Management of coal stockpiles

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Abstract

Stockpile management is an important part of the coal handling process from mine to customer. Virtually all coal producers and consumers make use of stockpiles at their facilities, either to serve as a buffer between material delivery and processing, acting as a strategic stock against supply interruptions, or to enable coal blending to meet quality requirements. With mounting pressure to minimise the capital tied up in stockpiles, there is a need to optimise coal inventories. Factors such as stockpile size, turnover period, timely stock management, and the ability to take advantage of cheaper coals have all assumed greater importance. This report begins by examining why stockpiles are employed. The stacking and reclaiming of piles, and the reduction of noise arising from the handling equipment is then discussed, along with stockpile automation and management. Good sampling and analysis procedures are essential for coal quality management. Sampling systems, representative samples and on-line analysis are described. Stock auditing to reconcile the amount of coal in the stockpiles is also covered. Most coals, particularly those of lower rank, are susceptible to weathering and atmospheric oxidation during storage in open-air piles. Properties and processes affected by coal oxidation and weathering, including heating value losses, handleability, cleaning, combustion and coking are examined. Spontaneous combustion poses safety, environmental, economic and handling problems if it becomes established in stockpiles. Factors affecting spontaneous combustion are discussed with the emphasis on prevention, detection and control. Stockyard operators are under constant social and political pressures to improve the environmental acceptability of their operations. Thus control, prevention and monitoring of fugitive dust emissions, and the composition, collection and treatment of stockpile runoff are addressed. The prevention and control of flowslides are also covered. Experience has shown that with good stockpile design and management, most coals can be safely stored in an environmentally acceptable way.
### Acronyms and abbreviations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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<tbody>
<tr>
<td>AS</td>
<td>Standards Australia</td>
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<tr>
<td>ASTM</td>
<td>American Society for Testing and Materials</td>
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<td>BS</td>
<td>British Standard</td>
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<tr>
<td>CRI</td>
<td>coke reactivity index</td>
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<td>CSR</td>
<td>coke strength after reaction</td>
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<td>db</td>
<td>dry basis</td>
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<tr>
<td>DTA</td>
<td>differential thermal analysis</td>
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<tr>
<td>EPA</td>
<td>Environmental Protection Agency (USA)</td>
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<td>FSI</td>
<td>free swelling index</td>
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<tr>
<td>GPS</td>
<td>global positioning system</td>
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<tr>
<td>IEA</td>
<td>International Energy Agency</td>
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<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
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<tr>
<td>mmf</td>
<td>mineral matter-free</td>
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<tr>
<td>PGNAA</td>
<td>prompt gamma neutron activation analysis</td>
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<tr>
<td>PRB</td>
<td>Powder River Basin (USA)</td>
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<td>SHT</td>
<td>self-heating temperature</td>
</tr>
</tbody>
</table>
Contents

1 Introduction 5

2 Why stockpile? 6

3 Stacking and reclaiming stockpiles 8
   3.1 Stacking 9
   3.2 Reclaiming 10
   3.3 Stockyard management and automation 13
   3.4 Environmental aspects 15

4 Sampling, analysis and auditing 17
   4.1 Representative samples 17
   4.2 Sampling systems 19
   4.3 On-line analysis 21
   4.4 Stock audits 23

5 Coal deterioration 26
   5.1 Heating value 26
   5.2 Coal handling 27
   5.3 Coal cleaning 28
   5.4 Combustion 29
   5.5 Coking 31
   5.6 Comments 34

6 Spontaneous combustion 35
   6.1 Factors affecting spontaneous combustion 35
      6.1.1 Coal properties 35
      6.1.2 Climatic conditions 37
   6.2 Risk assessment 37
   6.3 Prevention 39
   6.4 Detection 41
   6.5 Control 43
   6.6 Comments 43

7 Dust emissions 44
   7.1 Factors affecting dust emissions 44
   7.2 Prevention 45
   7.3 Monitoring and test methods 50
   7.4 Comments 51

8 Runoff and flowslides 52
   8.1 Runoff composition 52
   8.2 Runoff collection 52
   8.3 Runoff treatment 53
   8.4 Flowslides and their causes 54
   8.5 Prevention and control of flowslides 56

9 Conclusions 57

10 References 60
1 Introduction

Over the last few decades the amount of coal produced and traded internationally has risen considerably. In 1998, world coal production was about 4551 Mt, of which 3656 Mt consisted of hard coal. Around 524 Mt of this hard coal was traded, with the seaborne trade amounting to 476 Mt (IEA, 1999). Stockyards play an integral and vital part in the coal chain, with virtually all transport systems and most coal producers and consumers making use of stockpiles.

Stockpiling is carried out at coal mines, coal preparation plants, transhipment facilities (including export/import facilities) and end user sites such as power plants, coking plants and cement works. With mounting pressure to minimise the amount of capital tied up in stockpiles with no return on the investment, there is a need to optimise coal inventories wherever coal is stockpiled. Issues such as optimum stockpile size, stockpile turnover period, timely stock management, and the ability to take advantage of cheaper coals when available on the market have therefore all assumed greater importance. Growing economic constraints, the need for smaller stockyards with the ability to blend coals with the accuracy demanded by consumers, and the increasing use of just-in-time delivery has increased the significance of stockpile management within the international coal market. Terminals are having to handle more throughput and more grades of coal, at higher handling rates and with less impact on the environment, and to do it all at lower cost.

All these issues require improved stockpile management in order to avoid supply disruptions and their consequences, such as interruptions in the power supply.

The size of stockyards varies from a few thousand tonnes to over 6 Mt at a number of major coal export terminals, such as Richards Bay in South Africa and Port Waratah in Newcastle, NSW, Australia. The level of sophistication can therefore range from simple piles at some sites to highly automated stockyards used by major coal exporting ports or large tonnage consumers. Stockpiles are also employed for long-term storage, typically at places such as power plants, to guarantee supply. Thus the management of stockpiles will be specific to the site and will depend on the purpose of the facility. In addition, the optimal point between the money tied up in storage and security of supply can be difficult to determine.

This report on the management of stockpiles begins by examining why stockpiles are employed. The ability to blend coals is becoming increasingly important. Consumers can then take advantage of cheaper coals on the market that are outside the fuel specification normally used. This necessitates accurate blending at sites such as power plants. The cost-effectiveness and operating success of the stockyard system is partly dependent on the selection of suitable handling equipment. The stacking and reclaiming of stockpiles, and the reduction of noise arising from the handling equipment is discussed in Chapter 3. In addition, stockyard automation and management are described. Stockyards operating a large number of stockpiles are complex operations requiring integrated information management and control systems. These systems need to provide a real-time inventory for keeping track of the quality and quantity (tonnage) of coal passing through the stockpiles.

Coal is usually sampled and analysed either before or after arrival at a site. One reason is to determine whether the consignment meets the contract specification. Inability to meet the specification results in financial penalties or even cargo rejection, depending on the severity of the quality non-conformance. At most, if not all, sites, coal is analysed at some stage, either on its way to or from the stockpile or even from within the pile itself. It is therefore essential that the sampling procedures are accurate and precise to ensure that the small sample taken is representative of the thousands of tonnes of coal in a consignment or stockpile. Costly disputes can result when analysis of samples taken by the buyers and sellers disagree. Obtaining representative samples, and on-line analysis of the coal streams is reviewed in Chapter 4. This chapter also looks at coal stock auditing carried out to reconcile the amount of coal in the stockpiles to the book inventory.

Most coals are susceptible to weathering and atmospheric oxidation during storage in open-air stockpiles. Chapter 5 examines some of the properties and processes affected by coal oxidation/weathering including heating value losses, handleability, cleaning, combustion and coking. Spontaneous combustion poses significant safety, environmental, economic and handling problems if it becomes established in stockpiles. Factors affecting spontaneous combustion, and tests for assessing the self-heating tendencies of coal are outlined in Chapter 6. The emphasis in this chapter is, however, on prevention, detection and control.

Stockyard operators are under constant social and political pressures to reduce or remove the risk of environmental pollution inherent in their operations. Both air and water pollution regulations are becoming increasingly stringent. Chapter 7 discusses the control, prevention and monitoring of fugitive dust emissions. The composition, collection and treatment of stockpile runoff is addressed in the following chapter. Heavy rainfall and poor stockpile drainage can lead to flowslides, a potential safety hazard. The prevention and control of flowslides is examined in Chapter 8.
Stockpiling of coals is carried out at a number of points along the transport chain to the end user:
- at coal mines;
- at coal preparation plants;
- at transhipment points and terminals importing or exporting coals; and
- at the end user site, including power plants, integrated iron and steel works, coke works and cement plants.

The management of stockpiles depends on the purpose of the facility and is site-specific. For instance, managing a large number of stockpiles at a terminal blending different coal types to meet different customer requirements involves a much more complex operation than a stockyard dealing with only one coal type. This report will principally cover stockpiles at terminals and power plants, although some of the comments will apply to other sites employing stockpiles.

The main functions of a stockpile are:
- to serve as a buffer between material delivery and processing, acting as a strategic stock against short- and long-term interruptions; and
- to homogenise and/or blend coals to provide an even feedstock of the required quality.

Coal stocks
The coal stockyard provides a buffer capacity to accommodate fluctuations between supply and demand. Traditionally power plants have kept a large coal inventory in order to protect against long-term disruptions to fuel supply (such as labour strikes and weather-related events). This could amount to over a quarter of their annual burn requirements, that is over 90 days at average daily burn levels (Vaninetti and Myers, 1996). Up to 100–120 days storage was kept at several power plants run by American Electric Power (Chakrabarti, 1995). Coal represents 60–80% of a power plant’s operating cost. Therefore moving towards smaller inventories can reduce coal storage costs, as well as inventory carrying costs, property taxes, coal handling costs and coal degradation costs. In the USA, average utility stockpile levels (measured on an average daily burn basis) have declined to about 50 days since mid-1993 (Vaninetti and Myers, 1996). Lower coal inventories can be maintained at power plants built in the vicinity of one or more mines. These power plants are often supplied daily. This happens at the mine-mouth power plants in Victoria, Australia, because of the susceptibility of the brown coal to spontaneous combustion. A minimum of 7–10 days live buffer storage is kept at the Kendal mine-mouth power plant, South Africa, to ensure an uninterrupted supply to its six 600 MWe boilers. Reserve stockpiles are also used (de Wet, 1994).

In some instances, power plants have moved to a just-in-time delivery system. In the Netherlands, power plants hold stocks for only 5–8 days as insurance against interruptions to coal deliveries (CoalTrans International, 1993). The plants are supplied from the EMO terminal in Rotterdam on a just-in-time basis. Thus it is essential that the terminal has sufficient storage capacity to guarantee an uninterrupted supply to the power plants (or any other end user employing this delivery system). US utilities, such as Rochester Gas and Electric and Commonwealth Edison, are using coal stockpiles at centralised plants for just-in-time distribution to nearby power plants. This approach concentrates coal handling activities at fewer sites, thereby improving coal handling efficiency and equipment utilisation, as well as personnel utilisation (Vaninetti and Myers, 1996).

However, Tennessee Valley Authority (TVA) has had mixed success with this approach. Although just-in-time has reduced its coal inventory costs over the long term, regional coal shortages resulting from the 1993 coal miners strike were exacerbated by TVA’s emergency buying to keep from running out of coal. This caused an increase in coal prices that affected several other utilities supplied from the same pool of mines (Vaninetti and Myers, 1996). Also, with just-in-time delivery, the buying decision is more closely driven by demand rather than the ability to take advantage of lower coal prices on the spot market. Thus the cost of purchasing coal may increase (Katterhenry, 1995).

Determining and keeping an accurate coal inventory at a power plant, of particular importance for just-in-time systems, is addressed in Section 4.4.

Factors that need to be considered before a power plant can reduce its coal inventory (Chakrabarti, 1995, 1999) include the:
- number and reliability of transport modes (rail, barge, truck, run-of-mine conveyor);
- number of sources of supply;
- number of other plants from which coal can be delivered as a backup;
- variability of burn rate; and
- number of days needed to get coal to the plant from a supplier.

In addition, changes in fuel inventory levels cannot be considered in isolation solely from the electric utility perspective. The upstream elements in the fuel supply chain (mining and transportation) may suffer from changes in fuel inventory practices. For example, a typical saving of US$0.25 per ton in inventory carrying costs may result in a US$1 per ton upstream impact resulting from the loss of efficiency and equipment utilisation in both mining and transportation activities (Vaninetti and Myers, 1996).

Additional costs incurred by the coal supplier may be passed on in higher fuel costs, outweighing the savings realised by the utility.

Some US utilities have contracted out the management of their coal stockpiles. This approach is suited to utilities with mine-mouth plants or plants served by a single supplier. For example, BHP manages the stockpiles at the Public Service of New Mexico’s Four Corners power plant; the coal is sold...
on an ‘in-the-bunker’ basis. However, this approach may be limited in the USA to union-free plants (Vaninetti and Myers, 1996).

Homogenisation and blending
With the opportunity for electric utilities to buy coals of different qualities from a wider range of suppliers, and to take advantage of cheaper prices on the spot market, there is a greater need for coal blending capability in stockyards. In the USA in particular, increasingly stringent requirements over maximum sulphur contents has encouraged the blending of high and low sulphur coals to obtain a compliance fuel. Coals can be blended in a stockpile. Layers of coal are built up in the required proportions to give the average chemical composition of the desired blend when the pile is reclaimed (see Chapter 3). At trade orientated transhipment facilities especially, the differing types or grades of coal are more usually stored in separate stockpiles so that they can be blended according to customer specification. The required amounts of coals are reclaimed from the stockpiles and blended on belt conveyors, in bins, bunkers or silos, or occasionally in another stockpile (see Carpenter, 1995). A higher blending accuracy is required for coking coals than for thermal ones due to stricter quality criteria.

The quality of a coal varies both within and between delivery lots. Therefore some degree of homogenisation is usually required. This can be achieved in a stockpile. Stockpiling is also used for mixing coals. The terminology for homogenising, blending and mixing is not clearly defined, with terms being used interchangeably. In homogenisation, the purpose is to provide a product from one type of material so that the inherent fluctuations in respect of quality and/or size distribution are evened out. In blending, the aim is to achieve a final product from two or more coal types that has a well-defined chemical composition, where the elements will be very evenly distributed and no large pockets of one type can be identified. When sampled, the average content and the standard deviation from the average will be the same. In mixing, traces of the individual components can still be located within a small quantity of the mixed material of two or more coal types (Zador, 1991). The next chapter discusses stacking and reclaiming of stockpiles, with the emphasis on homogenisation and blending. Blending and mixing will not generally be distinguished in this report.
3 Stacking and reclaiming stockpiles

A discussion of the design and layout of a stockyard is outside the scope of this report. Nonetheless, the efficient management of coal stockpiles is partly dependent on the stockyard layout and the available equipment. These may limit the potential for changing the management of the stockpiles, such as the degree of automation that could be introduced. Power plants with a small stockyard may not have enough ground space to store different types and/or grades of coal in separate stockpiles. The ability of the power plant to take advantage of cheaper but lower quality coals for blending with the usual feedstock could therefore be limited. There may be enough room to stockpile the coal against one end of a current stockpile; but this may increase the risk of spontaneous combustion (see Chapter 6). The cheaper coal could be stacked with the usual feedstock and blended within a stockpile. Unless there are facilities for later blending with other coals on a belt conveyor or in a bunker, it is important that the stockpile is built so that the required blend composition is achieved. Major blend changes cannot generally be effected until the existing coal pile has been totally reclaimed.

The Lamma power plant, Hong Kong, has a small stockyard. The storage capacity needed to be increased when the reserve stockyard was lost due to the construction of new power units. To achieve a storage capacity of around 500,000 t, 10 high retaining walls were built to the north and south of the yard. The coal is stacked to a height of 25 m in two piles, one each side of the new stacker/reclaimer that has been installed. The compact arrangement does not allow for blending. Operation is on a first in first out basis, and in order to maximise storage space, adjacent piles are allowed to overlap. As many different coal types are used, it can be difficult to tell the operators the type of coal to expect in the next twenty four hours. The operators therefore have to be more vigilant so that operating parameters can be adjusted to suit the coal. In addition, logistic problems for handling trial cargoes occur, since ideally these coals should be kept separate for testing purposes. Since it is impractical to compact the coal, spontaneous combustion is likely to occur, especially in areas adjacent to the retaining walls in which the coal tends to stagnate. Problems areas include poor drainage, flowslides from heavy rainfall (see Section 8.5) and fugitive dust (see Chapter 7). Ways for increasing the storage area are being considered (Fretwell, 1995).

