E-ISSN : 2541-5794
P-ISSN : 2503-216X

Journal of Geoscience,
Engineering, Environment, and Technology
Vol 9 No 4 2024

RESEARCH ARTICLE

Review Of Stockpile Management To Reduce The Risk Of Coal Self-Heating, Which Can Cause Spontaneous Combustion

Edy Nursanto[1,*], Rahimatul Fadhilah[1], Nurkhamim[1]
[1] *Department of Mining Engineering, University of Pembangunan Nasional Veteran Yogyakarta, Yogyakarta 55283 Indonesia.*

* Corresponding authors : edynursanto@upnyk.ac.id
Tel: +6281254472184, +6282137269025, +6285878424247
Received: Jun 22, 2024; Accepted: Nov 21, 2024.
DOI: 10.25299/jgeet.2024.9.04.17132

Abstract

One of the energy requirements for fuel is in the form of solid hydrocarbons and as basic materials or feedstocks. Coal is formed from deposits of organic plant compounds that grow in an oxygen-free environment and are influenced by temperature and pressure for a long time.

Based on the coal formation process, coal from the highest to the lowest level is anthracite, bituminous, sub-bituminous, and lignite. Low-grade coal has a faster oxidation rate than high-grade coal because it contains inherent moisture, oxygen, and carbon in large quantities, has high porosity, and causes an increase in activation energy resulting in evaporation and a continuous increase in temperature causing spontaneous combustion.

Monitoring and control of coal, especially in the stockpile area as a temporary storage place, is carried out to prevent oxidation and self-burning, namely by arranging the piling pattern and applying demolition principles by taking into account the length of the pile, forming the design of the stockpile base surface, calculating the volume, height, side slope, and distance between piles, as well as taking into account wind speed and direction, which greatly influence particle size, porosity, and the rise in temperature of the coal during self-heating.

Efforts to handle self-heating in coal can be made by creating drainage in the stockpile area, reducing the height, and forming a slope angle of 15–30° to facilitate compaction of the coal pile so that it can be stored for a long time, as well as minimizing losses from spontaneous combustion and early self-heating detection for safe coal storage.

Keywords: Spontaneous combustion, Management Stockpile, Temperature, Model

1. Introduction

One of the solid hydrocarbon fuels that is produced by plants that develop in an oxygen-free environment and are subject to long-term temperature and pressure changes is coal (Achmad, 1992), while according to Law Number 4 of 2009, coal is a naturally occurring deposit of organic molecules made up of plants having the main components of hydrogen, carbon, and oxygen, as well as additional components of sulfur and nitrogen, where coal is one of the energy needed as feedstocks and fuel.

The coal mining system is generally surface mining with the open pit method, starting with land clearing, topsoil stripping, overburden removal, and stockpiling activities carried out continuously (Abd, 2023).

According to Wardana (2023), the coal produced is stacked and stored in the stockpile area, hence in order to constantly maintain quantity and quality and reduce the likelihood of spontaneous combustion, effective and efficient stockpile management is required.

A coal stockpile is a short-term coal storage space after transportation activities from the mining front so that the quality of coal can be ensured to be maintained as before (Jolo, 2016).

According to Carpenter (1999), the problem that often occurs is that the amount of coal production produced exceeds the stockpile capacity, which causes coal piles to not be in accordance with stockpile management recommendations, and when coal builds up in the stockpile, it frequently presents issues since the oxidation process that results from the interaction of oxygen with the coal's composition diminishes the coal's quality naturally (Nalbandian, 2010), so that it has the potential to cause self-heating and result in spontaneous combustion (Alfarisi, 2017).

When there is sufficient oxygen in the atmosphere to support the reaction between the coal and oxygen, coal self-heats. In this scenario, the temperature rises as a result of the heat that is retained in the coal bulk during coal oxidation at low temperatures. (Onifade et al., 2020).

Oxidation can increase coal brittleness and produce more coal fines (Carpenter, 1999), and according to Nalbandian (2010), lower-rank coal is more prone to oxidation and particle deterioration than higher-rank coal, and weathered coal typically has a higher moisture content than fresh coal. These factors combine to produce lower-quality coal (Pisupati et al., 1991).

The decline in coal quality in the stockpile area causes losses to the company because it has to dispose of the volume of burned coal and incurs additional costs for handling the burned coal (Syahrul et al., 2014).

Stockpile management activities are activities to control or monitor coal temperature, which can cause self-combustion and air pollution due to coal, coal quality, and environmental aspects. Therefore, based on observations made from various literature, the author's interest and motivation arose to draw conclusions about the effective and efficient management of coal piles with the aim of minimizing the potential for self-burning so that the quantity and quality of coal can be maintained and produce appropriate products. with consumer-demand specifications.

2. Research methods

The research stage begins with a literature review of international journals, national journals, and theses. According to Hasibuan (2016), a description of hypotheses, conclusions, and other study materials gleaned from reference materials to act as a foundation for research efforts is called a literature review.

Based on a review of various pieces of literature describing effective and efficient coal stockpile management with the aim of minimizing the potential for self-burning so that the quantity and quality of coal produced can be maintained and meet coal specifications in accordance with consumer demand, conclusions are drawn.

