

# Management of Spontaneous Combustion for Metalliferous Mines

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## ABSTRACT

Spontaneous combustion of mine waste is usually associated with coal mines. It occurs to a lesser extent with ore deposits that contain pyrite (FeS<sub>2</sub>) or pyrrhotite (Fe<sub>1-x</sub>S) and carbonaceous materials. Limited research has been conducted into the prediction of spontaneous combustion and currently no single method exists for all mine sites. Prediction requires classification of the material based on geochemical properties that can be coded into a block model. The potential spontaneous combustion materials are managed accordingly to minimize atmospheric oxidation and contact with water.

Spontaneous combustion results in the production of heat (> 270 °C near the surface and up to 1,200 °C deep in a Waste Rock Dump; WRD), which has implications for; *inter alia*, blasting while in the pit or underground and the release of hazardous gasses such as sulfur dioxide (SO<sub>2</sub>).

Spontaneous combustion often evolves and material can be classed according to stages of development, including: potential, current and extinct. The “potential” class includes material that has the geochemical properties that, under field conditions could lead to spontaneous combustion, but has not yet started reacting. “Current” spontaneous combustion materials have already begun to combust and therefore prevention is no longer an option; rather the material requires remediation and containment. Zones of “extinct” spontaneous combustion materials are usually associated with precipitated minerals that may contain elevated metal concentrations that need to be managed. Several metalliferous mines in Australia have issues with spontaneous combustion occurring within the pit and on WRDs. These mines have implemented a number of control techniques that can be incorporated into WRD design and mine planning to minimize the effects of spontaneous combustion and ultimately prevent it from occurring. This paper describes some of the control measures that are being implemented for one Australian metalliferous mine.

**Keywords:** Spontaneous Combustion, Metalliferous Mine, Pyrite oxidation

## INTRODUCTION

Spontaneous combustion of mine waste is usually associated with coal mines. It occurs to a lesser extent with ore deposits that contain sufficient pyrite (FeS<sub>2</sub>) and carbonaceous materials. Several metalliferous mines in Australia have issues with spontaneous combustion occurring within the pit and on the waste rock dump.

Limited research has been conducted into the prediction of spontaneous combustion and currently no single method exists for all mine sites. This paper outlines the factors of importance in spontaneous combustion and the onsite experience with this phenomenon at a metalliferous mine; the site is to remain anonymous and will be referred to as "Site X".

### Spontaneous Combustion Process

Spontaneous combustion (also referred to in this paper as "smokers") is a phenomenon usually associated with ore deposits that contain pyrite (but may also include the sulfide minerals, *inter alia*, pyrrhotite, galena, sphalerite, arsenopyrite, chalcopyrite and molybdenite) and carbonaceous materials. The oxidation of pyrite is exothermic and can lead to a significant increase in heat.

Spontaneous combustion is usually associated with finely grained disseminated pyrite (framboidal pyrite) which is a major constituent at some metalliferous mines. The mining process contributes to exposing the pyrite and decreasing the particle size of the rock mined. This results in an increase in the surface area and reactivity of the rock. The spontaneous combustion process begins with the exposure of the material to atmospheric oxidation or contact with oxygenated water (usually rainwater).

The oxidation of pyrite and other sulfides results in a gradual increase in temperature immediately surrounding the point of oxidation. This point is insulated by surrounding rocks, preventing the release of heat, which results in further increases in temperature. Over time, the temperatures become high enough to ignite any carbon and/or organic matter that may be present, releasing gas (e.g. CO<sub>2</sub>, SO<sub>2</sub>, etc.) and steam. As the heat increases the rate of pyrite reaction increases. The process has been determined to be a three-stage process: stage A (ambient to 100°C), stage B (> 100°C) and stage C (> 350°C) (Rosenblum and Spira 1995; Rosenblum et al. 2001). Once the reacted material cools down, complex minerals precipitate (e.g. sulfates, halides and native sulfur); usually containing a concoction of trace elements.