The current method of blending at the Kapar power plant, Malaysia, was restricting the use of cheaper low quality coal. The utility also wanted to widen the range of coals that could be fired in order to achieve further cost savings. A performance analysis of the coal yard handling facilities was carried out using the Coal Handling Simulation (CHAS) software package, developed by PowerGen, UK. The study demonstrated that the use of a flat back reclaimer or simple modifications to the dry coal store would allow accurate blending (Adams and others, 1999). Previously, the blending was achieved by simultaneous reclaim from separate stockpiles with bucket wheel reclaimers (see Section 3.2). McLachlan (1999) discusses the problems and some potential solutions for adapting existing coal export terminals to blend coals.

For the efficient management of stockpiles, the stockyard layout (CoalTrans International, 1995; Thompson and Raymer, 1981) should:

- provide easy access to the stored material;
- maximise the load distance efficiency factor;
- attain the required stacking and reclaiming rates, with the least effort;
- achieve the degree of desired remote control of equipment and automation of plant;
- meet the homogenisation and blending requirements;
- maintain or improve the uniformity, integrity and quality of the stored coal;
- minimise manpower requirement;
- maximise equipment capability and availability;
- provide a safe and dependable system;
- be able to deal with potential stockpile fires;
- meet environmental requirements such as dust emissions, noise levels, and water drainage;
- minimise the overall cost in terms of price per tonne of coal handled, and the operating and capital costs; and
- achieve optimum land usage, with the highest tonnes per hectare consistent with storage and environmental requirements.

When a coal delivery arrives at a power plant the decision has to made on where to stack the coal. The coal may be added to the live stockpile or sent for long-term storage in the reserve stockpile. Reserve stocks are normally held as an insurance against interruptions of deliveries for long periods, but they may also be used to take advantage of market conditions (lower prices). Buffer stockpiles are available at some plants. These short-term stockpiles act as a buffer between the live and reserve stockpiles. Coals of a similar type can generally be stacked in the pile, but different coal types/grades are normally stored separately.

In preparing the ground for a new stockpile, the top soil should be removed and a stabilising layer of crushed rock or similar material laid down. Adequate site drainage must be provided (see Section 8.2), and utility pipes and conduits should not run under the piles. The size, shape and load-bearing capacity of the land determine the pile height and quantity of coal that can be stored.

Although kidney-shaped stockpiles are used, the two shapes more commonly employed are:

- longitudinal beds, when at least two beds are present, one being stacked and the other reclaimed. The beds can be located side-by-side (parallel) or arranged end-on (in-line); and
- circular beds.

These two types of bed employ different stacking and
reclaiming methods and equipment. Thus the stockyard operator is unable to switch easily from one system to the other, once the initial choice and investment has been made.

Circular beds provide a more compact layout than linear beds. They are often used where, for environmental reasons, stockpiles need to be covered (see Section 7.2). It may be worth operating two small circular systems rather than one large one at a power plant. This greatly reduces the chance of a cessation in electricity production due to the reclaimer breaking down. There are also better opportunities for the maintenance of equipment (Gerstel and others, 1998). The Mai-Liao power plant in Taiwan will have four covered circular stockpiles, each with a diameter of 120 m and a capacity of 180,000 t (equivalent to a ship-load) (Walker, 1999b). The enclosed circular system was chosen instead of a longitudinal bed housed in an A-frame building because of the significant space savings (land is expensive in Taiwan) (Fischer, 1999a; Walker, 1999b).

Circular beds eliminate the non-standard end cones that occur when reclaiming linear beds. The end cones do not have equal representation of all layers in the stockpile. Only once during the first stacking procedure is a semi-cone built-up which has to be crossed during the first reclaiming procedure. In order to obtain a good homogenisation/blending efficiency in linear beds, the end cones should be recycled to another stockpile; but this is rarely done in practice. Robinson and Ross (1991) have derived simple formulae that can estimate the grade of portions of chevron stockpiles (see Section 3.1). The model can help in investment decisions, such as whether and how to reclaim the cone ends of the stockpile onto other piles. If the cone ends are not to be reclaimed onto other piles, then the extent of short-term grade variations as the ends are processed can be estimated before they are reclaimed.

However, the storage capacity of a circular stockpile is limited and cannot be increased once built. This may be less of a problem in today’s economic climate since end users may be reluctant to invest in excessive stocks without justification. A longitudinal stockpile holds more coal and, provided that space is available, can be extended cheaply by extending the running track and the conveyors. The layer length for a circular pile is much shorter than a layer in a linear pile. Because of its reduced pile capacity and short layer length, the input lot size for circular piles should be relatively small to ensure that several different lots are layered and blended (Mahr, 1988). The capital, operating and maintenance costs are generally lower than those of a comparable longitudinal bed, although the civil engineering work costs relatively more (de Wet, 1986).

3.1 Stacking

When building a stockpile, layers of coal are built up to give a pile with a triangular cross-section. The layers may all be of the same coal type or several different coal types. In the first case, reclaiming homogenises the coal and, in the latter case, combined blending and homogenisation is achieved. Each coal layer is carefully controlled for uniform volume. By increasing the number of layers the homogenisation/blending efficiency is increased; several hundred layers can be built up in a single stockpile. The coal is reclaimed in a plane perpendicular to the layers (see Section 3.2). Ideally the reclaimed coal is thus a blend of the individual layers, reflecting the average composition of the stockpile. As the reclaimer can only blend the material in the respective stockpile cut, a large pile cross-section is advantageous.

During stacking, particle size segregation should be minimised. Particle segregation can affect spontaneous combustion (see Section 6.1.1) and can contribute to flowslides (see Section 8.4). Thus dropping coals from excessive heights should be avoided, and the fall height minimised. This also helps to lessen dust formation. There is a greater potential for dust formation when stacking a more friable coal. This may require changes in the management of the stockpile. The control of dusts from stockpiles is addressed in Section 7.2. Coals that are more friable produce a higher percentage of fines. When wet, handleability problems, such as pluggage of chutes, may occur (see Section 5.2). Coal pile drainage is covered in Chapter 8.

The main methods for stacking coal are shown in Figure 1. Each of these methods uses different components and arrangements. They represent different amounts of flexibility, varying ability to blend and homogenise material, and a range of investment requirements. They require stackers with different capabilities; some of the different types of stackers employed are illustrated in Figure 2. Figure 3 shows a stacker in use at a power plant stockyard. The ability to switch from one stacking method to another if the function of the stockpile changes, partly depends on the available stacker. The stacker runs on rails which extend along the whole length of the bed. Transfer of the stacker from one row of linear beds to another is achieved either with transfer cars or by a slewing mechanism.

With the cone shell system, coal is continuously stacked along the central axis. It is not very efficient for blending coals (Zador, 1991) and can create a high degree of particle segregation. As with all the stacking methods, the final angle of repose of the pile (that is, the natural angle of settlement) depends on the coal type, particle size distribution and moisture content. The strata method stacks the coal in horizontal layers. If two or more coals are to be blended, they are laid out in alternating layers. Each layer is laid out from one end of the bed to the other, and the whole bed should be completed before reclaiming is started from the end of the pile. The skewed chevron is a variant of the strata method where the layers are inclined. Reclaiming is carried out from the side of the bed, for example with a portal scraper (see Section 3.2).

The chevron, windrow and chevron-windrow systems are all intended to be reclaimed from one end of the bed, and can achieve a high blending efficiency. The chevron is the simplest system since it only requires a stacker with one discharge point, along the central axis of the stockpile. Both the windrow and chevron-windrow stockpiles require more expensive stackers with a slewable boom containing multiple discharge points. However, particle segregation is minimised
with these two methods. The windrow method uses a pattern of triangular and rhomb-shaped rows. Since the stockpile is formed in several small parallel rows, the compaction and material distribution of the coal by bulldozers is easier (Wolpers and Weidenbach, 1993). One application of windrow stockpiles is where the coal being stored has a wide size-range distribution (Walker, 1999b). The individual windrows can be placed sequentially with the coarse material being trapped by the previously stacked coal. This could form the basis for simple blending since fewer windrows are stacked than in the case of chevron layers (which can reach up to 500 a time).

The chevron system is a combination of the cone shell and chevron methods. It utilises a circular rather than a linear bed. The coal is layered on the inclined leading section of the pile, while at the same time, blended coal is reclaimed from the other end. It requires a slewing stacker that is mounted on a central column. The reclaimer is a ‘one-sided’ machine since it does not have to reclaim in the reverse direction like a linear bed reclaimer. Machines (fitted with two harrows) capable of moving in both directions are also available.

3.2 Reclaiming

Ideally, the linear stockpile should be completed to a fixed profile and capacity prior to reclamation so that the necessary conditions for homogenisation/blending are achieved. The reclaimed material should reflect the average composition of the stockpile. Successful reclaiming is paramount to achieving optimum performance from a stockpile system. It is also important that system components are matched up with one another to ensure smooth transport coal flows, both to and from the stockpiles.

Reclaiming of stockpiles is carried out using a variety of reclaimers, some of which are illustrated in Figure 4. All these reclaimers are mounted on rails. Most of them employ a harrow or rake device to loosen the coal, causing it to fall down into the path of the reclaimer. The reclaimed coal is generally collected on a belt conveyor and transported to where it is required. The bucket-wheel, bridge-type and portal scraper (Fischer, 1999b) are the most important reclaimers in use today, making up about 90% of the coal applications.
The homogenisation/blending efficiency of the different types of reclaimers varies. Bucket-wheel reclaimers and gantry-type reclaimers both use a bucket wheel to reclaim the coal from the end of the stockpile. The bucket-wheel reclaimer operates from the side of the bed, and is often combined with a stacker (bucket-wheel stacker/reclaimer). It is only suitable for operation in the open because of the space required for the counterweight. But it does have the benefit of being highly selective if needed; for instance, in removing hot coal from the stockpile (see Section 6.5). Bucket-wheel stacker/reclaimers are generally used in stockyards handling large amounts of coal with a high throughput; they can handle capacities of over 4000 m³/h (CoalTrans International, 1998b). The homogenisation and blending efficiency of bucket-wheel stacker/reclaimers is not as good as reclaimers which reclaim across the entire cross-section of the pile. The gantry-type reclaimer may be equipped with multiple bucket wheels, thereby improving homogenisation/blending efficiency. In the drum-type reclaimer, the buckets are attached to a long rotating drum that reclaims the coal across the entire width of the pile. This helps to improve homogenisation/blending efficiency.

Bridge-type scraper reclaimers use a scraper chain to reclaim across the end (front-face) of the longitudinal pile (see Figure 5). Although their blending/homogenisation efficiency is very good, they cannot ‘jump’ over stockpiles – a disadvantage when compared with side-face reclaimers. Portal, semi-portal and cantilever scraper reclaimers all reclaim from the side of the bed. For blending purposes, the longitudinal stockpile can be stacked using the skewed chevron method. Side-face reclaimers can be used to remove
coal that shows signs of imminent spontaneous combustion.

Portal scraper reclaimers with capacities up to 4000 m$^3$/h are available (CoalTrans International, 1998b). Fischer (1997, 1999a) reviews the use of scraper reclaimers at a number of different sites. The advantages of the side- and front-face scraper reclaimers have been combined in the portal bridge scraper reclaimer, illustrated in Figure 6 (Fischer, 1993).

A modified version of scraper reclaimers is used for reclaiming circular beds: a bridge-type scraper for reclaiming from the pile end (see Figure 7) and a cantilever scraper for reclaiming from the side of the pile. Both are mounted on a portal while the bridge-type scraper is mounted on a gantry.
The former type can be used for homogenisation/blending. Fischer (1999a) compares the advantages and disadvantages of these two circular storage systems.

Reclaimers that can move over several in-line longitudinal beds, such as bucket-wheel stacker/reclaimers and the travelling (portal) bridge and portal scraper reclaimers, are able to reclaim from as many different stockpiles as required in any sequence. This is an advantage when blending different coal types stored in separate beds. Predetermined amounts of coal can be withdrawn from the required piles and blended to meet a customer’s specification. This could be especially useful at transhipment facilities blending imported coals to different specifications.

Front-end loaders and bulldozers are also widely used for stacking and reclaiming coals. Since they shift a smaller volume of coal than the stacking/reclaiming equipment described above, they are generally used for smaller stockpiles. They are also used for compacting the coal to prevent spontaneous combustion, and to move coal from reserve storage piles to the live ones.

Some stockpiles utilise gravity reclaim through hoppers located in a tunnel below the stockpile, with feeders to control the discharge rate onto the reclaim conveyors. The pile is not reclaimed uniformly as only a conical funnel on top of each feeder is reclaimed (see Figure 8). Around 25% of a conical pile cannot be gravity reclaimed (Chakraborti, 1995, 1999). Using a vibratory stockpile reclaimer will allow a larger area of the stockpile to be reclaimed (Bagust, 1998). Mobile equipment is required to move the coal from the inactive portion of the pile to the reclamation points. For safety reasons, mobile equipment and personnel should never be on top of the piles when the underground feeders are active. The use of multiple hopper systems which allow intersection of the flow channels improves reclamation performance. The optimal distance between the hoppers is dependent on the moisture content of the coal (Roberts and McBride, 1994). Thus changing coal supplies or allowing the stockpile to become wet will affect the reclamation performance. Blending efficiency within the stockpile is also poor. Several different coal types can be stacked out in separate piles. One or more feeders can then reclaim from the required piles onto a moving belt conveyor, where the coals are blended. For obvious reasons, underground reclamation systems are not recommended in areas prone to flooding by stormwater.

More information on the blending efficiency of the various stacking and reclaiming methods and equipment can be found in an earlier IEA Coal Research report by Carpenter (1995). Wöhlbier (1986, 1994) contains papers on stacking and reclaiming equipment, with examples of their use at coking plants, coal mines and other sites. Coking plants, in particular, are big users of blending stockpiles.

### 3.3 Stockyard management and automation

Stockyards operating a large number of stockpiles can be complex operations. This complexity has led to integrated information management and control systems being implemented. These systems can provide a real-time inventory for keeping track of the coal quality and quantity (tonnage) in the stockpiles. Computer programs are available for blending coals from different stockpiles; these can determine the cheapest blend that will meet the required specification. Inability to meet the coal specification can result in severe financial penalties or even rejection of the consignment by the customer, depending on the severity of the quality non-compliance. For a power plant, too high a level of ash or moisture could lead to a boiler derate. This would be unacceptable for a base load plant. Statistical process control techniques can be used to help control the blend quality. These can be incorporated into a Total Quality Management system for stockyards. Computer control systems are also leading to fully automatic operation of some of the stackers and reclaimers.

One example of a quality management and stockpile tracking system is QMASTOR®. This system is used to manage stockpiles at BHP Coal’s Port Kembla Number 4 area in New South Wales, Australia (Cameron, 1997). Three coal washeries (see Figure 9) feed the stockpile area, which contains four ‘pad’ areas, each consisting of numerous smaller stockpiles. Up to 20 coal types are stored. The residence time in the stockpile area is variable depending on...
shipping time and coal type; it can be up to 12 months, with numerous incremental additions and removals during this period. Stacking and reclaiming is performed on an ‘as needed’ basis, with client cargoes normally consisting of a complex blend from numerous stockpiles. A materials management system was therefore required to:

- optimise stockpile usage;
- reduce operating costs; and
- provide a real-time quality data management and planning facility.

The coal is moved primarily by a mobile fleet. A differential global positioning system (GPS) was developed to track the mobile equipment accurately and hence the movement and location of the coal parcels. A radio telemetry system transmits vehicle positions (coal parcel locations) to a central computer. A ‘live’ stockpile quality and tonnage model was created by multi-tasking various proprietary and customised software programs; this enables coal position data, delivery tonnage and quality information to be collated. A reclamation system can be generated to meet the shipping schedule quality requirements. An economic optimisation program finds the optimum blend of reclaimed coals from all available stockpile zones to match up to 13 quality parameters specified by the steel works; this has helped to maximise profits. The correlation between shipment and QMASTOR© predicted shipment analysis has been well within the analysis tolerance. The need for downstream sampling and analysis has been reduced by some 65%, and is likely to be eliminated in the future. The continual GPS record of the stockpile surface has virtually eliminated the need for the volumetric surveys discussed in Section 4.4 (Cameron and others, 1998; Keleher and others, 1998).