3. Analysis results

The process of planning, arranging, coordinating, and regulating resources to achieve objectives in order to function as a temporary coal stockpile effectively and efficiently necessitates the implementation of an appropriate system. This is known as stockpile management (Carpenter, 1999).

Stockpiling coal will slow down the potential for self-heating (Zhang et al., 2016), while according to Speight (2012), in the process of storing and stockpiling coal, there are undesirable things such as oxidation and self-burning, changes in the properties of coal that affect utilization, and degradation of coal size during loading and hauling, so attention needs to be paid to support production and utilization aspects.

When oxygen accumulates in the voids between the coal layers, a phenomena known as spontaneous combustion occurs in coal piles, causing an oxidation reaction that produces heat and progressively increases the coal's temperature. This process causes the coal to self-heat and seriously pollute the environment (Li et al., 2018).

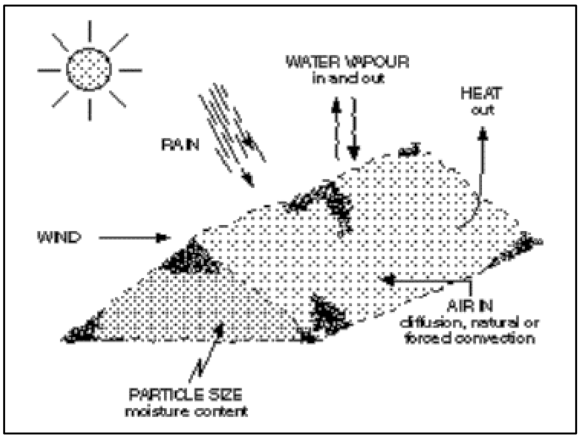

Fig. 1. Factors causing Self-Heating in the Stockpile Area (Carras et al., 1994)

According to Afif (2022), an Spontaneous combustion is produced by an exothermic oxidation reaction between the oxygen in the air and the contents of the coal, this is a phenomenon that happens to coal if it is stored in the stockpile area for a certain amount of time. The coal undergoes spontaneous combustion and temperature rise as a result of this reaction.

When coal spontaneously combusts in stockpiling areas, it poses serious risks to safety, the environment, the economy, and handling. This also makes coal damaged by heat unfit for use, resulting in cost losses.

The amount of carbon, hydrogen, oxygen, and sulfur that coal contains has a significant impact on how much heat is created during combustion, which is one of many controlled and uncontrollable parameters that determine the probability of coal self-heating in stockpile area (Figure 1) (Nalbandian, 2010).

3.1 Factors causing self-heating

Ozdeniz et al. (2008) found that temperature, air humidity, and atmospheric pressure are the three factors that affect the likelihood of spontaneous combustion in coal piles, Peng et al. (2017) found that several factors, including stockpile form, ash content, temperature distribution, and coal moisture, can influence the heating of coal that results in spontaneous combustion.

Low-grade coal has more molecules that can react with oxygen at low temperatures and more volatile chemicals that accelerate the oxidation process, which makes it more prone to spontaneous combustion than higher-grade coal (Jo et al., 2013). According to Carpenter (1999), it also has a higher concentration of oxygen and air.

According to Nugroho et al. (2001), coal blends have a higher activation energy and temperature reactivity than native coal, which makes them more prone to self-heating.

Nalbandian (2010) claims that low-rank coal is the most vulnerable due to its higher porosity, so as a result, lignite and sub-bituminous coal are more prone to spontaneous combustion than bituminous coal and anthracite (Fei et al., 2007).

3.1.1 Duration of storage time for coal stockpiles

Effective stockpile management is necessary to maintain the quantity and quality of coal without allowing it to self-heat, burn itself out, or cause financial losses.

According to Ozdeniz et al. (2008), When applying the FIFO (First In, First Out) method. it is important to take into account how long coal stockpiles need to be kept in storage, and It has been found that the windrow coal stockpiling pattern minimizes the risk of self-burning more effectively than the chevron method (Segara et al., 2021).

According to Carpenter (1999), Since the chevron method only needs a single discharge point along the center axis of the stack, it is the easiest system to put into practice, and Speight (2021) states that the windrow approach is better for coating coal than the chevron method since the chevron method is more prone to spontaneous combustion.

For coal that will be stored for an extended period, a porosity of less than 0.1 mm is strongly advised, whilst a porosity of less than 0.2 mm is advised to avoid large-scale coal degradation (Zhang et al., 2016).

Chakraborti (1995), suggests turning over the old coal pile and storing it with lots of fine grains, then unloading the coal again when the weather conditions are good. The aim is to minimize the potential for self-heating to occur.

3.1.2 Dimensions of coal stockpiles

a. Heap base design of coal stockpile

Good site preparation can help to avoid spontaneous combustion (Thompson et al., 1981), where the stockpile conditions must be free from dirt and flammable materials such as wood and have a solid base (Schmidt, 1945).

The design of the stockpile base surface must be made stable and covered with bedding using strong material to support the weight of the coal ple, besides that, the stockpile base must be convex to facilitate drainage (Mulyana, 2005).

The goal is to prevent puddles of water from forming when it rains and when watering using water spray, and to stop coal stocks' humidity from rising (Hatt et al., 1997).