Spontaneous combustion may also result from galvanic interaction. The presence of an electrolyte and two sulfides (e.g. galena and sphalerite) with different rest potential may form a galvanic cell (Kwong et al., 2003), with the sulfide with the higher rest potential forming the cathode and the lower forming the anode. Spontaneous combustion results from galvanic sulfide interaction with a rest potential difference ( $\Delta V$ ) greater than 0.2 V, whereas mixtures with  $\Delta V < 0.1$  V do not combust (Payant et al., 2011).

Spontaneous combustion is time dependent, and early detection of the potential sources of the problem may allow for the issues to be managed appropriately, preventing the problem from developing into full – scale combustion. If combustion has already begun, management of the materials is more problematic, as excavation and movement of materials will allow further atmospheric oxidation, allowing the conditions to be optimized for sulfide oxidation, potentially increasing the rate of pyrite oxidation.

### Spontaneous Combustion Prediction and Detection

Prediction of spontaneous combustion requires classification of the material based on its inherent properties. The characteristics of a material that can be used to identify the potential for material to spontaneously combust include (*inter alia*): the geochemical constituents of the materials and chemical analysis of drill core samples/waste piles (e.g. sulfur content (particularly pyrite); combustible carbon content; moisture content; environment oxygen content; oxygen avidity; presence of other volatile materials; and, temperature). Another method of prediction/ detection includes modeling the rate of heat generated versus the rate of heat dissipated (Carnes and Saghafi, 1998).

Early detection of spontaneously combustible materials allows for the associated materials to be managed appropriately, which may prevent the material from developing further into a smoker. The main detection characteristics include (*inter alia*) temperature increases, gas odor and observation of vapor/gases. Heat haze and “steam” plumes may be observed as well as efflorescence caused by the oxidation of pyrite and sublimation of sulfur. Infrared monitoring instruments or thermal probes inserted into the WRD may be used for early detection of spontaneous combustion. Spontaneous combustion has a distinctive smell; the most common and prevalent of the gases produced is SO<sub>2</sub>, which is odorless at low concentration, however, may have a pungent rotten egg smell at high concentrations.

The intensity and the rate at which a “smoker” develops are dependent on a combination of factors; some of these factors include: composition (the presence and availability of sulfide [pyrite and other sulfides,], carbon and oxygen); friability, particle size and surface area (which can be related to mining method, such as blasting); moisture content; climatic conditions (temperature, relative humidity, barometric pressure and oxygen concentration); and, stockpile compaction, height and method of stockpiling (e.g. end – dumping versus paddock dumping).

### METHODOLOGY AND SITE PROPERTIES

A spontaneous combustion management plan was developed for Site X, a metalliferous mine in Australia. The management plan was based on the factors that promote the evolution of spontaneous combustion, and has been separated into classes according to stages of development, namely: potential, current and extinct. The management options were developed based on site observations including monitoring of temperature. The Site’s historical geochemical database was reviewed to develop geochemical trends; however, the outcomes from this review are not discussed in this paper. Several of the more practical methods for managing (remediating) spontaneous combustion were tested at the Site.

All of the lithological domains at Site X contain sulfide minerals (pyrite, sphalerite and galena) with some units being characterized by elevated pyrite, ranging from 10 to 27 wt %. For lithologies containing galena and sphalerite, their median abundances were low, ranging from 1 to 2 wt %. All lithologies contain carbonates (dolomite, calcite and ankerite) with dolomite being the dominant acid neutralizing mineral in all lithological units. Other non-sulfide/carbonate minerals include: quartz, mica, K-feldspar (microcline) and moderate to trace quantities of kaolinite, chlorite, montmorillonite, vermiculite, plagioclase (albite) and gypsum.

Several of the waste lithological units contained elevated sulfide concentrations with average values including: X Shale (~8.6 wt % S), Y Shale (~7.2 wt % S) and Z Shale (~5 wt % S). The sulfide is

mainly associated with framboidal pyrite (Figure 1). The overburden waste also contains significant organic carbon (> 0.5 wt %).

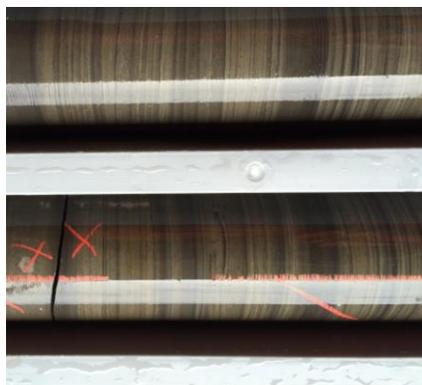


Figure 1 Interbedded framboidal pyrite and dolomite.