The operation of the Richards Bay coal terminal in South Africa, as with any other major storage and handling facility, is complex. There are no fewer than 90 individual piles representing different companies’ production of 34 different coal grades (Walker, 1999b). Day-to-day constraints include the need to offload trains to the correct stockpile, to select and use the best conveyor routes, and to keep the coal grades apart. Breakdown and planned maintenance of equipment have to be taken into account. To complicate matters, coal demand is seasonal, with peaks in loading corresponding to weather patterns in consumers’ countries, as well as to general cycles in the world economy. A computerised control system based on Yokogawa Marex’s PROMACE system is utilised to help ensure that each company’s coal is stored, handled and loaded correctly. The stacker/reclaimers, tipplers and belt conveyors are all automatically controlled by programmable logic controllers.

There are a number of computer programs available for blending coals from different stockpiles. Some of these programs, and other programs for determining the blending efficiency within a stockpile, have been briefly reviewed by Carpenter (1995). One example is the goal programming (GP) model incorporated into the coal blending management system at the Hsinta power plant, Taiwan (Lyu and others, 1995). At this power plant different coal types are imported from 15 suppliers from various countries. The delivered coal can be classified into 4 to 6 grades, based on prior
experience, before being stockpiled. The GP model determines the optimal quantities of coal to be taken from the different stockpiles to produce a consistent blend for each boiler whilst meeting environmental and performance requirements. A flowchart of the coal blending management system (which also includes coal inventory information) is given in Figure 10. The procedure is executed whenever a new coal shipment arrives. By integrating this system into others, such as imported coal distribution and shipping management systems, a more efficient overall management system will be achieved.

Automation of stockyard systems can save costs by minimising manpower requirements and maximising equipment capability and availability. Computer control systems can allow fully automatic operation of the stackers and reclaimers. Slewing bucket-wheel stacker/reclaimers can be difficult to automate because of their complicated operating geometry (International Bulk Journal, 1995). However, fully automatic systems are now available, as are completely automatic travelling bridge stackers (International Bulk Journal, 1997). Portal and semi-portal scraper reclaimers are more easily automated because of their relatively simple motions; many are operating automatically worldwide (International Bulk Journal, 1995). The Belledune power plant, New Brunswick, Canada, utilises fully automatic routines for stacking and reclaiming at its circular coal stockpile (Shehata and Wilton-Clark, 1993).

3.4 Environmental aspects

Coal stockyard operators are under constant social and political pressure to reduce or remove environmental problems inherent in their operation. These include dust emissions, water contamination and noise pollution. This section concentrates on noise pollution since it is mainly caused by the stacking and reclaiming equipment. The problem of animals burrowing into the stockpiles is also discussed. Dust emissions, stockpile runoff, and flowslides caused by pile instability are addressed in Chapters 7 and 8.

Stockpiles situated near residential areas can be faced with noise control problems. Noise from mobile equipment can be one of the most difficult environmental problems to solve. In general, the use of electrically powered equipment within the stockyard should be encouraged to reduce noise pollution. Diesel equipment can be fitted with special muffling devices, and enclosing conveyor belts reduces both noise and dust emission levels (Zonailo, 1998). In addition, berms (see Section 7.2) with trees and vegetation surrounding the stockyard can have both aesthetic and noise abatement benefits. In this case, incorporating a viewing point will enable people to see what is going on. Trees, though, can take a long time to grow.

Rabbits burrowing into the stockpiles at the Dürrnrohr power

Figure 10 Flowchart of the coal management system (Lyu and others, 1995)

Figure 11 A rabbit sheltering in a stockpile (photograph courtesy of EVN)
plant, Austria, have caused minor problems. When it is windy, snowy and cold, the rabbits dig sheltering holes (see Figure 11). Fortunately, they do not excavate long gangways and so no pile instability or additional ventilation leading to spontaneous combustion (see Chapter 6) has resulted (Aumüller, 1999). Moreover, they run away when the bulldozers approach the piles.
Coal arriving at a terminal or power plant is commonly sampled and analysed before it is stockpiled. One reason for sampling is to determine whether the consignment meets the contract specification agreed between the buyer and seller. In many contracts there are penalty and/or bonus clauses related to the specified coal properties. Very costly disputes can arise when the analysis of samples taken by the buyers and sellers disagree. The crucial question in these disputes is often whether the sample taken was truly representative of the consignment. With shipments becoming larger, more expensive and more varied in their specification, good sampling practice is therefore critical.

Knowing the quality of the coal consignment also enables the operator to stockpile the coal in appropriate piles. Coals of similar grade can be stockpiled together or different grades could be blended within a stockpile (see Chapter 3). The average composition of the pile can be determined from the composition of the component coals. Decisions can then be made on whether the reclaimed coal will meet the required specification or whether some additional blending of coals is necessary. Sampling of a stockpile in situ is also carried out in some cases. However, the properties of coal can change while it is in the pile (see Chapter 5). Therefore sampling and analysis is often carried out during reclamation. This is especially advisable when the stockpile has been left for a number of years. By knowing the properties of the coal before it is fired, operators of the power plant can adjust the boiler operating conditions accordingly. At terminals, the sampling may be carried out during loading operations to confirm that the consignment meets the contract specification. In all these cases obtaining a good and representative sample for subsequent analysis is of paramount importance. If the sample is improperly taken then it may be impossible or impractical to take another sample. However, if the analysis is in error, another analysis can easily be made of the original sample (except for moisture).

### 4.1 Representative samples

It is essential that the sampling procedures are accurate and precise to ensure that a representative sample is provided for the subsequent analysis. If the initial sample is not properly taken then the analysis will be meaningless. A spurious sample could lead to rejection of coal that is in fact suitable or to substandard coal being accepted, leading to problems later. Experience has indicated that about 70–80% of the accuracy of the analysis result comes from sampling, about 15–20% from sample preparation, and about 5–10% from the laboratory (CoalTrans International, 1998a; Laurila, 1997a); this demonstrates the importance of good sampling practice. When sampling to determine whether the consignment meets the contract specification, it is important to take samples and divide into three – one for the supplier, one for the buyer and one as a reference for independent analysis in case of dispute.

### Table 1 Analysis of different size particles in a single coal consignment (Reagan, 1999)

<table>
<thead>
<tr>
<th>Size, mm</th>
<th>% in consignment</th>
<th>Ash, % db</th>
<th>Heating value, MJ/kg db</th>
</tr>
</thead>
<tbody>
<tr>
<td>+50</td>
<td>6</td>
<td>12.1</td>
<td>30.67</td>
</tr>
<tr>
<td>50 x 25</td>
<td>24</td>
<td>12.6</td>
<td>30.49</td>
</tr>
<tr>
<td>25 x 12.5</td>
<td>20</td>
<td>13.3</td>
<td>30.25</td>
</tr>
<tr>
<td>12.5 x 6.3</td>
<td>22</td>
<td>14.8</td>
<td>29.73</td>
</tr>
<tr>
<td>6.3 x 0</td>
<td>28</td>
<td>16.5</td>
<td>29.27</td>
</tr>
<tr>
<td>100</td>
<td>14.3</td>
<td>29.91</td>
<td></td>
</tr>
</tbody>
</table>

Obtaining a representative sample implies that every particle has an equal chance of being selected. Thus the size distribution of the sample should also reflect the size distribution of the bulk coal since the composition of small particles may be different to that of large particles. This is demonstrated in Table 1, which shows how the ash content and heating value varies with particle size in a steam coal consignment from a single source mine. Coal is one of the most difficult materials to sample because of its variability and tendency to segregate by size or mass. Sampling is further complicated by the use of the analytical results, the sampling equipment available, the quantity to be represented by the sample (sample mass), and the degree of precision required (ASTM D2234). In addition, the coal may be a blend of different coal types. How the coal was blended has a profound effect on the way a representative sample is obtained; for instance whether it is intimately mixed or not (CoalTrans International, 1997).

Biased results can be introduced by the sampling procedure (and by sample preparation and analysis). The main sources of bias during sampling (BS 1017: Part 1) can be avoided by:

- choosing the most suitable location for the sampling point;
- only using sampling equipment that meets the necessary specifications; and
- taking any necessary special precautions if sampling for a specific purpose. For example, avoiding a loss or gain in moisture when sampling for total moisture, and minimising breakage when sampling for size analysis.

Various standards specify the procedures for collecting representative samples under different conditions of sampling. Standards from selected countries on sampling and sample preparation are listed in Table 2. This table only includes standards on sampling coal from moving streams, such as when the coal is being transferred to or from a stockpile, and sampling within a stockpile. A new ISO standard (ISO/DIS 13909), to replace ISO 9411 and part of ISO 1988, is currently under discussion. It is orientated towards mechanical sampling from moving streams; a separate standard for manual sampling, revising parts of ISO 1988, is planned. In addition, the British Standards Institution...
is discussing the adoption of ISO/DIS 13909 to replace the current British standard (BS 1017: Part 1).

When establishing a sampling scheme, it is important to recognise that the variability of lower rank coals, as shown by one property, does not necessarily reflect the variation of all other properties, as is often the case with higher rank coals (AS 4264.3). Therefore, sampling schemes designed for one property could indicate uniformity, whereas in the case of other properties a variable distribution is observed.

Generally, the standards specify the number and weight of increments to be taken for each sampling unit to achieve a given precision. An increment is a small portion of the coal lot collected in a single operation of the sampling device. The increments are taken throughout the entire lot so as to reflect the coal variability. They are combined to form what is termed the gross sample, which is then crushed and divided, following standard procedures, to produce the samples for analysis (see Figure 12). Once the increments have been collected, they should be protected from contamination and changes in composition.

The main factors that determine the number and weight of increments are:
- the coal quality variation;
- the degree of precision required;
- the size of the coal lot being sampled; and
- the particle size distribution.

There is an inverse relationship between sample mass and precision. Generally, the higher the number of increments taken, the better the precision. Too few increments reduce precision since some of the quality variability may be missed. Increment sizes that are too small can introduce bias since there is a tendency to exclude the larger particles.

ASTM D2234, for example, recommends a minimum of 15 increments for each 1000 tons (908 t) of mechanically cleaned coal for a 95% confidence interval. The minimum weight of the increments depends on the top size of the coal; the coarser the coal, the higher the minimum weight (1 kg for a top size of 16 mm to 7 kg for a top size of 150 mm in ASTM D2234). A greater number of increments are required when sampling coal blends since the variability is larger than for single grades of coal.
The individual increments over the coal lot can be evenly spaced in time or in position (systematic sampling) or randomly spaced (random sampling). For systematic sampling to be truly representative, it is necessary that the chosen sampling intervals do not coincide with known or visible periodic variation in either the quality (such as size distribution or moisture) or quantity (that is, the flow rate). Otherwise a consistent bias occurs. Where cyclical variations are suspected, then random sampling should be carried out. The various standards differ in their details and, in some cases, their perspective. Laurila (1997a) briefly shows how the proposed ISO/DIS 13909 standard differs from the ASTM standards, in regard to the minimum increment mass for size analysis. This is illustrated in Figure 13, which shows the differences in the range and number of data points for the two standards. The ASTM denies meaningful precision in measurement of the particle size distribution by reason of impracticality, providing a different perspective.

Coal sampling is a complex and difficult operation. Following the standard procedures should minimise any sampling bias and produce a representative sample. Nonetheless, the question still remains of whether the milligram or gram samples used in the standard analysis procedures or in many bench-scale tests can provide a truly representative sample of the hundreds of tonnes of coal in a stockpile or coal shipment. The next section will examine manual and mechanical sampling systems and their ability to produce representative samples.

4.2 Sampling systems

Sampling a stockpile in situ presents difficulties in obtaining a representative sample. Coal taken from the top or sides of the pile will almost always be different in quality from the rest of the pile due to size segregation and weathering/oxidation. Furthermore, stored coal gradually loses moisture by drainage and so moisture samples taken from the outer layers tend to give low values. The stockpile may have had additions from more than one source of coal at different times so they may contain regions of coal which differ markedly. One of the basic rules of sampling is that every point of the coal lot should be easily accessible; but sampling from the middle of the pile can be difficult. For these reasons it is often preferable to sample from a moving stream during stacking and/or reclaiming. However, there are cases when sampling of stockpiles in situ is necessary. In these cases the stockpile is sampled by coring, using a sampling drill or auger sampler.
The sampling drill should penetrate the full depth of the pile at each point sampled, extracting the whole column of coal. However, this is rarely possible and, because of the design of the sampling drill or auger, all of the fine material at the bottom of the pile may not be collected (ASTM D4916), producing a biased sample. Use of an auger can cause particle breakage and therefore affect size distribution and bulk density of the coal sample. Thus augers are not recommended when collecting samples for size analysis and bulk density determination (AS 4264.3, BS 1017: Part 1). Where it is proposed to reclaim the stockpile by removing coal in layers, it may be advisable to combine the core samples together, according to depth, in order to assess the quality of the horizontal layers. The choice of location of the sampling point is important. Various standards, such as AS 4264.3, ASTM D4916, BS 1017: Part 1 and ISO 1988 (which is currently being revised), specify the method and number of increments to be collected (see Table 2, page 18). The two latter standards also specify the methods for sampling at the working face of the stockpile during its reclamation using a scoop or during reclamation in horizontal layers across the entire pile using a scoop or auger. In addition, increments from the machine bucket can be collected.

There are standard scoops that allow every coal particle size an equal opportunity to be sampled. Spades are inappropriate since these have no sides, allowing the larger pieces to fall off, leaving a sample that is mainly fines (CoalTrans International, 1997).

Coal can be sampled while it is being transported on belt conveyors to or from the stockpile. Unfortunately, with each movement of coal there is a risk of mechanical loss, contamination and a change in moisture content due to evaporation or precipitation (Mazzone, 1998). The most accurate sampling method is the stopped belt or reference method. This involves stopping the belt so that a full cross-section of the flow can be removed. The sample collected will include a complete representation of the coal size content. In cases where repeated stopping of the belt to obtain the required number of increments is impractical or unecononic, the sample may be manually taken from the moving belt or from a falling column of coal at a transfer point.

Experience has shown that at tonnage rates in excess of a few hundred tonnes per hour, collecting all size fractions on the belt is problematic using manual techniques (CoalTrans International, 1997). In fact, some standards (such as BS 1017: Part 1 and ISO 1988) state that manually sampling from a stream of coal should not be undertaken where the nominal coal top size is greater than 63 mm or where the coal flow rate is more than 100 t/h. Mechanical systems should be used, and these are generally the preferred method when sampling from moving streams. Furthermore, manual sampling is inappropriate from a moving belt with a speed higher than 1.5 m/s, if the depth of coal on the belt is greater than 20 cm or from a belt containing layers of unixed coal. There may be a safety issue as well. Certainly, to avoid disruption at terminals transferring coal on high speed belts, mechanical samplers are probably the only option for the routine collection of sample increments.

The mechanical sampling system at the Qinhuangdao terminal, China, can handle a belt capacity of 6700 t/h and belt speeds of up to 4.83 m/s. Up to 84 increments are taken per hour to meet ISO 9411-1 requirements (Beenken and others, 1997).

An advantage with mechanical sampling systems is that statistics of precision and bias can be applied. It is difficult to develop precision and bias statements for manual sampling systems, with the exception of the stopped belt reference method (CoalTrans International, 1998a). However mechanical sampling systems cannot be applied to all situations, such as sampling within a stockpile. They are expensive and will not be cost-effective for facilities handling small tonnages. Moreover, there are many sites where coal is never transferred by a belt conveyor. This makes it difficult to install a mechanical sampling system, except possibly an auger sampler which is not applicable in all situations (CoalTrans International, 1998a, 1999). Since there is a risk of breakage of coal when using mechanical samplers, some standards, such as BS 1017: Part 1, recommend that samples for size analysis should preferably be taken by the stopped belt method. For these cases, manual sampling is the only option.