According to Carpenter (1999), the temperature and rank of the coal determine how much air content affects the self-heating process.

Heavy rainfall and other meteorological phenomena can raise the moisture content of coal in open-air piles and produce surface moisture in the stockpile (Smith et al., 1987).

According to Espag (2015), There is a significant linear relationship between rainfall intensity and the amount of water runoff from the surface of the stockpile. The infiltration rate stabilizes after the coal pile's surface gets saturated, which results in small empty spaces between coal particles due to compaction or a high fine grain content inhibiting infiltration, causing an increase in the runoff proportion.

According to Hatt et al. (1997), in estimating the humidity of coal piles effectively, you can use a cheap method (around US$20), namely a greenhouse moisture meter, and in controlling the water content in piles, you can use coal piles to reach the maximum height with a top that is not flat, compaction of the heap's surface and side slopes to enhance the proportion of outflow.

b. Stockpile capacity

According to Okten et al. (2008), generally, stockpile dimensions are shaped like cones, pyramids, and sharp pyramids, where a spatial formula that adjusts to the stockpile's shape can be used to calculate the volume of the stockpile dimensions.

According to Faseha et al. (2024), the use of UAV is better than GNSS in obtaining 3D coal pile data for volume calculations because it can be operated remotely, captures many data sets in a shorter time, and produces consistency when making stockpile volume calculations.

c. Stockpile height

According to Zhu et al. (2013), stockpile height significantly affects the likelihood of self-heating in coal, and depending on the coal type, additional dimensions, and pile circumstances, the ideal stockpile height would vary (Carpenter, 1999).

Coal heaps built with sloping sides can reduce the potential for spontaneous combustion and self-heating (Krishnaswamy et al., 1996), and according to Zhang et al. (2023), reducing the height of the coal heap will result in less gas entering the coal heap when it is lowered in height. and reduce areas of oxidative erosion that are affected by wind exposure (Zhang et al., 2016), and extend the induction period (Zhang et al., 2011).

According to Sumantri (2019), A coal pile that has a calorific value between 3,900 and 4,300 Kcal/kg cannot be higher than 6 meters, whereas according to Walker (1999), the maximum height for fine coal is 8 to 9 m and for coarse coal is 3 to 4 m.

d. Side slope of coal stockpile

One of the primary determinants of the long-term safety of coal storage is the side slope of a coal heap (Krishnaswamy et al., 1996).

A coal heap with a slope angle of 15 to 30° will make it easier to compact the sides of stockpiles and make tool work easier, but it will have the disadvantage of reducing the capacity of the stockpile area (Carpenter, 1999).

According to Zhang et al. (2016), the mixture of CO2 gas with high concentrations can be minimized by forming coal stockpiles on steep slopes, where coal with a steep slope angle reduces the duration of coal-water interaction (Espag, 2015), and avoids the potential for particle size segregation (Van Vuuren, 1995).

e. Distance between coal stockpiles

The distance between coal stockpiles has an effect on the self-heating process and denser coal piles increase in temperature more slowly, but the space between stockpiles can lead to the buildup of undesired carbonate gas (Zhang et al., 2016).

3.1.3 Environmental conditions of the stockpile area

In coal piles, it's important to consider both the direction and speed of the wind to prevent self-heating and possibly spontaneous combustion (Zhu et al., 2013).

Wind plays a major role in coal stockpile self-heating (Moghtaderi et al., 2009). The wind that blows up against the coal pile's side will enter the mass of coal and add more oxygen, which will increase heat creation and slow down the rate of heat loss (Carpenter, 1999).

The oxygen content of coal increases with decreasing calorific value (Hong et al., 1994), therefore, wind barriers or bund walls are made around coal piles to maintain wind speeds of <2 m/s so that coal safety is maintained, the thermal value of coal is maintained, and greenhouse gas emissions are reduced (Zhang et al., 2023), for example, by making a 6 m high fence made from 200 mm pine planks with a distance between the planks of 85 mm, and it has been successful in lowering the temperature in low-rank coal piles. (Fiero et al., 1999).

Wind speed will raise the amount of damaged coal and the possibility of self-heating, where wind speed is one of the parameters that have the strongest influence on coal self-heating in the stockpile area based on the 2D Diffusion Reaction Model (Krishnaswamy et al., 1996), and weather conditions such as wind speed will affect the rate of evaporation (Espaq, 2015).

According to Roberts et al. (1994), evaporation in removing moisture from coal piles will be significant if conditions are hot and dry (Roberts et al., 1994), and a smooth coal stockpile's surface will evaporate more quickly than a coarse coal heap. However, due to the coarse coal stockpile's porous structure, evaporation will be more effective there. A fine coal layer will only show evaporation at the surface, whereas a coarse coal layer will show evaporation down to a depth of 0.4 m (Espaq, 2015).

3.1.4 Physical properties of coal

a. Coal particle size

CPT (Crossing Point Temperature) studies show that when coal particle size rises, its activation energy and reactivity decrease (Nugroho et al., 2021), and according to Zhang et al. (2016), based on the findings of CPT and GC (Gas Chromatography), coal porosity is known to have a significant influence on the incidence of self-heating.