## RESULTS AND DISCUSSION

### Spontaneous Combustion Prevention, Control and Remediation

There are a number of control techniques that can be incorporated into the WRD design and mine planning to minimize the effects of spontaneous combustion and ultimately prevent it from occurring; however, there is no single control that has been proven to be completely reliable or successful. Effective control of spontaneous combustion is usually achieved by using a combination of techniques, and these techniques are dependent on individual mining situations.

Some of these controls include measures to reduce or eliminate oxygen. This may be achieved with: sealing agents; compaction of the surface material (dozing over, truck haulage routes or compaction); buffer blasting; covering the area of concern with inert material (e.g. non-acid forming [NAF] material, clay); application of a final cover layer with good water retention properties (e.g. fly ash-water slurry); and, subaqueous deposition. Control measures that have been proposed or used at several Australian sites to reduce the temperature and lower the reaction rate include: water cannons; firefighting foam; injection of water; water spraying; nitrogen injection; and, carbon dioxide injection. Other control measures to eliminate the process may include: excavation of hot or burning material; controlling the morphology of high sulfide material cells (layering etc.); the use of low-angle slopes to minimize the effects of wind (i.e. reduce “chimney effect”); the use of artificial wind barriers; submersion in water (e.g. backfill in pit and flooding); and, spreading the affected material into thin piles to allow to cool. The effectiveness of a cover is generally dependent on composition, particle size and bulk density; water content of the cover; air filled void space; heat transfer capacity; oxygen transfer; and cover thickness.

### Geochemical Management: Spontaneous Combustion

The management options for spontaneous combustion can be separated according to the different stages of development of smokers, these stages include: potential smokers, current smokers and extinct smokers. The “potential smokers” class includes material that has the geochemical characteristics of a smoker, but is not currently combusting or is not currently associated with elevated temperatures (> 60 °C). Current smokers have already begun to combust and therefore prevention is no longer an option; rather the material requires remediation and containment.

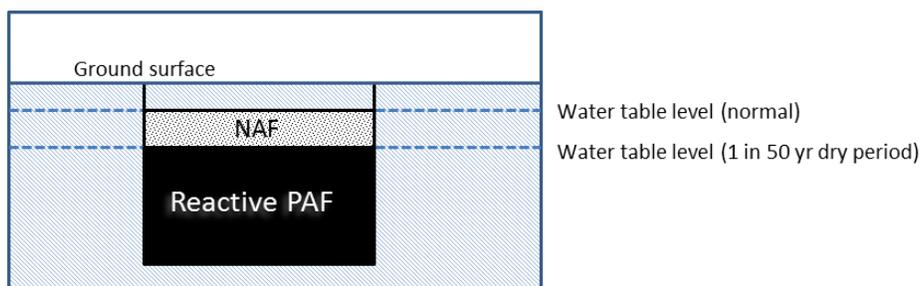
Extinct smokers are materials that were active smokers but became extinct due to depletion of sulfide, oxygen or combustible carbon. These materials may result in precipitation of soluble minerals which contain trace elements that need to be managed.

**Potential Smokers**

Potential smokers can be detected through the block model (populated by drilling sample analysis) and/or field investigations (handheld XRF of drill mounds) prior to blasting and excavation. The most critical step in preventing spontaneous combustion from developing is to limit contact or reduce contact time with oxygen and water. Therefore, if material has the characteristics that may result in spontaneous combustion it is handled preferentially with appropriate management controls. This can prevent the material from developing spontaneous combustion and reduce the need for remediation. Potentially reactive materials are be mined shortly after blasting and managed appropriately.