Mechanical sampling systems that are capable of collecting unbiased samples from moving coal streams can be categorised into two types:

1. cross-belt samplers (sweep arm or hammer samplers) that sweep a cross-section of coal from the moving conveyor belt into a hopper. They must be properly adjusted to avoid leaving any coal fines on the belt that could compromise sample accuracy. An example of a sweep arm sampler is illustrated in Figure 14.
2. cross-stream (or falling-stream or cross-cut) cutter samplers which collect a cross-section from a freely falling stream of coal. Thus the installation of these samplers requires a gap at a transfer point, typically between two conveyor belts. Figure 15 shows a cutter-chute type cross-stream sampler.

The design and operation of mechanical samplers are covered in various standards (see Table 2, page 18). In general, the design should minimise disturbances of the coal to avoid separation of the various coal densities and/or sizes. The samplers require sufficient capacity to collect the sample increment without any loss or spillage, and should be as self-cleaning as possible. The material needs to flow freely through all the stages of the sampling system, without clogging or losing material. Sampling coal when it is sticky is a problem since it can stick to or clog the samplers, biasing the results. The standards cover the size of the cutter opening (typically three times the coal top size), that the cutter should move at a uniform speed and, for cross-stream samplers, the speed of the cutter. The size and number of increments to be collected to minimise bias are also specified. A full cross-section of the stream should be taken whenever possible since it provides a more representative sample than a partial cross-section. Recent technological advances in mechanical sampling systems, and a comparison of cross-belt and cross-stream systems is given in Reagan (1999).
Bias testing

All sampling systems need to be checked for bias, that is for systematic errors that may have been introduced. Generally, a loss or gain in the mass of the increments during collection causes a systematic error. This can include spillage of coarse or fine particles, or failure to collect the fine particles at the bottom of the stockpile. A consistent bias occurs if the time intervals during systematic sampling coincide with cyclical variations in the coal quality.

Tests for bias can be tedious and expensive. A good bias test programme design should not only determine the overall bias of the system but that of the components as well, so that their contribution, if any, to the overall bias is known. Some systems are inherently biased and the test simply determines the extent of that bias (Laurila and Corriiveau, 1995). The actual bias test procedure depends on the local conditions, and the sampling system in use. Therefore standards, such as AS 4264.3 and BS 1017: Part 1, only give general principles for bias testing. Bias testing of mechanical samplers is covered in the new ISO/DIS 13909: Part 8 standard, which requires an annual bias test for mechanical sampling systems.

The ASTM is currently discussing bias testing of mechanical sampling systems.

The first phase of any bias test is the preparation for conducting the test and a careful inspection of the sampling system and equipment to see if any systematic errors have been introduced. ASTM D4702 provides a number of guidelines for inspecting cross-cut, sweep arm and auger mechanical sampling systems. The coal is then sampled twice, once by an intrinsically unbiased reference method (the stopped belt reference method is preferred), and once by the system under test. The corresponding increments are usually collected from the coal in close proximity. The series of differences between the analytical results on the corresponding members of the pairs are then statistically analysed. The standards also include statistical techniques for checking the precision of the sampling system. Bias testing is a complex issue. More details on this subject can be found in Gould (1996), Laurila (1997b), Laurila and Corriiveau (1995), Lyman (1993), Merks (1991) and Rose (1990).

4.3 On-line analysis

The previous section has shown that obtaining samples that are representative of the many thousand tonnes of coal in a stockpile or consignment can be an onerous task. By its very nature, laboratory analysis carried out on the samples according to standard procedures can be time consuming, with results only available some time after the coal has been sampled. This could be a matter of hours if the coal is analysed on-site or a few days if the sample is analysed at a distant location. Thus the analysis results do not necessarily reflect current operating conditions. Real-time information on coal quality could help to manage stockpiles more efficiently. This can be provided by on-line analysers which give almost instantaneous results on certain coal quality parameters, such as ash and moisture contents. On-line analysers are the only system which can show variations in coal quality as they are occurring. In systems where coal can be analysed directly on the conveyor belt, errors due to sampling and sample preparation are minimised. However, on-line analysers are expensive and their cost-effectiveness depends on the site and application. On-line analysers can cost from about £30,000 to £150,000 for a single parameter unit, with prices rising to as much as £400,000 for a PGNAA unit (described below). Installation costs can substantially increase these figures (Page, 1998).

Few on-line analysers, if any, are used at coking plants where stricter quality controls apply than to thermal coals. Most coking coals are washed and the mechanical and physical properties used in their assessment (see Section 5.5) cannot be determined by on-line analysis. Thermal coals are generally not washed completely. On-line analysers can determine their ash content, which is related to their heating value (see below).

Questions about the accuracy of on-line analysers have been raised. Certainly their performance in practice has been found to relate strongly to initial installation, calibration, subsequent maintenance and application environment
(Kirchner, 1991). Of these, the initial calibration was of prime importance. The analyser unit must be adapted to its particular installation by being carefully calibrated, using known samples that have been analysed in the laboratory (reference samples). The chosen samples must represent the range of coal which the machine might be expected to encounter in service. Analysis of coals beyond the range of the initial calibration will not have the same accuracy. Changes in coal supply can thus necessitate re-calibration. The calibration may also drift over time, requiring the analyser to be frequently re-calibrated.

Standard methods for the evaluation of the performance of on-line analysers, including statistical assessment procedures, are currently being discussed by ISO (ISO CD 15239, entitled Solid mineral fuels – evaluation of the measurement performance of on-line analysers) and ASTM (Laurila, 1997a; Page, 1998). An Australian standard (AS 1038.24 Coal and coke – analysis and testing. Part 24: guide to the evaluation of measurements made by on-line coal analysers) has recently been published. These standards outline the principles of the reference test method; because of the range of configurations for on-line analysers and their relationship to sampling/analysis systems, it is impossible to provide particular test methods to cover all situations. More details on the evaluation and performance testing of on-line analysers are given in Laurila and Corriveau (1995). They include statistical methods for evaluating precision and bias, and sampling procedures designed to obtain samples that can be used for calibration, accuracy and verification. Renner (1999) describes the planning and evaluation necessary prior to the installation of on-line analysers. He also emphasises the importance of calibration and quality assurance, particularly the impact from mechanical sampling systems. Despite frequent disappointments, on-line analysers are gradually approaching the levels of precision and reliability needed for confident usage (Osborne, 1998).

On-line analysers have been employed:

- to monitor the incoming coal at a site to determine whether it meets the required specification. At the Hendrina power plant, South Africa, on-line analysis of the coal delivered by conveyor from the Optimum surface mine will be used for payment purposes. In addition, the analysis data will provide feedforward control of the boiler plant for combustion purposes (Walker, 1997);

- to sort and segregate coal into different stockpiles, according to its quality. How far this is practical for coals arriving from a number of different sources is limited by the calibration range of the analyser. An on-line analyser (Coalscan 2500) has been installed at the Rotowaro coal handling facility, New Zealand, to sort the run-of-mine subbituminous coal onto the stockpiles after it has been crushed (Emond, 1997);

- to blend coals from different stockpiles to meet the required specification. By maximising the amount of lower cost coal in a blend, savings can be made. It is also possible to blend coals automatically, for example by allowing the on-line analyser to control the feeders beneath the stockpiles involved. A Coalscan 9500 monitors the quality of the blended coal at the Rotowaro coal handling facility. It can automatically determine the ratio of coal from each feeder beneath the stockpiles to deliver the required specification. Up to three different types of coal can be blended (Emond, 1997); and

- for monitoring coal during reclamation to check it meets the desired specification.

This section outlines four of the main on-line measuring techniques in use today. More details on these and other on-line analysis techniques and their applications can be found in Couch (1996), IEA Coal Research (1993), Jenkinson (1998), Kirchner (1991), Kirchner and Maude (1994) and Page (1998). Recent developments in X-ray fluorescence technology leading to the testing of an on-line analyser at the Monroe power plant, MI, USA, is discussed in Fiscor (1999) and Laurila and Bachmann (1999).

**Natural gamma systems** require no radioactive source. They measure the gamma emission from the conveyed coal and calculate the ash content by combining this with a measurement of the weight of the load. Although it may not be the most accurate system, it is the least expensive (Kirchner, 1991).

In **dual energy gamma-ray transmission systems**, the bulk coal ash content is determined by combining measurements of the intensity of two narrow beams of high and low gamma-rays that are passed vertically through the conveyor belt (see Figure 16). These analysers only work properly if the coal on the belt is well mixed since the small beam only determines a small area in the middle of the belt (Krumrey, 1993).

![Figure 16 Dual energy gamma-ray transmission system](image-url)
Instruments are available that split the beam into a number of corresponding detectors that determine the ash content at separate points across the full belt width; these may provide a better measure of the ash content. Varying chemical composition, especially the iron content, can lead to inaccuracies. Therefore better accuracies are achieved for low ash coals. For instance, an accuracy of ±0.5% for low ash coals and ±1% for high ash coals is claimed for the Coalscan 2500 model (Walker, 1997). The RAMM system can analyse coal on conveyor belts with tonnages up to 6000 t/h and belt speeds of more than 5 m/s (Bulk Solids Handling, 1997). Triple energy gamma-ray transmission systems have been developed to improve the accuracy (Fauth and others, 1997).

**Prompt gamma neutron activation analysis (PGNAA)** provides an elemental analysis of coal by measuring the gamma radiation emitted when coal is exposed to a neutron source. Carbon, hydrogen, sulphur, nitrogen and chlorine are measured directly and the ash content is indirectly determined by combining the elements that comprise the ash (mainly silicon, iron, calcium, aluminium, potassium and titanium). A separate ash analyser is included in some PGNAA systems (Page, 1998). The heating value (if a moisture meter is present), ash fusion (slagging factors) and oxygen content can also be indirectly determined. Some systems require a small slipstream of coal to be diverted from the main coal flow to the analyser. Conventional PGNAA can give problems for brown coals and lignites with a high moisture content, or coals with large and variable ash constituents. Instruments using multiple sodium iodide detectors have been developed to cope with coals from multiple sources. Instruments have also been specifically designed for high moisture brown coals (Howarth and Gault, 1993). According to Kirchner (1991) PGNAA offers the best accuracy; but it is significantly more expensive than dual energy gamma-ray transmission and natural gamma systems. Gamma Metrics’ 1812C on-line analyser, for example, has a capacity of 400 t/h of -100 mm coal, and an analysis time of one minute, operating to an accuracy of 0.04% sulphur, 0.4% ash, 0.2% moisture and 175 kJ/kg heating value (Walker, 1997).

**Microwave moisture meters** determine the moisture content by measuring the attenuation and phase shift of microwaves passed through the coal. Microwave moisture measurements are often incorporated in dual energy gamma-ray transmission and PGNAA systems, enabling the heating value of the coal to be calculated.

Both ash and moisture analysers need to know the amount of coal at any point in time to enable an assessment of the required measurement. Weighing becomes particularly important when blending coals. The weighing system must be accurate and repeatable. Belt scales are discussed in Section 4.4.

There are situations, such as small operating units, where the use of on-line ash analysers is not convenient or cost-effective. In these cases a **portable subsurface gauge** is available for determining the ash content of coal within a stockpile. These gauges are based on the natural gamma-ray technique. Consequently, they require no artificial radiation sources and are relatively inexpensive. An example of a natural gamma ash gauge is illustrated in Figure 17. It can measure the ash content of low ash coal (<20% ash) with an accuracy of 0.6% (Mathew and Aylmer, 1993). The counting time was 100 s, which can be reduced to 50 s or less without significantly affecting the accuracy of ash prediction. The gauge requires calibration for each coal type, since coals of different origin require different calibration equations. However the accuracy of ash determination by this method is relatively unaffected by variations in ash composition or normal variations in moisture content. It should be noted that a large number of measurements have to be taken over the whole of the coal stockpile while it is being built up in order to determine its average ash content.

### 4.4 Stock audits

Periodically coal stock audits are carried out to reconcile the amount of coal in the stockpiles to the book inventory. The coal stockpile tonnage is determined by measuring the volume and density of the stockpiled coal. This value is then used as the reference against which to compare the book inventory. Book inventories are maintained from recorded weights of coal going into and coming out of the stockpile. When the book inventory deviates considerably from the measured inventory, the book inventory is adjusted. Sometimes the adjustment is an addition to inventory, but more often the book inventory is less than that measured by the density and volume, and is written off (Rose, 1992; Voorhis, 1988).

Both the book and measured inventories are subject to measurement errors. These errors can represent a considerable amount of money. In a 500,000 t stockpile, for example, a 10% error of 50,000 t at US$30 per tonne
Volume determination

Both ground surveys and aerial surveys are used to determine the volume of a stockpile. The pile surfaces should be reasonably smooth (no washouts or gullies), the measuring points taken at frequent intervals, and an accurate record of the stockpile base configuration in the form of a contour plan or grid should be available (Craven, 1990). The accuracy of the volume (and bulk density) determination is partly dependent on the number of observed values and how representative the combined values are of the entity being measured. Because stockpiles come in all shapes and sizes, and the only method of determining volume is by measurement, it is impossible to arrive at an exact degree of tolerance in volume measured as there is no way of determining the exact volume for the purpose of comparison.

Photogrammetry is probably the more dominant method. Experience with large stockpiles of 50,000 to 500,000 t has indicated that an accuracy of about ±5% is obtainable between photogrammetrists using the same photograph (Craven, 1990).

An electro-optical distance ranging system has been developed to improve the accuracy of ground surveys (World Coal, 1997). The profile of the stockpile is surveyed using a theodolite which employs an infrared laser for distance measurement. Measurement of the horizontal and vertical angle by the theodolite enables each point to be accurately positioned on the pile surface. The measurement is repeated hundreds of times over the stockpile to provide three dimensional information about the surface of the stockpile. Taking into account the density contours within the stockpile determined by density measurements (see below), the total mass of the stockpile is calculated using specialised computer software. An example of the profile surveying is given in Figure 18. Since large stockpiles can deform the ground on which they stand, the depth of holes drilled down to the substrate are measured, and their position is determined by the laser. Thus the material below the ground level can be defined.

Density determination

The bulk density of coal can vary within a stockpile as it is dependent on the degree of compaction and the coal properties, including moisture and particle size. Thus the choice of the measurement locations is important. Methods used to determine the bulk density include volume displacement procedures, and nuclear surface and depth density determinations. An empirical method for estimating the bulk density of a stockpile from the packing conditions (such as pile size, dropping height, coal moisture content and particle size distribution) has been developed (Standish and others, 1991; Yu and Standish, 1991). It is claimed that the calculated bulk densities are within 5–7% of the measured values.

Nuclear depth density gauges are probably the more dominant method. They measure the density at different locations and depths within the stockpile. The vertical and horizontal location of each measurement is determined so that the exact position of each density reading is known.

Weighing systems

Accurate weight measurements can yield better control over coal pile inventory, and eliminate overpayments for coal receipts. Weighing systems include truck (weigh bridge) scales, hopper scales and conveyor belt scales. Major weighing errors in belt scales can result from belt tension fluctuations and from off-centre belt loading. The combination of a parallelogram scale suspension and precision weigh roller minimises both sources of error (Walker, 1997). Another source of error common in all the weighing systems is scale misalignment. Thus all weighing systems must be properly installed, maintained and regularly calibrated to minimise any errors. They should also be materials tested to check for bias. The location of the weighing system is also important. For instance, if the coal is weighed after being sprayed with significant amounts of water for dust suppression, then the weight of the water can affect the book inventory. Weighing systems and procedures are outlined by Katterhenry (1995), and Rosenberg (1993) and Shepherd and Slauson (1999) provide a guide to the selection, installation, and testing of conveyor belt scales.