According to Schmal (1985), the self-heating process without water vapor is directly or indirectly influenced by the porosity and speed of coal particles and thermal conductivity.

Coal particle size is an important parameter that influences the increase in coal seam temperature and the relationship between oxidation and the potential for self-heating (Akgun et al., 1994).

Compared to bigger particles, smaller coal particles produce more heat and have a faster rate of oxidation (Nelson et al., 2007), because they have a larger surface contact area with oxygen (Yilmaz et al., 2010).

Coal with smaller particles will have a greater surface area and a higher chance of self-heating (Unal, 1995).

Natural convection causes spiral air flows on the coal stockpile's side, and as temperatures rise, so does the airflow pressure. During this method, it is ineffective to isolate oxygen using coal whose particle size is smaller than 3 mm (Zhou et al., 2024).

The oxidation rate is directly proportional to the coal pore volume and is mostly determined by the coal pore structure. O2 gas cannot pass through coal pores smaller than 12A (Kaji et al., 1985), and the coal's porosity dictates the size of the coal particles (Unal, 1995).

b. Coal porosity

The capacity of coal to self-heat is significantly influenced by porosity and as porosity rises, so does coal temperature; nevertheless, porosity has a greater effect on oxygen availability than on heat transfer (Zhu et al., 2013). According to Krishnaswamy et al. (1996), porosity in coal seams can be determined using the 2D Diffusion Reaction Model and based on Numerical Investigation.

Compacting coal seams requires a lot of labor and is expensive (Blaschke, 1995), however, it has advantages for the long-term storage of coal stockpiles (Handa, 1997), especially for coal, which has a temperature between 35 and 60°C. (Carpenter, 1999).

According to Zhang et al. (2023), in addition to preventing self-heating, compaction of coal piles to lower porosity helps preserve the pile's thermal value and lowers greenhouse gas emissions.

Coal compaction in layers in new coal piles every 2 m thick aims to reduce voids where gas can be stored in the pile (Sumantri, 2019).

Although it does not always slow down the rate of increase in maximum temperature, it can reduce the volume of oxidized coal and reduce greenhouse gas emissions (Zhang et al., 2016).

According to Miranda et al. (1995), coal piles that are compacted when exposed to wind have a much lower temperature compared to piles that are not compacted and require a longer oxidation time, thereby slowing down the occurrence of self-heating, while piles of coal that have not been compacted must be concave in shape to avoid air infiltration. (Van Vuuren, 1995).

c. Coal temperature

The highest coal heating rate occurs in coal with inherent moisture >7% of the coal weight and occurs at temperatures <80°C based on DTA (Differential Thermal Analysis) data (Vance et al., 1996), where based on experimental results, each increase in temperature is 10°C, and the oxidation rate increases twofold (Schmal, 1989).

High-bituminous coal grades up to semi-anthracite have a coal heating temperature between 1.800°C to 2.700°C, where oxidation results in changes in self-heating and final combustion temperature, and volatile substances are released up to a temperature of 4.250°C (Pis et al., 1996).

3.2 Monitoring and detection of coal self-heating

Early detection of self-heating is important for coal storage safety and minimizing potential losses due to self-burning (Carpenter, 1996), it can be accomplished with regulated stockpile management, even though it is intricate and challenging since there are a wide range of variables at play (Nalbandian, 2010).

Preventing particle segregation, limiting airflow in the pile, as well as creating self-heating analysis and prediction methods (Mastalerz et al., 2009).

The main techniques for detecting and monitoring the early stages of self-heating are temperature measurement and gas analysis, and there are several methods used and developed to evaluate, monitor, and analyze any occasions where the coal heap has spontaneous combustion nearby.

In 1989, Tarafdar et al. obtained a correlation between measurements of temperature differences and potential differences during the coal oxidation process, and this is based on CPT (Crossing Point Temperature) readings and can be used to forecast when self-heating will occur.

DTA (Differential Thermal Analysis) can be used, according to Clemens et al. (1990), to analyze coal's susceptibility to low-temperature isothermal oxidation, which raises temperature and exotherm and can lead to self-heating. COMSOL Multiphysics can then be used to analyze the data, and the results showed that there was a 0.9% deviation between the results of experimental modeling and field temperature data. This implies that the oxygen content and porosity of coal both contribute significantly to inhibiting spontaneous combustion (Saleh et al., 2017).

Garcia et al. (1999) state that the DSC (Differential Scanning Calorimeter) can be used to calculate the oxidation enthalpy, which helps understand the early phases of coal oxidation the early phases of coal oxidation. The temperature at which coal oxidation begins is the first sign of coal spontaneous combustion. It has been demonstrated that the DSC (Differential Scanning Calorimeter) is superior to the CPT (Crossing Point Temperature) in terms of accuracy and efficiency for estimating the temperature at the coal crossing point and producing self-heating forecasts (Sahu et al., 2004).

Beamish et al. (2000) found that there was a correlation between coal rank and self-heating rate. According to Beamish et al. (2001), coal has a strong propensity for self-heating and is highly reactive to oxygen. Sub-bituminous coal was found to have the highest initial heating rate and the lowest activation energy. Coal oxidation kinetic parameters are described by the Adiabatic Method and are associated with coal reactivity. Accordingly, stored or partially pre-oxidized coal has higher active energy (Beamish et al., 2003).