***Management of potential smokers - Option P1:***

One of the preferred options to consider for future operations is subaqueous disposal of reactive waste. The disposal method typically involves the storage of reactive waste in a series of pits below the water table (Figure 2); the material is stored below the water table where oxygen is inhibited. The process reduces the risk of natural or manmade incidents associated with flooded impoundments or complex engineered covers. In addition to groundwater saturation, a thick (3 to 4 m) pervious cover (which may include oxygen consuming materials such as organics), is placed over the reactive waste. The reactive waste is placed such that it will remain saturated under the water table to beyond a 1 in 50-year dry condition. During the periods when the reactive waste is not saturated (for example if water tables and infiltration decrease in a prolonged drought) the system will rely on the oxygen consuming cover. Similarly, excess water from dewatering may be pumped over the reactive PAF such that the material is not exposed over dry periods. Additional benefits of this option include the reduced foot print compared to conventional disposal facilities as well as reducing volumes of encapsulation materials required elsewhere on site for waste mitigation.



**Figure 2** Subaqueous disposal of reactive PAF below groundwater level.

***Management of potential smokers – Option P2:***

A second option to consider for future operations is co-disposal, which involves the disposal of both tailings and waste rock simultaneously within a storage compartment (e.g. compacted clay lined dam) (e.g. Figure ). The waste rock at the Site is commonly coarse, meaning there are large void spaces when placed on the WRD. The tailings waste is very fine and may be deposited within

the void spaces of the waste rock. Co-disposal also has a number of other benefits, including: provides a storage option for both waste streams (waste rock and tailings); the tailings act as a barrier to atmospheric oxidation of the PAF, therefore reduced ARD generation; low permeability of the WRD means reduced seepage; structural integrity; smaller footprint (excludes the tailings facility); and, potentially less post closure maintenance.

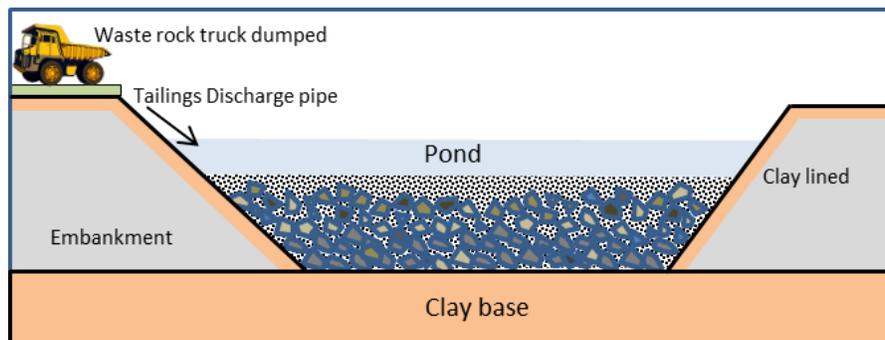


Figure 3 Co-disposal of tailings and waste rock (including reactive PAF).

### Current Smokers (Remediation)

Current smokers are materials that are currently combusting (i.e. when excavated, stockpiled or during transportation; Figure 4) and are characterized as having temperature  $> 60\text{ }^{\circ}\text{C}$  and/or produce gases. Remediation of current smokers also includes small quantities of material that may begin to react within the pit. There are also instances at Site X where materials used as windrows have been constructed with reactive PAF and begun to combust. These materials are all treated as current smokers.



Figure 4 Current and extinct smokers at Site X.

### Remediation - Option R1

Remediation (Option R1) is only applicable for material that is combusting directly below the surface (e.g.  $\sim 50\text{ cm}$ ; Figure 4). This option should not be considered for areas affected by deep “hotspots” as the material will continue to combust when encapsulated and could potentially develop into a much larger problem. Encapsulating a deep “hotspot” may cause the buildup of heat

and gases which may ultimately lead to an eruption – like event at the surface. A good understanding of the depth of the hot-spot is gathered at the monitoring stage or at least prior to any remedial work being conducted.

Generally, the smokers at Site X are associated with very steep sections of the WRD; the steeper slopes are also more difficult to compact and may be conducive to the “chimney” effect. The main step in this remediation is to reduce the WRD slopes; the chimney effect is significantly reduced and the hot-spot may be less exposed to atmospheric oxidation.