Errors associated with the book inventory value include weighing errors both into and out of the stockpile, unaccounted changes in the coal moisture in the stockpile, losses due to spontaneous combustion, and losses due to water runoff and wind erosion (Craven, 1990; Rose, 1992; Tivy, 1996). In addition, coal at the base of the pile can become contaminated with the underlying strata, resulting in a loss (Tivy, 1996). Inventory values obtained from volume and density measurements are also subject to error (see below). With audits commonly undertaken only once a year, discrepancies between the book and survey inventories will increase over the year. For instance, a stockpile may represent a 60 day burn at a power plant. This means that the plant actually consumes six times as much coal in a year than is in the stockpile. If the belt scales are out by an error of 0.75%, then a 4.5% error will occur in the stockpile over the year. More frequent inventories are likely to decrease the discrepancy between the book and survey inventories. When any significant discrepancies are observed, then their cause should, of course, be investigated. Sylvester and Gotch (1998) review procedures for taking a stockpile inventory. Tivy (1996) discusses the benefits of implementing a Total Quality Management (TQM) approach to a coal inventory system. This includes assessing (and correcting) errors in the sampling, analysis and weighing systems and implementing appropriate quality assurance/quality control systems.

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Nuclear depth density gauges are probably the more dominant method. They measure the density at different locations and depths within the stockpile. The vertical and horizontal location of each measurement is determined so that the exact position of each density reading is known.
However, the measurements are subject to calibration errors; the gauges require calibration for each coal type since they are influenced by the coal’s composition (Voorhis, 1989). This could cause difficulties when the stockpile contains several different coal types, or when a number of stockpiles of different coal types are being surveyed. Nuclear depth gauges are expensive to buy. Their accuracy also depends on penetrating the coal without disturbing its in situ density, as well as the location and number of density tests. Forming the hole for the access tube by driving a sampling tube appears to increase the density of the coal contiguous to the hole, resulting in an error of about 3% in density readings (Craven, 1990). Once the access holes are no longer required, they should be backfilled to lessen the risk of spontaneous combustion. Reasonable estimates of the variance of stockpile density errors can be obtained by proper experimental design, taking into account the variance of calibration errors as well as the variance of sampling errors (Rose, 1992). It should be noted that depth nuclear density measurements of a stockpile can vary because of hardware variations, different calibration procedures, different density test procedures and different data handling procedures (Voorhis, 1989). Nuclear depth density gauges and procedures have not yet been standardised, although the ASTM is currently developing a standard (Sylvester and Gotch, 1998).

Figure 18 Profile survey of a stockpile (World Coal, 1997)
5 Coal deterioration

Most coals are susceptible to weathering and atmospheric oxidation during storage in open air stockpiles. Both these processes involve the reaction of coal macerals and minerals with oxygen and moisture at ambient conditions. Additionally, weathering involves the physical degradation of coals caused, for instance, by frost action. Weathering and oxidation alter a coal’s properties and structure, and hence its subsequent behaviour. The alteration is usually for the worse and may, in some cases, render the coal unsuitable for the purpose for which it was originally intended. These changes are effectively irreversible, and the resultant economic losses can be difficult to evaluate. Generally, the longer the exposure the greater the oxidation.

In certain circumstances, coal oxidation may be advantageous. Oxidation destroys the agglomeration properties of bituminous coals. Therefore processes that involve combustion of coals on grates or in fluidised beds, where agglomeration is undesirable, may actually benefit from the use of oxidised coals (Gray and Lowenhaupt, 1989). Preoxidation of swelling and caking coals can be beneficial in gasification processes.

This chapter examines some of the properties and processes affected by coal weathering/oxidation, including heating value losses, handleability, cleaning, combustion, and coking. Oxidation resulting in spontaneous combustion is covered in Chapter 6. Natural oxidation of coal has been reviewed in the IEA Coal Research report by Davidson (1990). This chapter will therefore mainly be concerned with post-1990 literature. Other reviews on weathering and oxidation of coal include books edited by Klein and Wellek (1989) and Nelson (1989). The majority of the literature pertaining to research on coal weathering aspects is limited to coal samples oxidised under controlled laboratory conditions. Properties of laboratory-oxidised coals may be slightly different from those naturally oxidised. Consequently, this report will concentrate on stockpiled coals.

5.1 Heating value

Oxidation can reduce the heating value of the coal, leading to economic losses. For instance, Powder River Basin (PRB) subbituminous coal loses on average more than 1.5% of its heating value, or approximately US$0.33/t (US$0.30/short ton), between the time it is bought at the mine and the time the coal is burned at the Sherburne County Plant, MN, USA (Lehto, 1995). When and where this loss occurs is not clear, although greater losses in heating value occur over the longer storage time in the stockpiles. The rate of oxidation varied among the PRB coals. Handling costs due to oxidation were estimated to be US$0.27/t (US$0.25/ton) for the Wyoming coal reclaimed within 10 days from the berm area (open-air stockpiles), US$0.27/t (US$0.25/ton) for the Montana coal in the enclosed barn, and US$1/t (US$0.90/ton) for coal reclaimed from the longer term storage piles (up to 2 years).

Thus the reactivity of a coal to oxidation and the rate of deterioration are important information for determining cost-effective stockpiling times if the coal properties and its end-use are not to be adversely affected.

The exact mechanisms involved in coal oxidation have yet to be clearly defined. Oxidation is principally affected by the:
- properties of coal (composition, including the minerals components, and rank);
- coal particle size;
- moisture content;
- temperature;
- storage time;
- depth in the pile;
- ventilation flow through the pile; and
- seasonal climatic changes.

The oxidation rate is coal-rank dependent, with low rank coals being more prone to weathering and oxidation than higher rank coals (Roberts and others, 1994). High rank coals lose about 1% per year in thermal value (Thompson and Raymer, 1981). Storage of low rank, high ash Candiota coal (Brazil) in a stockpile for 10 months resulted in a 5.6% loss in the heating value (from 29.018 MJ/kg to 27.402 MJ/kg). The first 30 to 40 days were the most critical with the highest rate in heating value loss (see Figure 19). As can be seen from the figure an increase in the heating value occurred after the initial decrease (Correa da Silva and others, 1997; Sampaio and others, 1991). This increase could be due to the loss in oxygen from decarboxylation. Although carbon oxidation reduces the heating value, this can be offset by decarboxylation increasing it (Davidson, 1990). Davidson also notes that the determination or estimation of heating value may not take into account the loss in mass that generally occurs with oxidation.

The ash content increased in coal samples from a size fraction of –0.59 mm and a density range of –1.60 g/cm³, and the percentage of fines increased with storage time in the 150 tonnes stockpile (Correa da Silva and others, 1997;
Sampaio and others, 1991). In general, smaller particles tend to oxidise more rapidly than larger ones due to the increased surface area. Shimada and others (1991) also found that the heating value was strongly related to the ash content for a Polish bituminous coal stored for 1.5 years at the Dürnrohr power plant, Austria; as the heating value decreased with time, the ash content increased. The heating value of the coal at the time of storage was 28.33 MJ/kg dry basis.

Both the temperature and moisture content in the stockpile influence the rate of oxidation, with consequent effect on the heating value. Localised hot spots can lower the heating value. Stored coal loses or gains moisture depending on the atmospheric conditions. Moisture strongly influences the handleability of coal and so will be discussed in the next section, along with ways of controlling the moisture content of stockpiles. Cycle changes in moisture have also been implicated in spontaneous combustion. This aspect and the role of moisture and temperature in oxidation is covered in Chapter 6.

Heating value losses vary over a stockpile, generally decreasing with depth. The losses are highest at the surface of the pile where the coal is in intimate contact with the atmosphere. This was observed in a stockpile of Czech brown coal stored for one year (Teyssler and Jehlika, 1989) and a Polish bituminous coal stockpiled at the Dürnrohr power plant (Shimada and others, 1991). The reduction in heating value was divided into two components by Shimada and others (1991): a ‘volumetric reduction’, which occurred over the entire coal stored, and a ‘surface reduction’ which only occurred at the surface of the pile. The ‘volumetric reduction’ was 0.5% and the ‘surface reduction’ was 0.25% per metre. The samples were taken 3 and 5 months after storage and up to a depth of about 2 m.

Air flow through a pile promotes oxidation and hence heating value loss. Thus uncompacted stockpiles have a higher rate of heating value loss than compacted piles. Heating value losses in stockpiles at the Teruel power plant in Spain over 11 months varied from 19% per year for the loosely piled (30% porosity) subbituminous Spanish coal to 1.1% per year for the same coal with high compaction (10% porosity). For a less reactive low rank Spanish coal, the reduction in the heating value was 2.2% per year in the slightly compacted (17% porosity) pile (Miranda and others, 1994). Coal samples taken from the slope of the stockpile showed that the wind accelerates coal oxidation (Miranda and others, 1995).

Therefore, building long stockpiles with the narrow side facing the prevailing winds, the strategic use of wind breaks (see Section 7.2), and compacting the pile can help to minimise oxidation and heating value losses. In addition, stacking at a small angle reduces the wind pressure on the sloping faces. However, not all stockpiles can be tightly compacted. Piles created from some run-of-mine coals that have widely diverse particle sizes are not amenable to tight stacking. Models simulating wind flow over stockpiles coupled with oxidation within the pile are discussed in Section 6.2.

The rate of oxidation is affected by seasonal climatic changes. Heating value losses are increased by factors such as increased solar intensity (temperature) and rainfall frequency (Teyssler and Jehlika, 1989). In cold weather, ice formation on the surface blocks the air, reducing the oxidation rate. Investigations have found that winter stored bituminous coal lost 1.4% and the summer stored coal lost 2.1% of its heating value during the first year (Thompson and Raymer, 1981).

It would be useful to be able to predict the weathering propensity of a coal before it is stockpiled, and to monitor the extent of the weathering/oxidation while it is in the pile. But the complex nature of coal can make it difficult to quantify oxidation. Various tests and techniques are available that reveal whether a coal has been oxidised; most of these only provide a relative measure of the extent of oxidation. Davidson (1990) reviews some of these techniques. They include petrographic indicators, loss of thermoplastic properties (see Section 5.5), the alkali extraction test, fluorescence intensity and parameters derived from Mössbauer spectroscopy and infrared spectroscopy. Some of these tests are extremely sensitive to the onset of oxidation whereas others are better at following its progress over longer periods. However, low rank coals with their naturally higher oxygen contents and non-coking coals may ‘fail’ certain oxidation tests. Fourier transformation infrared based parameters and the distribution of pyrite compounds by Mössbauer spectroscopy have been successfully used to follow the evolution and extent of weathering of stockpiled low rank coals. The aliphatic hydrogen content and the pyrite-to-jarosite ratio decreased with increasing time and pile activity (Ibarra and others, 1993). The fluorescence intensity measured on vitrinite macerals has also been used to detect oxidation in stockpiles (Kruszewskas and du Cann, 1996). Gas sampling for oxygen and carbon monoxide from samples stored in cans over 1 to 4 days provided a simple and inexpensive technique for determining the relative rate of coal oxidation. The measurements were in agreement with the heating value losses experienced in the stockpiles at the Sherburne County power plant, MN, USA (Lehto and others, 1998). Knowing the properties of a coal before it is processed can help in optimising the process. On-line analysis of the coal as it is reclaimed and transported can show the variations in the coal properties as they occur (see Section 4.3).

5.2 Coal handling

One factor that strongly influences the handling of coal and affects the operation and efficiency of coal handling equipment is water. The amount of surface moisture primarily determines the flowability characteristics of a coal. Usually, as the surface moisture increases, so does the difficulty in handling. Heavy rainfall and other climatic processes can increase the coal moisture content in open air stockpiles to such an extent that handling problems occur, such as plugging of belt conveyors and chutes. It can also lead to moisture contract penalties. In climates where the ambient temperature can drop below freezing, the problem of handling wet coal can become severe with the wet coal freezing in chutes, bins etc. In addition, coal on the surface of the stockpile may become frozen. Water infiltration and
accumulation within a stockpile has been associated with slope stability failures (see Section 8.4). Moisture loss by evaporation is usually small but may be significant in hot, dry conditions (Roberts and others, 1994). It can increase the friability of a coal, as well its dustiness (see Section 7.1).

How the coal responds to changing moisture levels is influenced by properties such as its clay content and percentage of fines. Coals with a high clay content tend to be sticky as they are better as holding moisture. Fine coals retain moisture better than large-sized coals due to their increased surface area. Reclaiming these coals when wet may therefore lead to problems unless the handling equipment is designed for them. Chakraborti (1995) suggests that it is advisable to turn over the section of the pile where ‘old’ coal is stored with a lot of fines and reclaim that coal during good weather conditions. The ‘good’ coal is left for rainy days. In addition, coal can be blended to minimise handling problems.

The reactivity of the coal to weathering and oxidation influences the approach used for stockpiling and handling. Weathering and oxidation increase the friability of coals and produce more fines. This is caused by cracks introduced by dehydration or oxidation reactions such as pyrite swelling. The handleability characteristics of a coal therefore change over time. Low rank coals are more prone to particle degradation and oxidation than higher rank coals. In addition, the moisture content of weathered coal tends to be higher than the fresh coal because water is a product of hydrogen oxidation and the weathered coals have a higher moisture-holding capacity (Pisupati and Scaroni, 1991). A high percentage of fines in conjunction with a high moisture content, as noted above, increases the potential for pluggage. Typically, the acceptable fines content in as received coal in power plants is no more than 15%, although less than 10% is preferred. Coal fines content also affects the performance of coal preparation plants (see Section 5.3) and coking plants. Factors affecting oxidation and weathering have been covered in Section 5.1.

Loy and others (1987) vividly describe the problems encountered by the Tennessee Valley Authority (USA) when reclaiming a stockpile of nearly three million tons of oxidised coal at its Paradise coal preparation plant. Over the years the total moisture content of the coal had risen from about 6–8% to over 11%. The fines content had also increased due to the friable nature of oxidised coals. The combination of wet, very fine coal created tremendous handling problems, with blockage of chutes and routine feed rate swings of up to 300 tph of the desired feed rate to the preparation plant. Derating the plant was required to avoid overloading the intermediate and fine cleaning circuits. Increased wear and corrosion of plant equipment also occurred (see Section 5.3).

Hatt (1997) found that an effective estimate of the stockpile surface moisture can be made using a cheap (about US $20) greenhouse moisture meter. These meters incorporate a probe that is placed in the soil of a flower pot to determine if the plant needs watering. The meter readings can be gradually correlated to plant experience with pluggage problems. Various indices have been proposed to predict the handleability of coal. Some of these incorporate coal properties, and have been briefly reviewed by Carpenter (1998).

Practices used by the coal stockyard can impact the moisture content. Ones that can increase moisture content of coal (Hatt, 1997) and so should be avoided include:

- large flat stockpiles that allow little, if any, runoff;
- the possibility of ‘ponding’ on the surface;
- pushing the coal through low areas that have standing water in them while reclaiming; and
- ground water levels that are actually higher than the pile.

The following practices could be beneficial in controlling the moisture content within the stockpile (Hatt, 1997; Nolan, Davis and Associates, 1991):

- construct the pile so as to achieve the maximum height over the smallest area, consistent with stable side slopes;
- avoid flat tops;
- enhance the percentage of runoff by compacting the surface, including the side slopes;
- allow good drainage of the pile or elevating the reclaim area to allow efficient drainage. The potential contamination of ground water by water drainage is discussed in Section 8.1;
- reduce the moisture content of the incoming coal to the maximum degree practical (especially at coal preparation plants); and
- application of sealants for long-term storage (see Section 7.2).

When forced to handle wet coal or hard to handle coal, then chutes can be lined with plastic liners to improve flowability; but this can be expensive. Intermittent air blasts and vibrators can assist in the removal of pluggage. The presence of large chunks of coal can help to break up the initial stages of pluggage caused by fines building up. Further details on some of the problems that have occurred when handling difficult coals, and methods used to solve them, are briefly covered in Carpenter (1998). According to Hatt (1997), chemicals can rarely be applied in sufficient quantities and mixed well enough to solve the problems. In addition, some chemicals may affect the behaviour of coal in end use processes. Chemical treatments are discussed in Sections 6.3 and 7.2.

### 5.3 Coal cleaning

Utilisation of oxidised or weathered coal can adversely affect coal cleaning processes, such as flotation. Loy and others (1987) describe the problems they encountered at the Paradise coal preparation plant, KY, USA, when reclaiming a stockpile of oxidised coal for flotation. Major problems were experienced from acidic oxidation products forming on the surface of the coal; these products readily dissolve into the process water, lowering the pH. This decreased the flotation recovery and increased wear on plant equipment and process piping. For instance, the sump pump impellers, made of conventional materials, were completely dissolved in less than eight hours! Most of the exposed metal surfaces were replaced with wear and corrosion resistant materials, and magnesium hydroxide was added to raise the pH of the
process coal water. Blending up to 20% of the oxidised coal with fresh coal diluted most of the detrimental effects of the oxidised coal. No method for efficiently cleaning the oxidised coal by itself was found.