Hot spot locations in compacted coal seams, the effect of coal kind, and porosity in embankment layers on self-heating can be predicted using the Two-dimensional Unsteady-state Model, according to Akgun et al. (2001).

Self-heating will not occur in coal embankments with a maximum height of 2 m, an embankment duration of ≤15 days, and an embankment temperature between 60 and 80ºC, while according to Fierro et al. (2001), the use of TNO Modifications and Mathematical Simulation Models can provide predictions of the time sequence, location of self-heating, and reduction in coal calories. So, periodic compaction can be effective in reducing self-heating and checking the temperature of the coal, at least once a day to determine the temperature increase. That compaction can be carried out immediately at a point that is approaching the critical temperature for self-combustion, namely 50°C (Sumantri et al., 2019).

Using quantitative modeling techniques, Humphreys (2005) ascertained the direct relationship between a coal pile's initial temperature, dimensions, and time of piling, and considering the impact of coal particle size on the possibility of spontaneous combustion as determined by laboratory testing and field behavior predictions made using fundamental parameters like oxidation, reactivity, and heat of oxidation. Ozdeniz et al. (2008) developed a data collection system such as calorific value, temperature, and humidity in coal piles in the stockpile area using Artificial Neural Network Modeling so that measurement data can be stored in a database according to the desired time interval and measurement and An assessment technique is available to forecast the likelihood of self-heating.

In 2009, Yuan et al. carried out self-heating simulations on large-scale coal using computational fluid dynamics and found that the self-heating process occurred in four stages, including:

1. The induction stage is the stage of slowly increasing the temperature.
2. The second stage is the increase in heat in the coal due to the increasing temperature.
3. In the third stage, coal's oxygen content rises in proportion to temperature increase, which in turn causes the high-temperature pile zone to begin advancing towards the front of the coal stockpile layer.
4. The high-temperature heap zone needs to be restricted to the center portion of the coal heap layer during the fourth stage.

Shorter induction times are produced by higher air flow rates in the coal pile layer space, and it is well known that the reaction sequence greatly influences induction time prediction; shorter induction times are produced by lower reaction values. Predicting the induction time is therefore crucial to avoiding self-heating.

4. Conclusion

Based on several literature reviews, managing coal stockpiles to avoid and minimize self-heating, which has the potential to result in spontaneous combustion, is a component of keeping the amount and quality of coal that is delivered to the client from the mine.

Stockpile management is the process of monitoring and controlling resources as a temporary storage place, so attention needs to be paid to prevent oxidation and self-burning, changes in properties, and size degradation to suit production and utilization aspects.

To prevent self-heating, stockpile management must take into account several factors, including setting the stockpile pattern, applying demolition principles, forming the stockpile base surface design, calculating the volume, height, side slope, and distance between stockpiles, as well as calculating the speed and direction of the wind. These factors have a related impact on the coal's porosity, temperature rise, and particle size.

Efforts to handle self-heating in coal can be made by making drainage in the stockpile area, reducing the height, and forming a slope angle of 15–30° to facilitate heap compaction activities so that the coal can be stored for a long time, as well as detecting the occurrence of self-heating early for safe storage coal and minimizing potential losses due to spontaneous combustion.

Various analyses and methods are used to monitor and detect self-heating. To ascertain the initial stage of coal oxidation, one can utilize the DSC (Differential Scanning Calorimeter), the CPT (Crossing Point Temperature) to measure differential temperature, the DTA (Differential Thermal Analysis) to ascertain the vulnerability of coal at low temperatures, which isothermal, and a two-dimensional unsteady-state model to forecast the location of hot spots in coal stockpile layers.

Acknowledgements

The writer wishes to express gratitude to various parties, especially Dr. Ir. Edy Nursanto, S.T., M.T., IPM, as Supervisor I, Dr. Ir. Nurkhamim, S.T., M.T., as Supervisor II, and the Master of Mining Engineering Study Program at the Veteran National Development University of Yogyakarta, as well as friends who have provided moral support in the preparation of this paper.

References

Abd, M., 2023. *Technical Design and Mining Scheduling (Mine Scheduling) in the Fourth Quarter of 2022 PT. Bumi Bara Makmur Mandiri Pit Tiga Batin XXIV District, Batanghari Regency, Jambi Province (Doctoral dissertation, Jambi University)*.

Achmad, P., 1992. Coal Definition.

Afif, F., 2022. *Stockpile Geometry Analysis for Self-Burning Prevention at PT. Bukit Asam Tbk, Tanjung Enim, South Sumatra (Bachelor's Thesis, Faculty of Science and Technology, Syarif Hidayatullah State Islamic University, Jakarta)*.

Akgün, F. and Arisoy, A., 1994. Effect of Particle Size on The Spontaneous Heating of A Coal Stockpile. *Combustion and Flame*, *99*(1), pp.137-146.

Alfarisi, A., Ibrahim, E. and Asyik, M., 2017. Analysis of the Potential of Self Heating Coal in Live Stock and Temporary Stockpile Banko Barat PT. Asam Hill. Mining Journal, *1*(3).

ASTM., 1998. ASTM D388: Standard Classification of Coals by Rank. American Society for Testing and Materials.