If the smoking material can be spread loosely, it may be able to cool. Once cooling has occurred (this may take several weeks depending on the carbon and pyrite content of the affected area) and the slopes have been reduced, the affected area (which should show evidence of being dormant/extinct with low temperatures and no evidence of gases) is covered with NAF or clay and compacted (Figure 5). Given the intensity of the smoker and the likely minerals/metals which make up the efflorescence, a clay layer is also applied and compacted to prevent the mobilization and transportation of metals and further oxidation of any unreacted pyrite/ combustible carbon.

This management option has been tested at Site X and the observations and ongoing monitoring have indicated the materials have stopped combusting and become extinct.

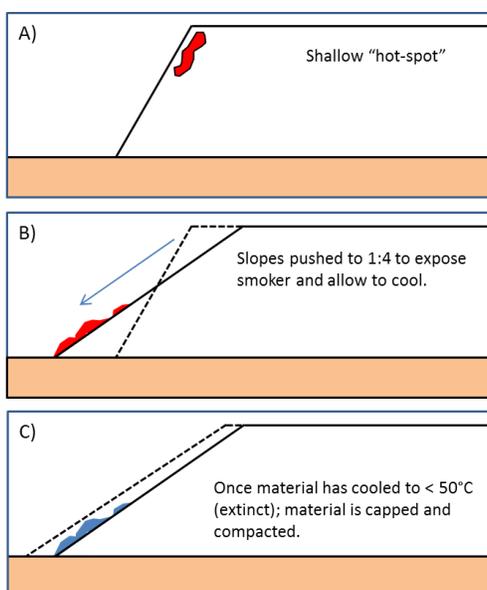


Figure 5 Spontaneous combustion remediation option 1 (R1) for shallow affected materials.

### Remediation - Option R2

Remediation option R2 is used if the hot – spot proceeds deep into the WRD or for material that begins to react in the pit. Deep hotspots are usually associated with the precipitation of native sulfur, and the presence of hydrogen sulfide (H<sub>2</sub>S) gas and cracks in the surface (presumably to release excess pressure). H<sub>2</sub>S is generally only formed when there is not enough oxygen available for complete oxidation; often deep within a waste facility. The H<sub>2</sub>S<sub>(g)</sub> is oxidized to native sulfur once exposed to atmospheric oxidation, and the presence of native sulfur often indicates that the formation of H<sub>2</sub>S forming deep within the WRD where there is likely to be limited O<sub>2</sub>.

The affected areas are excavated from the WRD and transported to a specially designed facility at identified and managed disposal locations. All material that is excavated and has a temperature > 60 °C is spread thinly and allowed to cool. The material is ideally truck dumped into loose ~ 2-m piles (via paddock dumping) within a specially designed facility (e.g. compacted clay layer) (Figure A). Previous investigations have shown that 2-m piles are below the critical mass for spontaneous combustion to occur (Waters and O’Kane, 2003); this assumption will also be investigated for materials at Site X. The 2-m piles are to be monitored until the material is below 60°C and become extinct. This monitoring includes daily observations and the inclusion of several temperature probes in the piles to assess whether there are any temperature spikes. Once the material is shown to be extinct (i.e. monitoring indicates there are no temperature rises and there is no visible smoke), it can be spread evenly as a 2-m lift and then covered with inert material and compacted (Figure B). The excavation of the affected material causes rapid combustion once disturbed (i.e. the rate of pyrite oxidation is enhanced due to the availability of oxygen) producing excessive gas and vapor.

The spontaneous combustion storage facility should not be located in a place that receives runoff from other facilities, or above or adjacent to major streams. Similarly, the site should not be located near clean material (NAF and clay) stockpiles. The number of spontaneous combustion management sites is minimized, including the size of the footprint.

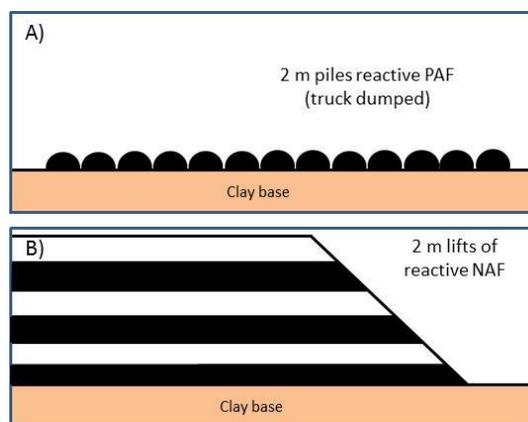


Figure 6 Spontaneous combustion Emplacement Facility.