This example demonstrates how oxidised or weathered coal can adversely affect the performance and hence the economics of coal preparation plants. More information on the effects of oxidation and weathering on coal cleaning, particularly flotation, can be found in Davidson (1990). He reviews work showing that oxidation causes a change in the wettability of coal. Changes in wettability affect surface-based separation processes such as flotation and oil agglomeration. Oxidation reduces the coal’s ability to repel water (hydrophobicity) and consequently, inhibits attachment of the nonpolar parts of the frothing reagents to the coal surfaces. Other changes affecting the performance of coal preparation plants include increases in the specific gravity, increased friability, changes in the zeta potential, and decreasing pH.

Generally, flotation performance of stockpiled coals decreases with storage time. For example, the flotation yield of a bituminous coal decreased from about 56% to about 30% after 13 months in the stockpile (Fuerstenau and others, 1994). One of the coals began to weather almost immediately, but the floatability of the two other bituminous coals did not begin to decrease until about five months had passed (see Figure 20). Thus the rate of deterioration is important in determining cost-effective stockpiling times if flotation performance is not to be adversely affected. Monitoring oxidation was discussed in Section 5.1. The ambient temperature was found to correlate well with the weathering rates of the coals. Fuerstenau and others (1994) also report that the flotation response of two of the coals improved after 10 months of weathering. They suggest that this may be due to summer rain washing away the dissolved ions from the coal samples, thus making the coals more floatable.

The susceptibility of a coal to oxidation is not only influenced by the duration of storage and climatic factors, but also by the characteristics of the coal itself (see Section 5.1).

Oxidation of both the organic matter and minerals, especially the sulphide minerals, occurs (Davidson, 1990). The presence of even small amounts of pyrite in stockpiled coal can depress flotation recovery. Coals containing significant amounts of clay minerals can also have a deleterious effect on flotation at low pH. However, flotation efficiency does not always correlate well with the oxidation level of coals. For instance, Axelson and others (1987) report that the least oxidised bituminous coal had one of the poorest flotation performances. The construction of stockpiles to minimise oxidation, for instance by compaction, is discussed in Sections 5.1 and 6.3.

Remedial measures to improve flotation performance of weathered/oxidised coals have included attempts to neutralise surficial oxygen-complexes with alkalis, and the use of a surface conditioner (or collector). Cationic collectors (amines) were found to be effective in the flotation of an oxidised coal; the floatability was highest at neutral pH (Sarikaya and Ozbayoglu, 1995). Low concentration electrolytes (such as iron chlorides) can increase the floatability of oxidised bituminous coals (Bolat and others, 1998). Fuerstenau and others (1994) found that grinding coarse weathered coal to -28 mesh (-600 µm) before flotation can help to minimise the effects of weathering. They also report that washing the weathered coal before flotation to remove dissolved metal ions improved the flotation yield. Aplan (1993) reviews how coal properties, including oxidation, dictate coal flotation strategies.

5.4 Combustion

Coal stockpiled outdoors for long periods can undergo changes that affect boiler operations. As well as lowering the heating value, oxidation can retard devolatilisation, thus reducing the reactivity of the char (Nieminen and Moilanen, 1989). The composition of the volatiles from oxidised and fresh unoxidised coals is also likely to be different (Gray and Lowenhaupt, 1989). Changes in parameters such as the swelling index, maceral composition and chlorine can impact NOx emissions, carbon burnout and slagging behaviour.

The effects of storage time and conditions on the combustion behaviour of bituminous coals were studied at the Dürnrohr power plant, Austria (Aumüller and Raffelsberger, 1990; Shimada and others, 1991). Drill hole samples were taken over a period of 4 years or more at different depths from stockpiles of about 200 m by 50 m and up to 20 m in height (see Figure 21). The heating values and volatile matter were nearly unchanged, probably a result of the stockpiles being well compacted. Changes in the Free Swelling Index (FSI) depended on the coal type. No change occurred for the coal with an initially low FSI. But coals with a high initial swelling index suffered a significant loss in this parameter and hence their reactivity (see Figure 22). The loss in reactivity led to higher NOx emissions in boilers using overfire air for NOx abatement (compared with the ‘fresh’ unoxidised coal), and lower NOx emissions when fired without overfire air.

The loss-on-ignition (LOI), and hence the amount of
unburned carbon in the fly ash, increased significantly when weathered coals were fired. The amount depended on the FSI and ash content. Any increase in the fly ash carbon content affects its saleability and utilisation, especially in the cement industry, the main market for fly ash. The decrease in FSI and reactivity was characterised by the appearance of oxidised vitrinite, especially in the cracks and microfissures that occur during weathering. Bengtsson and Moilanen (1987) showed that oxidised vitrinite particles produce compact char structures requiring long combustion times. In a ‘normal’ coal, vitrinite rapidly devolatilises with a high degree of swelling to produce thin-shelled cenospheres; these require only a short combustion time. The combustion tests were carried out in a drop tube furnace using weathered coals and ‘fresh’ coal (taken from larger lumps) from Finnish stockpiles. More details on the effects of oxidation and weathering on char formation and coal combustion can be found in Bend and others (1991). Since LOI is directly related to char burnout, one way to achieve a satisfactory burnout for weathered coals would be to increase their residence time in the furnace burning zone. Nandi and others (1982) report that the effect can be reversed by heat treatment of the oxidised coal in the presence of carbon monoxide.

However, oxidation does not necessarily lead to chars with lower reactivities than the fresh coals. Combustion tests carried out by Pisupati and Scaroni (1993) on fresh, weathered and laboratory-oxidised bituminous coals found that the weathered coal chars had the highest reactivities. This is thought to be due to greater accessible surface areas and higher H/C ratios of the weathered coal chars, and catalytic effects from inorganic species in the chars. The volatile matter content of the weathered and laboratory-oxidised coals were higher and their heating values lower than the corresponding fresh coals. The weathered coals were taken from outcrops rather than a stockpile, and the fresh coals were taken from the same seam as the outcrop coals. Thus boiler efficiency may not decrease when weathered coals are fired.

Coal samples taken from stockpiles at the Dürnrohr power plant found that the chlorine content increased with depth due to the influence of intrinsic water (see Figure 23). This effect was dependent on the storage method and coal properties. Sodium chloride (NaCl) accumulated in piles where the surface is renewed in cycle periods, whereas coal stored without the addition of new material was able to build up a protective layer. Washed coals have fewer fines and a lower initial NaCl content than unwashed coals. These washed coals are difficult to compact; the intrinsic water percolates through the stockpile, accumulating NaCl in the bottom layers. The NaCl content was also higher in the slope sample (Shimada and others, 1991). An increase in coal NaCl can promote high temperature corrosion in boilers, especially in those using overfire air where reducing atmospheres can occur. NaCl also contributes to slagging and fouling. Slagging tendencies were slightly reduced when stored coals were fired due to their lower reactivity. The heat distribution in the boiler changed, with the higher temperatures in the superheaters resulting in slightly increased fouling (Aumüller and Raffelsberger, 1990).

A gain in coal moisture has significant consequences in the power plant in terms of handleability (see Section 5.2), mill capacity (especially drying capacity) and boiler efficiency.
Not only does additional moisture lower the heating value of the coal, but it retards ignition, decreases flame stability, reduces combustion efficiency and changes the heat distribution in the boiler. Generally, the higher the moisture content, the lower the boiler efficiency. A higher coal moisture content may also adversely affect the performance of fitted pollution control equipment. Ways of controlling the moisture in open air stockpiles, such as allowing for good drainage or applying chemicals to the pile surface are addressed in Sections 5.2, 7.2 and 8.5. It should be noted that the addition of chemicals may affect the coal’s combustion behaviour. More details on the effect of changes in coal properties on power plant performance can be found in Carpenter (1998).

The main ways to minimise the negative impacts on power plant performance caused by the open air storage of coals are:

- to modify the power plant operating parameters (see Carpenter, 1998);
- to blend the oxidised coals with unoxidised coals (see Carpenter, 1995); and
- to minimise the storage time of sensitive coals.

Coal blending was found to be the best way to mitigate the problems when firing weathered coals at the Dürnrohr power plant (Aumüller and Raffelsberger, 1990).

5.5 Coking

Weathering and oxidation generally have adverse effects on the coking of coal. Work reviewed by Davidson (1990) summarises these effects as:

- reduced coke stability;
- coal bulk density control problems;
- reduced coke production;
- overheated charges;
- carbon deposits;
- oven damage;
- generation of fines (coal handling problems, discussed in Section 5.2);
- increased coke reactivity; and
- decreased coking rate.

The bulk density of coal is affected by the moisture content and particle size distribution (see Section 5.2). It tends to decrease as the particle size distribution decreases and increase with additional moisture over about 8% (Gray and Lowenhaupt, 1989). Good thermoplastic and caking properties are important in order to produce a good metallurgical coke. Unfortunately, storage in an open-air stockpile may cause a deterioration in these properties, leading to a coke of impaired quality. The losses will be greatest at or near the surface of the pile. This section mainly considers the effects of storage in a stockpile on the thermoplastic properties of coal and the consequent coke reactivity and strength. A more comprehensive review of the chemical reactions and effects of weathering and oxidation on the thermoplastic properties and coking of coal can be found in Davidson (1990) and Khan and Jenkins (1989).

Tests for assessing the thermoplastic properties and coking qualities of a coal are sensitive to oxidation and can be used, to a certain extent, for detecting and monitoring coal oxidation on stockpiles. For example, Axelson and others (1987) consider that the Free Swelling Index (FSI) alone is a poor indicator of coal oxidation due to its dependence on maceral composition. Some of these tests are discussed by Carpenter (1988) and Davidson (1990). Generally, as oxidation proceeds, the FSI, Gieseler maximum fluidity and Audibert-Arnul dilatation decrease. How fast these properties deteriorate during exposure to the atmosphere is generally unpredictable. It depends on a number of interrelated factors, including the coal characteristics (see Section 5.1). Where one coal may deteriorate only modestly, another apparently very similar one will, under virtually identical storage conditions, lose almost all its plastic properties (Berkowitz, 1989). Nonetheless, Boyapati and Oates (1993) have developed a one-dimensional model for estimating the extent of deterioration in the plasticity (Gieseler fluidity) of the coal as a function of stockpile size, time and storage conditions. The model was tested using three Australian coking coals.

The influence of weathering on the coking properties and coke quality is illustrated using a recent study carried out in Spain. A typical blend of 13 different coals was stored in an open-air 100 t stockpile for up to one year (Alvarez and...
Four of the component coals were also subjected to weathering for 5–6 months in piles of 50–60 t. Unlike the blend, these coals were stored without grinding and were ground just before the carbonisation tests in a semi-industrial oven. The main characteristics of these four coals and the blend are given in Table 3. The weathering conditions were mild; the blends were not significantly oxidised as shown by the alkali extraction test. The Gieseler maximum fluidity was the most sensitive indicator of loss of thermoplastic properties and oxidation, followed by the Audibert-Arnu dilatation. The Gieseler maximum fluidity decreased over time for the blend and the four individual coals (see Figures 24 and 25). There were no significant changes in the FSI over time for the blend or the four coals, except for Coal C (a Canadian coal), where it decreased from 7 to 4½ after 138 days. Aumüller and Raffelsberger (1990) and Shimada and others (1991) also found that oxidation reduced the Audibert-Arnu dilatation of stockpiled coal at the Dürnrohr power plant; in this case the FSI decreased from 6 to 1½–3 after only two months storage (see Section 5.4). Thus oxidation is strongly influenced by the coal characteristics. FSI is generally considered to be not very sensitive to slight-to-moderate weathering, although there are exceptions (Davidson, 1990). Berkowitz (1989) suggests that moderately caking coals with FSIs in the range 3–5 tend to be much more prone to losing their caking properties completely than coals with higher FSIs.

Table 3  Main characteristics of the blend and four of the component coals (as received) (Alvarez and others, 1996)

<table>
<thead>
<tr>
<th></th>
<th>Blend</th>
<th>Coal A</th>
<th>Coal B</th>
<th>Coal C</th>
<th>Coal D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ash, wt% db</td>
<td>7.7</td>
<td>8.3</td>
<td>9.9</td>
<td>9.4</td>
<td>10.0</td>
</tr>
<tr>
<td>Volatile matter, wt% db</td>
<td>26.6</td>
<td>32.7</td>
<td>23.2</td>
<td>22.0</td>
<td>21.3</td>
</tr>
<tr>
<td>Sulphur, wt% db</td>
<td>0.74</td>
<td>0.92</td>
<td>0.60</td>
<td>0.34</td>
<td>0.61</td>
</tr>
<tr>
<td>FSI</td>
<td>7½</td>
<td>7</td>
<td>7½</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>Gieseler maximum fluidity, ddpm</td>
<td>857</td>
<td>6143</td>
<td>639</td>
<td>35</td>
<td>158</td>
</tr>
<tr>
<td>Ts, °C</td>
<td>406</td>
<td>395</td>
<td>406</td>
<td>414</td>
<td>416</td>
</tr>
<tr>
<td>Mean reflectance, %</td>
<td>1.10</td>
<td>0.92</td>
<td>1.14</td>
<td>1.14</td>
<td>1.27</td>
</tr>
<tr>
<td>Maceral analysis, vol% mmf</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vitrinite</td>
<td>84.2</td>
<td>80.7</td>
<td>77.3</td>
<td>74.2</td>
<td>83.0</td>
</tr>
<tr>
<td>Exinite</td>
<td>3.3</td>
<td>8.6</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Semifusinite</td>
<td>8.0</td>
<td>7.2</td>
<td>15.1</td>
<td>19.2</td>
<td>10.2</td>
</tr>
<tr>
<td>Fusinite</td>
<td>4.5</td>
<td>3.5</td>
<td>7.6</td>
<td>6.6</td>
<td>6.8</td>
</tr>
</tbody>
</table>

Figure 24  Variation of Gieseler maximum fluidity with weathering time for the coal blend (Alvarez and others, 1996)

Figure 25  Variation of Gieseler maximum fluidity with weathering time for the four individual coals (after Alvarez and others, 1996)
Alvarez and others (1996) also examined the damage to coke oven walls from weathered coals. Carbonisation tests in a semi-industrial oven found a clear decrease in the internal gas pressure with weathering for the blend and for the two individual coals (coals A and B) on which it could be measured. For the blend, a decrease in wall pressure after two months of weathering was followed by a period of stabilisation before it increased after about 10 months storage.

Impairment of coke quality (reactivity to carbon dioxide (CRI), post-reaction strength (CSR), and mechanical strength determined by the IRSID test) only occurred after 10 months weathering. However, the behaviour of the individual coals was rather different. Weathering effects on coke quality showed different responses depending on the parent coal. This is illustrated in Figures 26 and 27 for the CRI and CSR tests, respectively. Similarly, coke strength (IRSID index) improved with some coals (Coal A) and was impaired with others (Coal C). There was virtually no change for Coal D, whereas coke strength initially increased for Coal C before decreasing after 76 days of weathering. The behaviour of the blend can therefore be explained by the competing effects of the component coals.

From these results it can be seen that weathering and oxidation does not necessarily lead to a deterioration in coke quality. Mild weathering and oxidation can help to produce a coke of improved quality not only in high volatile and high fluidity coals but also in some medium volatile coals. Identifying these coals (and coals that are easily weathered) and optimising their storage times is therefore an important aspect in stockpile management.

Weathered and oxidised coals can be utilised by blending with unoxidised coking coals. In general, as the amount of weathered coal in the blend increases, the coke quality and coking rate decreases. Thus the amount of weathered coal that can be blended is limited. Work discussed by Davidson (1990) showed that even a small amount (<10%) of a weathered Kentucky coal reduced the ASTM coke stability measure by as much as two points; even this small decrease could result in an appreciable decrease in hot metal production in the blast furnace. In some cases, however, oxidation can be an advantage. Oxidised coals could be exploited in blends to reduce, for example, the excessive fluidity of an unoxidised coal. Grinding oxidised coals in order to generate fresh surface can, in some cases, help to mitigate the effects of oxidation.