Beamish, B.B., Barakat, M.A. and George, J.D.S., 2001. Spontaneous-combustion propensity of New Zealand coals under adiabatic conditions. *International Journal of Coal Geology*, *45*(2-3), pp.217-224.

Beamish, B.B., Cooper, A.L., Barakat, M.A. and St George, J.D., 2000. Self-heating rates of New Zealand and Australian subbituminous coals.

Beamish, B.B., George, J.S. and Barakat, M.A., 2003. Kinetic parameters associated with self-heating of New Zealand coals under adiabatic conditions. *Mineralogical Magazine*, *67*(4), pp.665-670.

Blaschke, W.S. ed., 1995. *New trends in coal preparation technologies and equipment* (Vol. 1). Taylor & Francis.

Brooks, K. and Glasser, D., 1986. A Simplified Model of Spontaneous Combustion in Coal Stockpiles. *Fuel*, *65*(8), pp.1035-1041.
Carpenter, A.M., 1999. *Management of Coal Stockpiles* (Vol. 23). London: IEA Coal Research.
Carras, J.N. and Young, B.C., 1994. Self-heating of coal and related materials: models, application and test methods. *Progress in Energy and Combustion Science*, *20*(1), pp.1-15.
Chakraborti, S.K., 1995. American electric powers coal pile magagement program. *Bulk solids handling*, *15*.
Clemens, A.H., Matheson, T.W. and Rogers, D.E., 1990. DTA Studies of The low Temperature Oxidation of Low Rank Coals. *Fuel*, *69*(2), pp.255-256.
Djunaidi Adenan, Djoni., 1999. *Relationship between Self-Burning Properties and Coal Storage Techniques, Tekmira, Bandung*.
Ejlali, A., Mee, D.J., Hooman, K. and Beamish, B.B., 2011. Numerical Modelling of The Self-Heating Process of A Wet Porous Medium. *International Journal of Heat and Mass Transfer*, *54*(25-26), pp.5200-5206.
Espag, C.B., 2015. *Water Transport Mechanisms in Coal SStockpiles* (Doctoral Dissertation, North-West University (South Africa), Potchefstroom Campus).
Faseha, O.M., Ono, M.N. and Adeboboye, A.J., 2024. Geodetic Investigation Coal Stockpile Volume Measured from A Mining Site in Okaba, Ankpa LGA, Kogi State.
Fei, Y., Abd Aziz, A., Jackson, W.R., Marshall, M., Hulston, J. and Chaffee, A.L., 2007. A comparison of the spontaneous combustion behavior of brown coal and a range of dried products.
Fierro, V., Miranda, J.L., Romero, C., Andres, J.M., Arriaga, A. and Schmal, D., 2001. Model Predictions and Experimental Results on Self-heating Prevention of Stockpiled Coals. *Fuel*, *80*(1), pp.125-134.
Garcia, P., Hall, P.J. and Mondragon, F., 1999. The Use of Differential Scanning Calorimetry to Identify Coals Susceptible to Spontaneous Combustion. *Thermochimica acta*, *336*(1-2), pp.41-46.
Handa, S.U.S.H.I.L., 1997. Coal handling-environment friendly approach.
Hardianti, S. and Billi, B., 2018. The Influence of Temperature, Piling Time, and Piling Dimensions on the Occurrence of Self-Burning. Patra Academic Engineering Journal, *9*(02), pp.4-13.
Hasibuan, M.S. and Hasibuan, H.M.S., 2016. *Human Resource Management. Earth of letters*.
Hatt, R. and Versailles, K.Y., 1997. Sticky When Wet. *World Coal, August*.
Hong, B.D. and Slatick, E.R., 1994. Carbon dioxide emission factors for coal. *Quarterly coal report*.
Humphreys, D., 2005. Anatomy of a heating and assessment of critical self-heating parameters.
Indonesia, 2009. *Law no. 4 of 2009 concerning mineral and coal mining. Justika Public Broadcasting*.
Jo, W., Choi, H., Kim, S., Yoo, J., Chun, D., Rhim, Y., Lim, J. and Lee, S., 2013. A Comparison of Spontaneous Combustion Susceptibility of Coal According To Its Rank. *Korean Journal of Chemical Engineering*, *30*, pp.1034-1038.