### Remediation - Option R3

Remediation option R3 is based on management and remediation strategies undertaken by another mine with similar geology, waste material and climate, which has also had issues with spontaneous combustion from reactive shale. A number of options were tested at this analogue site, with the most successful being the addition of a mixture of quicklime (CaO) and water to the affected area; this is now part of routine operations. The addition of the mixed quicklime/water slurry were able to achieve a reduction in temperature from 300 to 60 °C within 30 minutes of application for a 20-m cut/0.5-m lift.

Although the application of the quicklime/water mixture is proving to eliminate the issue, it is an expensive solution. The cost of quicklime delivered to site is ~A\$600 ton (> A\$2,000 for a single mixture).

**Remediation - Option R4**

The location of some smokers is such that this material is difficult or impossible to excavate and remove in a safe manner (e.g. smokers on the pit walls). There are limited remediation methods to deal with the issue in these cases. There are a few gel sealants which can be sprayed onto the affected area, although these are effective, they can generally be expensive. Miron (1995) and Chakravorty and Kolada (1988) investigated a number of gel sealants for the mitigation of spontaneous combustion for coal mines. These may be effective but were not considered applicable due to cost or scale at this Site.

**Extinct Smokers**

Extinct smokers should be closely monitored to make sure they are actually extinct. Residual heat (> 60 °C) is indicative that the material may still be combusting under the surface. The dormant/extinct smokers are associated with mineral precipitates (ash/efflorescence; Figure 4) which are likely to carry a large quantity of soluble solids and metal loads. The metals that are present as readily soluble salts are susceptible to leaching particularly after the first rains which may dissolve and transport these materials to sensitive receptors. For this reason the ash/efflorescence is excavated and encapsulated.

**CONCLUSIONS**

The management options for spontaneous combustion were separated according to the stages of development of spontaneous combustion (potential smokers; current smokers; and, extinct smokers). As spontaneous combustion develops from a potential smoker to a current smoker, the management options must change from prevention and confinement to remediation and confinement, respectively. The various options are summarized in Table 1 for each stage of spontaneous combustion development. Some of the management options have tested this for current spontaneous combustion. The outcomes of these trials are summarized in Table 2.

**Table 2** Remediation, management and monitoring options summary.

Development Stage	Management/Remediation Option	Description	Trial Outcome
Potential Spontaneous combustion	P1 – Subaqueous Disposal	Disposal of reactive PAF material (and other reactive material) below groundwater table.	Not tested to date
	P2 – Co-disposal	Co-disposal of reactive PAF material with tailings within a facility.	Not tested to date
Current Spontaneous combustion	R1 – Decline slopes	Reduce the spontaneous combustion affected WRD slopes to 1:4, allow affected material to cool and then encapsulate. Closely monitor.	The trial was successful at eliminating spontaneous combustion with temperatures reduced to < 60 °C and reduction of gas emissions.

	R2 – Layer – cake	Material > 60°C is be spread thinly as a < 2 m <sup>3</sup> pile and allowed to cool. Once cooled the material is spread as a 2 m lift and covered with NAF. Closely monitor.	The trial was successful at eliminating spontaneous combustion with temperatures reduced to < 60 °C and reduction of gas emissions.
	R3 – Quicklime/ water	Application of quicklime/water mixture to spontaneous combustion affected areas.	The trial was not successful and enhanced pyrite oxidation resulting in the production of gases.
	R4 – Gel application	Application of gel to spontaneous combustion affected areas.	Not tested to date
Extinct Spontaneous combustion	Extinct material	Close monitoring.	
	Extinct Ash (soluble minerals)	Ash is excavated and encapsulated within a PAF cell.	

All of the management and remediation options need to be monitored closely to assure spontaneous combustion is not developing and contaminants are not being released to the environment. Monitoring may include: Oxygen levels; temperature; gas (O<sub>2</sub>, SO<sub>2</sub> and H<sub>2</sub>S associated with spontaneous combustion); surface water, seepage water and groundwater qualities and volumes; and, physical stability.

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