Methods for inhibition of weathering and oxidation of coking and thermal coals include compacting and building the stockpiles with the narrow side facing the prevailing winds (see Section 5.1), the strategic use of wind breaks (see Section 7.2), and the application of chemical inhibitors (see Sections 6.3 and 7.2). Hattori and others (1994) found that, as well as compaction, nitrogen gas blowing was effective in reducing coal degradation. It is also preferable to store the coal in large heaps, when practicable, since the smaller the heap, the greater the deterioration. However, no extra advantage is gained by building a pile with linear dimensions over 20 m (Boyapati and Oates, 1993). Additionally, smaller piles will need to be compacted to a greater bulk density than larger ones.

An interesting recent development at steel works is the utilisation of thermal coal injected into the tuyeres of the blast furnaces. With the increased use of pulverised coal injection (PCI), the amount of coke used has dropped. In the 1980s (before PCI), between 500–600 kg of coke was used for each tonne of iron. Nowadays, 100–200 kg/t hot metal of injected coal has reduced coke by about the same amount. This means that coke strength and reactivity are especially important. Blending is now needed for both coking and thermal coals and the trend is to use fewer coking coals. Steel works therefore pay a lot of attention to getting the coke blend right (Osborne, 1999).
5.6 Comments

For many coals exposure to the atmosphere can, over time, cause significant deterioration of technologically important properties. In general, the longer the exposure to the elements the greater the coal weathering and oxidation. Unfortunately even slight oxidation can have major impacts on certain sensitive properties such as the Gieseler fluidity. The relative importance of these changes depends on how the coal is to be utilised. Possible impairment of coking power would not be as important a factor for coals to be burned as for coals to be coked. Barring emergencies, the length of time that the coal is left in a stockpile is a balance between the cost of storage and recovery against the extent of deterioration of the coal. Knowledge of the reactivity of the coal to oxidation and the rate of deterioration can help management to determine cost-effective stockpiling times. However, methods for predicting the behaviour of coal are hindered by a lack of understanding of the fundamental chemistry of coal oxidation, and the interactions of the many and complex parameters affecting the oxidation and weathering reactions.

Compacting the stockpiles and building them with the narrow side facing into the prevailing wind are among the methods that can be used to inhibit oxidation. As well as economic losses resulting from the degradation in coal properties, there are safety implications. The risk from spontaneous combustion is the subject of the following chapter.
6 Spontaneous combustion

Spontaneous combustion poses significant safety, environmental, economic and handling problems if it becomes established in stockpiles. As well as the economic loss of coal due to fires, the heat affected coal may become partially or totally unsuitable for its intended use. Thus prevention and early detection of spontaneous combustion is of paramount importance. It is not clear how frequently fires occur as there is a lack of information published on this topic. This probably reflects two factors: producers’ need to market coal of a specific quality; and reticence for liability reasons on the part of the handling and transport organisations to acknowledge incidents that may occur whilst the coal is in their care (Walker, 1999a).

Even if spontaneous combustion does not occur in the stockpile, fires can later result when hot coal is loaded into confined spaces such as ship holds or railroad cars. Shipboard fires due to spontaneous combustion have been reported when coals from New Orleans, LA, USA, were exported to the Far East (Smith and Lazzara, 1993). Measures introduced to prevent the loading of coal with temperatures greater than 40°C and compacting the coal in the cargo hold were successful in stopping the fires.

The prevention and control of spontaneous combustion is accomplished by understanding the factors that increase the potential for self-heating, monitoring for the early detection of spontaneous combustion and a rapid response in the event of a fire. This chapter will discuss the factors affecting the spontaneous combustion of coals in open-air stockpiles, followed by tests for assessing their self-heating tendencies. With proper stockpile design and management even coals with a high propensity to spontaneous combustion can be safely stockpiled and handled. Ways of achieving this are covered in Section 6.3. Finally, monitoring stockpiles to detect signs of spontaneous combustion and ways of dealing with fires when they occur are described. Spontaneous combustion of coals has been recently reviewed by Ünal (1995) and Walker (1999a).

6.1 Factors affecting spontaneous combustion

The self-heating of coal in open-air stockpiles is dependent on a number of controllable and uncontrollable factors. The uncontrollable factors include the coal itself and the ambient conditions (the climate). The controllable factors involve the management of the stockpile, particularly its design and construction.

6.1.1 Coal properties

All coals are not equally susceptible to spontaneous combustion. Thus the identification of coals that are more susceptible is important so that measures can be taken to ensure their safe storage. Figure 28 illustrates the main elements involved in the self-heating of coal. Heat is generated in the pile by the reaction of coal with atmospheric oxygen, and the moderating or enhancing effect that water has on the reaction. Experiments have shown that for every 10°C rise in temperature, the rate of oxidation approximately doubles (Schmal, 1989; Walker, 1999a). Consequently, if the heat generated cannot be sufficiently dissipated, the rate of oxidation and generation of heat becomes self-accelerating. In time the temperature reaches the point where combustion of the coal occurs.

The properties of coal influencing the oxidation rate (see Chapter 5) and hence the self-heating of coal include:
- coal rank;
- moisture content;
- particle size and its distribution; and
- mineral content and composition.

Coal rank is perhaps the most important factor in determining a coal’s tendency towards spontaneous combustion. Generally, as the rank of coal decreases, the hazard of spontaneous combustion increases. Low rank coals (lignite and subbituminous coal) are usually the most susceptible to spontaneous heating due to their higher reactivities. They are typically higher in moisture, oxygen content and volatile matter, factors contributing to their faster rate of oxidation. However, there are often anomalies to a straight rank-based prediction as other coal properties also influence their self-heating.

There appears to be a critical moisture content before spontaneous combustion can occur. A coal pile with a higher moisture content has a lower tendency towards self-heating, taking longer to reach the ignition point (Monazam and...
Spontaneous combustion

others, 1998). This implies that wet lignite may be less likely to self-ignite than, say, higher rank moist subbituminous coal.

Coal may gain or lose moisture during storage, and it is these changes in moisture content that have been implicated in spontaneous combustion events. Moisture changes are primarily determined by the air humidity (see Section 6.1.2). When dried or partially dried coal absorbs moisture, heat is generated. This ‘heat of wetting’ can be considerable and may, in some cases, increase the temperature of the coal by as much as 30°C if the heat cannot escape (van Vuuren, 1995). Thus spraying water to extinguish fires in stockpiles is not generally recommended since it liberates the heat of wetting. In addition, in piles where spontaneous combustion is a problem, water should not be used for dust suppression; chemical dust suppressants may be a better option (see Section 7.2).

The loss of moisture from coal by desorption and evaporation are endothermic processes. The temperature of the coal is lowered, retarding the self-heating process. Moisture loss occurs, for example, when air with a low relative humidity flows through the pile. Ultimately, a constant temperature is reached and this is maintained as long as there is moisture in the coal. As soon as the coal has dried, the temperature at the site will rise because the heat of oxidation can no longer be removed by evaporation. This can lead to local ignition (‘hot spots’) in the pile (Schmal, 1989).

Low rank coals have inherently high moisture contents, ranging from some 25% to as much as 70% for some Australian brown coals. A high moisture content typically decreases the value of a coal, increases transport costs, and can cause handling problems. Drying these coals minimises these problems but will increase the risk of spontaneous combustion in stockpiles. Bench-scale tests carried out on three low rank coals by Clemens and Matheson (1996) suggested that over 50% of the moisture content of low rank coals can be safely removed without the risk of self-heating. These coals are often stored for only short periods. By taking appropriate measures (see Section 6.3), low rank coals, including brown coal briquettes, have been successfully transported and stockpiled for extended periods of time.

Oxidation and heat of wetting processes occur on the surface of the coal. A decrease in the particle size provides a greater surface area and hence a higher self-heating risk. The effects of particle size can also depend on the coal porosity (Ünal, 1995). A more porous coal has greater areas exposed to oxidation. Generally, coal porosity increases with decreasing rank.

The pile porosity helps determine the air flow patterns through the stockpile. Ventilation patterns that do not allow deep penetration of oxygen and moisture into the coal mass, where heat losses are minimal, are desired. The porosity of the pile is related to the particle size distribution (and the degree of compaction). If the coal particles are uniformly large, the pore spaces in the pile are also relatively large. Heating may take place but this is usually balanced by the cooling effect of the higher air velocities in the pile and the relatively low reactivity of the larger coal particles. If the coal particles are smaller and more variable in size, the relative reactivity is higher; but the pile porosity will be relatively low and the convection currents will not be able to penetrate as deeply into the pile (Smith and Lazzara, 1993). The amount of coal fines generated and the particle size distribution are related to the friability of the coal; low rank coals are more friable than higher rank coals. Moreover, weathering can make coal more friable.

Particle size segregation can occur during stockpile construction (see Section 3.1), influencing the ventilation patterns. For instance, size segregation of coal can occur in conical piles, particularly if a range of particles sizes is being stacked (see Figure 29). This gives ideal conditions for self-heating; air is able to pass freely through the outer part of the pile, rising up in a chimney effect as heating proceeds (see Figure 30). The finer fraction in the middle of the pile is exposed to oxygen and moisture with the potential for producing heat; the diminishing porosity leads to reduced heat losses from convection (Cudmore and Proudfoot, 1988; Smith and Lazzara, 1993). Thus it is not advisable to stack differently sized coals together.

Both the mineral content and composition can play a role in the spontaneous heating of coal (Didari and Ökten, 1994; Schmal, 1989; Sujanti and Zhang, 1999; Ünal, 1995). A higher ash content generally reduces the risk of self-heating, although the mineral components may either enhance or retard the effect. For example, oxidation of pyrite is an exothermic reaction which helps to accelerate spontaneous heating. Sodium and potassium can catalyse spontaneous combustion especially when they are present as organic salts (low rank coals).

![Figure 29 Particle size segregation in a conical stockpile (Cudmore and Proudfoot, 1988)](image1)

![Figure 30 Air flow through the segregated stockpile (Cudmore and Proudfoot, 1988)](image2)
Additional coal properties that have been linked with spontaneous combustion include the petrographic composition. Work reviewed by Gray and Lowenhaupt (1989) has shown that exinite has a greater oxidation rate, particularly above 75°C, than vitrinite and inertinite. The thermal conductivity of coal affects the rate of heat loss from the pile. The extent of oxidation of the stored coal can influence the self-heating process; as coal ages, the rate of oxidation decreases (Gray and Lowenhaupt, 1989; Ünal, 1995). Thus the risk of spontaneous combustion is greater when stockpiling fresh (run-of-mine) coals, especially during the early weeks of storage. For instance, high moisture, high volatile run-of-mine Indian coals have caught fire within 25 to 28 days (Singh and others, 1997). However, the effects of previous oxidation can break down with time and temperature. For example, the enhanced moisture-holding capacity (Pisupati and Scaroni, 1991) of oxidised coals compared to their ‘fresh’ state, and their ability to retain it more tenaciously (Berkowitz, 1989), contributes to self-heating through their higher heats of wetting. Furthermore, laboratory tests carried out by Arief and Gillies (1995) found that a coal from a washery stockpile took about 25 days to reach 100°C; but when the same coal was later taken from a power plant stockpile, it took only 17 days to reach 100°C.

To conclude, the coals most prone to spontaneous combustion are the low rank (lignite and subbituminous) coals. Potential problems exist for some high volatile thermal (bituminous) coals, such as those exported from Colombia and Indonesia; self-heating of these coals have occurred in Europe from time to time (Walker, 1999a). Some southern African coals also have a reputation for self-heating (van Vuuren, 1995). The effect of coal properties on spontaneous combustion is complex and interrelated with other factors, such as residence time, stockpile design and climatic conditions.

### 6.1.2 Climatic conditions

Climatic factors that are important in the self-heating of coal include:
- air humidity;
- rainfall;
- temperature;
- exposure to the sun; and
- exposure to the wind.

As noted in Section 6.1.1, the humidity, or moisture content, of the ambient air plays an important role in the self-heating of coal. Coals lose or gain moisture depending on atmospheric conditions. Dry ambient air can partially dry the coal, creating sites for moisture adsorption and the subsequent generation of heat due to the heat of wetting effect. Moisture loss by evaporation is usually small but may be significant in hot, dry conditions (Roberts and others, 1994). An increase in the incidence of fires is commonly found following periods of heavy rain after an extended period of dry, sunny weather, particularly in low rank coal piles (Berkowitz, 1989). Heavy rain can result in the formation of channels within the stockpile, facilitating access of air which can promote the self-heating process. Sudden fluctuations in relative humidity and barometric pressure have also resulted in fires (Cudmore and Proudfoot, 1988). Fires have occurred at the interface between wet and dry coals (Berkowitz, 1989; Cudmore and Proudfoot, 1988; Ünal, 1995). Therefore stacking wet coal on top of dry coals is not recommended.

Differences in temperature between the ambient air and the coal pile play an important role in establishing the air flow patterns within the pile, the oxidation rate and hence the magnitude of the temperature rise (Krishnaswamy and others, 1996; Schmal, 1989). Air transport by natural convection occurs when the pile temperature is higher than the ambient air. The initial temperature of the coal when stockpiled is therefore important. It is advisable to cool ‘hot’ coal before it is stacked. Coal after ship transport often has a higher temperature than the ambient air (Schmal, 1989).

Marked differences in daily or seasonal temperatures will raise the pile temperature. Radiative heating by the sun can lead to temperature increases over time. Coal pile temperatures can be higher in winter than in the summer. This is due to the higher air flow velocities caused by the relatively large temperature differences between the pile and the ambient air at this time of year (Schmal, 1989). Heat generation and transfer in coal piles are slow processes and time lags of some months are typical. This is another possible explanation for the relatively high coal temperatures in winter that have arisen in some coal piles.

Wind plays a major role in the self-heating process. Wind blowing into the side of the pile forces fresh air deeper into the mass of coal (forced convection), adds more oxygen, so increasing heat generation, and reduces the heat loss rates. It also leads to partial drying and weathering of the coal. Large-scale tests have shown that fires are most likely to occur on the windward side of the pile, and where the pile sides are steep. Tests were carried out on specially constructed stockpiles of subbituminous coal at the Teruel power plant in Spain. Over an 11-day period, temperatures in an uncompacted pile increased to around 90°C within 1.5 m of the windward surface slope. Temperatures recorded from the leeward side (not facing the prevailing wind) reached only around 50°C. Compaction reduces pile porosity and hence air flow within the pile. The temperature of the windward side of the compacted pile were considerably lower than those in the uncompacted pile and took a longer time to reach (Miranda and others, 1995). Mathematical modelling of the phenomenon by Krishnaswamy and others (1996) indicated that wind velocity, side slope and coal porosity were the principal factors determining whether or not long-term storage will be safe.

### 6.2 Risk assessment

It is clearly important that coal producers and users know the self-heating propensity of coals before they are stockpiled. Various laboratory tests to achieve this have been devised and used by the coal industry. Some of these have been reviewed by Carras and Young (1994), Cliff and others (1996) and Walker (1999a). The tests generally measure some aspect of
the reactivity of coal towards oxidation. They provide a relative ranking of the propensity of coals to self-heat. If a particular coal is shown to perform ‘better’ on a test than a coal whose self-heating behaviour is, to some extent, understood, then the behaviour of an unknown coal can be assessed. None of the tests has yet been the subject of a standard.