Jolo, A., 2016. Stockpile Management to Prevent Coal Burning at PT. PLN (Persero) Tidore. Dintek, *9*(2), pp.6-14.
Jones, J.C. and Vais, M., 1991. Factors Influencing The Spontaneous Heating of Low-rank Coals. *Journal of Hazardous Materials*, *26*(2), pp.203-212.
Kaji, R., Hishinuma, Y. and Nakamura, Y., 1985. Low Temperature Oxidation of Coals: Effects of Pore Structure and Coal Composition. *Fuel*, *64*(3), pp.297-302.
Krishnaswamy, S., Agarwal, P.K. and Gunn, R.D., 1996. Low-temperature Oxidation of Coal. 3. Modelling Spontaneous Combustion in Coal Stockpiles. *Fuel*, *75*(3), pp.353-362.
Küçük, A., Kadıoğlu, Y. and Gülaboğlu, M.Ş., 2003. A Study of Spontaneous Combustion Characteristics of A Turkish Lignite: Particle Size, Moisture of Coal, Humidity of Air. *Combustion and Flame*, *133*(3), pp.255-261.
Li, S., Ma, X. and Yang, C., 2018. Prediction of Spontaneous Combustion in The Coal Stockpile Based on An Improved Metabolic Grey Model. *Process Safety and Environmental Protection*, *116*, pp.564-577.
Mastalerz, M., Solano-Acosta, W., Schimmelmann, A. and Drobniak, A., 2009. Effects of coal storage in air on physical and chemical properties of coal and on gas adsorption. *International Journal of Coal Geology*, *79*(4), pp.167-174.
Miranda, J.L., Romero, C., Andres, J.M. and Schmal, D., 1995. Evolution of temperature and gas composition in coal piles.
Moghtaderi, B., Dlugogorski, B.Z. and Kennedy, E.M., 2000. Effects of wind flow on self-heating characteristics of coal stockpiles. *Process Safety and Environmental Protection*, *78*(6), pp.445-453.
Muchjidin, M., 2006. Quality Control in the Coal Industry. ITB Bandung Publisher.
Mulyana, H., 2005. Coal Quality and Stockpile Management. PT Geoservices, LTD.
Nalbandian, H., 2010. *Propensity of coal to self-heat* (Vol. 172, pp. 5-8). London: IEA Clean Coal Centre.
Nelson, M. I., Chen, X. D. (2007). Survey of Experimental Work on The Self-heating and Spontaneous Combustion of Coal.
Nugroho, Y.S., McIntosh, A.C. and Gibbs, B.M., 2001. On The Interpretation of Oxidation Studies of Single and Blended Coals. *Fuel*, *13*(80), pp.1983-1985.
Okten, G., Kural, O., Algurkaplan, E. (2008). Storage of Coal: Problems and Precautions. *Energy Storage Systems*, *2*.
Onifade, M. and Genc, B., 2019. A Review of Spontaneous Combustion Studies–South African Context. *International Journal of Mining, Reclamation and Environment*, *33*(8), pp.527-547.
Onifade, M. and Genc, B., 2020. A Review of Research on Spontaneous Combustion of Coal. *International Journal of Mining Science and Technology*, *30*(3), pp.303-311.
Onifade, M., Genc, B. and Carpede, A., 2018. A New Apparatus to Establish The Spontaneous Combustion Propensity of Coals and Coal-shales. *International Journal of Mining Science and Technology*, *28*(4), pp.649-655.
Ozdeniz, A.H., Ozbay, Y., Yilmaz, N. and Sensogut, C., 2008. Monitoring and ANN Modeling of Coal Stockpile Behavior Under Different Atmospheric Conditions. *Energy Sources, Part A*, *30*(6), pp.494-507.
Peng, G., Wang, H., Song, X. and Zhang, H., 2017. Intelligent Management of Coal Stockpiles Using Improved Grey Spontaneous Combustion Forecasting Models. *Energy*, *132*, pp.269-279.
Pis, J., de La Puente, G., Fuente, E., Morán, A. and Rubiera, F., 1996. A Study of The Self-Heating of Fresh and

