inhibitor of spontaneous combustion, such as calcium chloride with a binding agent and a filler such as bentonite. Often the inhibitors have poor stability and widespread application over exposed faces can be very expensive.
- dozing over. Here sand is dumped directly over the highwall to close off the old workings as soon as possible after they have been exposed to the atmosphere. The sand has to be pushed into the old openings and compacted to minimise air ingress. Venting can still occur, and so this technique can have limited impact.
- buffer blasting. This is the process of blasting material *in situ* to form a barrier to air ingress by collapsing the old roadways and forcing material into them in advance of extraction. This has been found to the most effective method in South Africa. This technique has the added advantage of improving highwall stability and reducing the risk of subsidence.
- cladding. This is the process of placing weathered overburden on top of a buffered highwall. This reduces the air flow and heat through the buffer, which helps reduce the chimney effect inside the highwall.

CONCLUSIONS

The developments in research over the past twenty years have contributed significantly to the reduction in risk posed by spontaneous combustion to Australian Coal Mines. Incidents still occur which suggest that there is an ongoing need to remain vigilant to this hazard. ACARP has made significant investment in spontaneous combustion research and this has facilitated this improvement in safety performance. It is important always consider the potential for spontaneous combustion when designing mines and the advent of new technology, and bigger, longer, wider longwalls will pose their own issues that require management.

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