Oxidized Coals by Differential Thermal Analysis. *Thermochimica acta*, *279*, pp.93-101.
Pisupati, S.V. and Scaroni, A.W., 1991, January. The Inflence of Weathering and Low-Temperature Oxidation on The Combustion Behavior of Bituminous Coals. In *1991 International Conference on Coal Science Proceedings* (pp. 199-202). Butterworth-Heinemann.
Roberts, C., Sagahfi, A. and Conroy, A., 1994. Chemical Instability of Coal During Handling, Storage and Pulverising.
Sahu, H.B., Panigrahi, D.C. and Mishra, N.M., 2004. Assessment of Spontaneous Heating Susceptibility of Coal Seams by Differential Scanning Calorimetry.
Sahu, H.B., Panigrahi, D.C. and Mishra, N.M., 2005. Assessment of Spontaneous Heating Susceptibility of Coal Seams by Experimental Techniques-a Comparative Study.
Saleh, M., Muharram, Y. and Nugroho, Y.S., 2017. Modeling of The Crossing Point Temperature Phenomenon in The Low-temperature Oxidation of Coal. *Int. J. Technol*, *1*, pp.104-113.
Sanwani, E., Ibrahim, A., Sudarsono, A., Sule, D. and Handayani, I., 1998. Coal Washing. Bandung Institute of Technology: Bandung.
Sarana, A.P.B.S., 2022. Self Combustion Prevention Study in Stockpile at PT. Baramulti Success Means. Journal of Mineral Technology FT UNMUL, *10*(1), pp.38-42.
Schmal, D., 1989. Spontaneous heating of stored coal. *Chemistry of coal weathering*, pp.133-215.
Schmal, D., Duyzer, J.H. and van Heuven, J.W., 1985. A Model for The Spontaneous Heating of Coal. *Fuel*, *64*(7), pp.963-972.
Schmidt, L.D., 1945. Changes in coal during storage. *Chemistry of coal utilization*, *18*, pp.627-676.
Segara, R.B., Guskarnali, G. and Oktarianty, H., 2021, December. Analysis of the Influence of Self-Burning Potential on the Implementation of Stockpile Patterns in the PT Coal Stockpile. Tanjung Enim Asam Hill. In *Proceedings Of National Colloquium Research And Community Service* (Vol. 5, pp. 29-32).
Singh, P.R.A.S.O.O.N., 2014. *An Investigation Into Spontaneous Heating Characteristics of Coal and Its Correlation with Intrinsic Properties* (Doctoral Dissertation).
Smith, A.C. and Lazzara, C.P., 1987. *Spontaneous combustion studies of US coals* (Vol. 9079). US Department of the Interior, Bureau of Mines.
Speight, J. G. (2021). *Coal-Fired Power Generation Handbook 2nd Edition*. John Wiley & Sons, Limited.
Speight, J.G., 2012. *The Chemistry and Technology of Coal*. CRC press.
Sujanti, W., Zhang, D.K. and Chen, X.D., 1999. Low-temperature Oxidation of Coal Studied Using Wire-mesh Reactors with Both Steady-state and Transient Methods. *Combustion and Flame*, *117*(3), pp.646-651.
Sumantri, A., 2019. Analysis of Coal Stockpile Management to Prevent Self-Burning in the Stockpile of PLTU Teluk Sirih Village, West Sumatra Province. *Advances in Transportation and Logistics Research*, *5*, 1086-1099.
Sunarto, B., 2013. Art Creation Methodology. Surakarta: Indonesian Art Institute Surakarta.
Syahrul, S., Yusuf, M. and Handayani, H.E., 2014. Effectiveness of Using Compaction Methods to Prevent Self-Burning in Temporary Stockpile Pit 1B at PT. Bukit Asam (Persero) tbk Tanjung Enim. Journal of Mining Engineering.
Tarafdar, M.N. and Guha, D., 1989. Application of Wet Oxidation Processes for The Assessment of The Spontaneous Heating of Coal. *Fuel*, *68*(3), pp.315-317.
Thompson, T.L. and Raymer, F.B., 1981. Transportation, storage, and handling of coal. *Chemistry of Coal Utilization*, pp.523-570.
Ünal, S., 1995. A review of spontaneous combustion of coals. *Fuel science & technology international*, *13*(9), pp.1103-1120.
Van Vuuren, M.C., 1995. Guidelines for the prevention of spontaneous combustion of coal during storage and transport.
Vance, W.E., Chen, X.D. and Scott, S.C., 1996. The Rate of Temperature Rise of A Sub-bituminous Coal During Spontaneous Combustion in An Adiabatic Device: The Effect of Moisture Content and Drying Methods. *Combustion and Flame*, *106*(3), pp.261-270.
Walker, S., 1999. Uncontrolled fires in coal and coal wastes.
Wardana, Y.R., 2023. *Analysis of Coal Stockpile Management to Minimize the Occurrence of Self-Burning in PT's Coal Crushing Plant (CCP) Area. Banyan Koalindo Lestari Musi Rawas Utara, South Sumatra (Doctoral Dissertation, UPN "Veteran" Yogyajarta)*.
Xia, T., Zhou, F., Liu, J., Kang, J. and Gao, F., 2014. A Fully Coupled Hydro-thermo-mechanical Model for The Spontaneous Combustion of Underground Coal Seams. *Fuel*, *125*, pp.106-115.
Yilmaz, N. and Ozdeniz, A.H., 2010. Internet-based monitoring and prediction system of coal stockpile behaviors under atmospheric conditions. *Environmental monitoring and assessment*, *162*, pp.103-112.
Yuan, L. and Smith, A.C., 2009. CFD Modeling of Spontaneous Heating in A Large-scale Coal Chamber. *Journal of Loss Prevention in the Process Industries*, *22*(4), pp.426-433.
Zhang, J., An, J., Zhou, A., Wang, K., Si, G. and Xu, B., 2023. Development and Parameterization of A Model for Low-temperature Oxidative Self-heating of Coal Stockpiles under Forced Convection. *Fuel*, *339*, p.127349.
Zhang, J., Liang, Y., Ren, T., Wang, Z. and Wang, G., 2016. Transient CFD Modelling of Low-temperature Spontaneous Heating Behaviour in Multiple Coal Stockpiles with Wind Forced Convection. *Fuel Processing Technology*, *149*, pp.55-74.
Zhang, Y.T., Zhang, X.C., Tien, J.C. and Li, Y.Q., 2011. Evaluation of The Propensity for Coal Spontaneous Combustion Based on Catastrophe Theory. *Journal of Coal Science and Engineering (China)*, *17*, pp.265-269.
Zhou, A., An, J., Wang, K., Zhang, J., Liu, Y., Wang, J., Si, G. and Wang, W., 2024. Modeling and Parametric Analysis of Low-temperature Oxidative Self-heating in Coal Stockpiles Driven by Natural Convection. *Fuel*, *361*, p.130670.
Zhu, H.Q., Song, Z.Y., Tan, B. and Hao, Y.Z., 2013. Numerical Investigation and Theoretical Prediction of self-Ignition Characteristics of Coarse Coal Stockpiles. *Journal of Loss Prevention in the Process Industries*, *26*(1), pp.236-244.