The tests include:

- adiabatic heating techniques. These typically involve heating the coal in a heat insulated vessel and controlling the temperature of the oven to follow closely the temperature of the coal sample as it reacts with oxygen. The maximum temperature attained by the sample (Carras and Young, 1994) or the gradient of the linear section of the plot of temperature versus oxidation time (Cliff and others, 1996) have been used to rank different coals. One technique relies on determining the minimum self-heating temperature (SHT). Coals with minimum SHTs <70°C are considered to have a high spontaneous combustion potential, those with minimum SHTs between 70 and 100°C a medium potential, and those above 100°C a low potential (Miron and others, 1992);
- isothermal calorimetry. The rate of thermal energy released as the coal oxidises under a constant temperature provides a measure of the self-heating propensity. The measurement can also be carried out at different temperatures by placing the calorimeter in an oven (Carras and Young, 1994);
- crossing point temperature measurements. The coal is heated under specified conditions and the temperature at which the coal sample temperature exceeds that of the oven or the inert reference material is determined. This value indicates that ignition has taken place (Carras and Young, 1994; Cliff and others, 1996; Mikula and others, 1992). Sujanti and others (1999) use the crossing point temperatures (where thermal conduction becomes zero) determined at the centre of a cylindrical heated wire-mesh reactor at different ambient temperatures and the rates of temperature rise at these points to estimate the oxidation kinetics. From these, the critical thickness (size) above which a stockpile becomes capable of spontaneous combustion can be determined;
- differential thermal analysis (DTA). The coal is heated at a constant rate and the temperature difference between the coal and an inert reference material is measured (Carpenter and Skorupska, 1993). This temperature difference is plotted against the inert material temperature or the furnace temperature. The crossing point temperature (see Figure 31) where the thermograph plot crosses the zero reference line provides a measure of the coal’s spontaneous combustion propensity (Cliff and others, 1996). The rate of heat release during Stage II (see Figure 31) has also been used to rank coals, as has the amount of released energy when the DTA is operated in an isothermal mode (Mikula and others, 1992);
- oxygen sorption. The amount of oxygen absorbed by the coal sample at a fixed temperature is determined (Carras and Young, 1994; Cliff and others, 1996; Mikula and others, 1992; Miron and others, 1992). The test can take several days.

![Figure 31 Typical DTA thermogram (Cliff and others, 1996)](image)

As well as the single indices derived from the above tests, composite indices have been proposed. Some of these are based on properties derived from these tests, such as the FCC index in which the average heating rate over 110 to 220°C is divided by the crossing point temperature. Other indices can additionally include intrinsic coal properties, such as its heating value. Cliff and others (1996) discuss some of these indices.

Interpreting the results of the various tests can present a number of difficulties. Only small samples of coal are used. This poses the question of how representative the samples will be of the tonnes of coal commonly stored in a stockpile. The tests are empirical, with results dependent on the test conditions and apparatus (as well as the coal characteristics). Thus they can provide only a relative ranking of a coal’s propensity to self-heat. The test conditions do not simulate the actual conditions encountered in stockpiles. Chen and Stott (1997), among others, have shown the difficulty of relating adiabatic laboratory experiments to the spontaneous heating and ignition of piles of stored coal.

Although coals can be classified according to their susceptibility to spontaneous combustion, their self-heating behaviour is controlled by a number of parameters besides the reactivity of the coal. These include the stockpiling conditions, such as the degree of compaction, and climatic factors. This has led to the development of mathematical models that include some of these factors, often with a measure of the coal’s reactivity. No single property can be employed to assess a pile’s self-heating behaviour.

Models have been developed:

- to help understand spontaneous combustion;
- for predictive purposes, such as predicting safe storage times; and
- to design and manage stockpiles to prevent spontaneous combustion. Thus the effectiveness of measures applied to prevent or restrict spontaneous combustion can be assessed.

A number of these models have been reviewed by Carras and Young (1994). Typically the models take into account the heat and mass transfer processes occurring in the pile. Some models include the effect of moisture adsorption, desorption
and migration (for example, Arisoy and Akgün, 1994; Monazam and others, 1998) and the effect of natural and/or forced convection. For instance, Anne and Pantelis (1997) have coupled a computational fluid dynamics (CFD) wind flow model with a model that simulates heat and mass transfer within the stockpile. In general, the models provide semi-quantitative predictions of stockpile behaviour. Since the reactivity of the coal plays an important role in the self-heating process, each coal stockpile will have to be examined separately.

A major limitation with the models is their lack of validation on a large scale or practical stockpiles (Carras and Young, 1994). A full description of the chemical and physical processes leading to self-heating is complex and is still not fully understood. Thus a number of assumptions have had to be made when formulating the models. Field trials have been used to compare actual events with modelling predictions, with varied success. The trials have often employed small stockpiles. The effects of scaling up to commercial-sized stockpiles, especially the effect on convection and other heat and mass transfer processes in the models, needs to be investigated. Validation of the models is both an expensive and difficult experimental task, but essential if the models are to be utilised with any confidence. An advantage with the laboratory tests, such as the crossing point temperature and minimum SHTs, is that at least they are simple, although they only provide a preliminary indication of the self-heating propensity of a coal.

### 6.3 Prevention

Experience and studies of the self-heating of coal (see Section 6.1) have shown that, by following certain practices, spontaneous combustion in stockpiles can be largely eliminated. The design and safety monitoring of a stockpile should start at its inception in order to avoid having to take preventative measures later. A poorly constructed stockpile may well present problems at a later stage.

The preparation of the site, construction of the pile, its maintenance and the coal residence time are factors that can be controlled to minimise the likelihood of spontaneous combustion. The procedures undertaken are largely dependent on the time the coal will spend in the pile. Compaction and other preventative measures discussed below may not be necessary for high volatility coals kept for a limited period of time, although this does depend on the reactivity of the coal; for instance high moisture, high volatile matter Indian coals have caught fire within 25–28 days (Singh and others, 1997).

Experience has indicated that it is not advisable to stack (Cudmore and Proudfoot, 1988):  
- coals with different propensities to spontaneous combustion, such as low and high rank coals;  
- differently sized coals, such as lump coal with coal fines;  
- weathered and fresh coals;  
- wet and partially dry or dry coals; and  
- run-of-mine and washed coals.

If possible, these coals should be stored in separate stockpiles. Any blending that is required can be accomplished after the coals have been reclaimed, using one of the methods discussed by Carpenter (1995). Mixed sized coal may be safely stored if the fines content is sufficient to fill in the voids formed by the larger particles (van Vuuren, 1995).

Good site preparation can help avoid spontaneous combustion (Cudmore and Proudfoot, 1988; Thompson and Raymer, 1981; Ünal, 1995; van Vuuren, 1995). The storage site should:

- be free of any debris and combustible material such as timber;
- have a base that does not promote the entry of air through loose or uncompacted rubble at the bottom of the pile;
- be dry and well drained. US Indiana coal loaded onto wet ground with some puddles of water fired quickly for no other observable reason (Schmidt, 1945). The base should be reasonably level, although a gentle slope can facilitate drainage. Any drains provided should not go under the pile as these may assist spontaneous combustion by encouraging an air current through the pile; and
- be clear of external heat sources such as buried steam lines and sewer lines.

There should also be good access around the perimeter of the pile to permit the removal of hot spots (see Section 6.5).

Correct stockpile formation is critical to minimising the potential for spontaneous combustion. The recommended measures rely on either restricting the entry of oxygen into the pile or providing adequate ventilation to remove the generated heat. The measures discussed below should be considered for the long-term storage of coal, although some of the measures may be advisable for short-term stockpiles of reactive coals. These methods will also impede deterioration of the coal properties, discussed in Chapter 5. The main recommendations in the design and construction of the stockpiles are concerned with:

- the amount of compaction;
- avoiding sources of hot spots;
- avoiding particle segregation;
- pile size (height);
- side slope angle;
- shielding from the wind;
- initial coal temperature; and
- sealing the pile.

In general, lump coal can be stored with through ventilation to remove any generated heat, while unsized coal piles require compaction to prevent air flow through them (Walker, 1999a). In practice, it is difficult to achieve adequate ventilation of large piles (Smith and others, 1991). In many instances, instead of dissipating the heat, the ventilation flow aggravates conditions that are already bad. At a high coal reactivity, for example, air velocities will generally be too low to remove the heat (Schmal, 1989). The degree of ventilation could be increased by installing perforated pipes projecting vertically and horizontally into the piles; but this may be uneconomical. It is also impractical in large piles where big machines are used for stacking and reclaiming.
Compaction of the pile is generally effective in preventing fires in long-term stockpiles. However, compaction can work in the wrong way if not done well. Temperatures were higher in the slightly compacted pile than in the uncompacted and densely compacted test piles of Australian bituminous coals (see Figure 32). Thus dense compaction is preferred (Schmal, 1989). This is achieved by placing the coal in layers of about 0.5 to 1 m thick and compacting each layer with bulldozers and rollers before commencing the next layer. Van Vuuren (1995) describes the different types of rollers available and their application. The sides of the pile should also be consolidated to prevent any air ingress. Dynamic cone penetrometer or densimetric tests will indicate the effectiveness of the compaction. Compaction is labour intensive and expensive (Bere and others, 1994; Handa, 1997) but will pay off for long-term stockpiles. The overall surface of the pile should be contoured to provide adequate rainfall runoff without the risk of ponding on the surface or erosion to the sides. The formation of gullies could encourage the entry of air. Uncompacted stockpiles should have a concave shape to avoid water ingress (van Vuuren, 1995).

Very wet coal should not be compacted immediately but should be allowed to partially dry through seepage or evaporation of the excess moisture (van Vuuren, 1995). Measures for controlling the moisture content of the stockpile are covered in Sections 5.2 and 8.5. Conversely, very dry coal will not compact. It can be sprayed with water to add just enough moisture to allow compaction (Chakraborti, 1995). Coarse coal with a low percentage of fines is also difficult to compact as the fines generated by compaction are not sufficient to fill the voids. However, an inert atmosphere in the pile is achieved over time provided the voidage is sufficient low that little or no air enters the body of coal.

Upright vertical structures in or adjacent to piles, such as conveyor supports or retaining walls, can cause problems (Thompson and Raymer, 1981). They are sources of hot spots or fires since, to avoid damage to compacting equipment and the structure, coal adjacent to them cannot be compacted. At the Lamma power plant, Hong Kong, coal is normally stored for less than 6 weeks in uncompacted piles. The fires that have occurred were mostly in the areas adjacent to the retaining or supporting walls, where the coal tends to be stagnant, or in the areas where adjacent piles are allowed to overlap (Fretwell, 1995).

Particle size segregation should be avoided because of the chimney effect. Segregation invariably takes place as the coal is stacked (see Section 3.1). Conical piles are particularly prone to it. Therefore this type of pile needs to be compacted or reclaimed as quickly as possible on a ‘first-in first-out’ basis (Chakraborti, 1995). The windrow method is preferred to the chevron mode for stacking coals liable to spontaneous combustion (Cudmore and Proudfoot, 1988). The drop height from the end of the stacker should be minimised particularly if the coal is friable and prone to spontaneous combustion.

The optimum height of the pile depends on the type of coal as well as other pile dimensions and stacking conditions. Lower piles allow heat to escape more readily but hold less coal. Where short-term storage is envisaged without compaction, a maximum height of 8–9 m is suitable for fine coals, reducing to 3–4 m for larger material (Walker, 1999a).

Long-term compacted piles can be higher, although the depth of coal in the pile may be controlled by the stability of the ground beneath it. Where highly mechanised stockyard systems are used, as in export and import ports, and where stock turnover is likely to be rapid, stockpile heights can be increased to 20–30 m provided that adequate monitoring systems (see Section 6.4) are in place.

Stockpiles built with gently sloping sides can have a beneficial effect on spontaneous combustion. An investigation on two stockpiles of low rank fresh coals by the US Bureau of Mines and discussed by Krishnaswamy and others (1996) found that the pile with a 34° side slope had problems with fire; the pile with a 14° slope was found to be safe over a period of two years. The wind-induced pressure on steep slopes is greater than for shallow slopes and, as a result, more air flows through the pile. A smooth pile surface also minimises differential pressures due to the wind. Stockpiles should be constructed with a sufficiently shallow gradient (15–30°) that facilitates side compaction and allows equipment to work safely. But the downside is that the capacity of the stockpile is reduced. Decreasing the side angle also helps to avoid particle size segregation (van Vuuren, 1995) and flowslides (see Section 8.4).

Since fires are more likely to occur on the windward side of the pile (see Section 6.1.2), building the pile with the face having the smallest area exposed to the prevailing wind is recommended. Wind direction can, of course, change during different climatic conditions. Screen banks of sufficient height can be built alongside to shield stockpiles from the wind, although these can take up valuable stockpile area. A 6 m high fence (built of 200 mm pine boards with a gap of 85 mm between the boards to give a permeability of about
28%) was effective in reducing the temperature rise in a 2017 ton low rank coal stockpile (Fierro and others, 1999). Spontaneous combustion only developed in the slope at the opposite end to the fence towards the end of the 250 day test period.

Hot coal should be cooled before it is stored as the initial coal temperature influences the rate of self-heating (see Section 6.1.2). This can be achieved by spreading it out in thin layers, turning it over repeatedly and, if necessary, leaving it overnight when temperatures are cooler (Kok and others, 1989; Schmal, 1989). However, turning the coal over repeatedly increases the risk of fragmentation. Kok and others (1989) suggest that bituminous coal delivered at a temperature of 35°C or less can be stockpiled in a loosely stacked state for two months without problems. Long-term storage of coals at a temperature of 35–60°C is not recommended but, if it is unavoidable then the pile should be compacted to a high density and sealed with some form of coating, such as latex. Coal delivered at a temperature over 60°C must be cooled before stockpiling. It has been suggested that coal should not be stacked in hot weather (Schmidt, 1945; Ünal, 1995), but this is not an option in countries with hot climates.

Long-term stockpiles can be surface sealed to prevent air ingress. Sealing stockpiles also protects against dust formation (see Section 7.2) and erosion. The entire surface of the pile can be covered with a 300 mm thick layer of soil or some other low permeability material (Walker, 1999a). Covering a 2045 ton low rank coal stockpile in Spain with a fly ash-water slurry was effective in preventing spontaneous combustion (Fierro and others, 1999). It was the most effective method of those tested (periodic compaction, low angle slopes and wind screens) with a moderate application cost of 46 pesetas (approximately 0.28 Euro or US$0.28) per ton of coal. The fly ash was obtained from the power plant where the stockpiles were built. Some power plants in Austria have even planted grass on their long-term stockpiles.

Spraying the exposed surfaces with chemical sealants that form a surface skin on the pile can help prevent self-heating from developing. Road tar, asphalt, coal tar and various surfactant dust-control binders have been employed (Chakravorty, 1984; Cudmore and Proudfoot, 1988; Kok and others, 1989; van Vuuren, 1995; Walker, 1999a). Chemical inhibitors that have been used to reduce the reactivity of coal include phenols, aniline, ammonium chloride, sodium nitrate, sodium chloride, calcium carbonate and borates (Cudmore and Proudfoot, 1988; Dong and Drysdale, 1995; Sujanti and Zhang, 1999; Walker, 1999a). The chemicals can be sprayed onto the coal whilst it is being stacked, but further spraying of the stockpile surface is usually needed for effective control. Spraying the piles with water to prevent dust emissions is not recommended as subsequent drying encourages self-heating. Where watering programmes have been implemented to prevent or control self-heating, it is imperative to adhere to schedules that preclude the drying out of the coal between successive applications of water (Berkowitz, 1989).

Handa (1997) describes the use of a proprietary dust suppressant product, Coalgard (an oil emulsion), at the Kota power plant stockyard in India. By wetting the surface of individual particles, oxidation is reduced. The effective dose rate depends on the level of fines and/or surface area; a typical dosage is 15 litres of Coalgard in aqueous spray for every 100 t of coal. At the Rockport power plant, IN, USA, the compacted stockpiles are sealed with the proprietary sealant, Soil-Sement (an aqueous acrylic vinyl acetate polymer emulsion). An application usually lasts for 6–9 months (Chakraborti, 1995).

The use of foam to apply polymers to surface seal short-term stockpiles of a Polish coal that is susceptible to spontaneous combustion has been tested (Bere and others, 1994). The 20 cm thick layer of foam formed an elastic skin over the pile, protecting it against dust emissions and reducing the ability of air to flow through the coal. Over a six month period, internal temperatures averaged some 10°C lower in the treated pile compared with the untreated reference pile. The relative benefits of surface treatments and simple compaction, compared to uncompacted coal storage, in preventing self-heating are illustrated in Figure 33.

Questions remain about the cost-effectiveness of chemical treatments, particularly on a large-scale, both in terms of the direct cost of the chemicals and the potential disadvantage for end users such as power plants. Bere and others (1994) and Handa (1997) found no adverse effects on boiler operation from the chemically treated coal.

Stockpiles should be regularly monitored and maintained. Any breaches in the stockpiles’ defences against air ingress, such as gullies, wash-outs, erosion sites or cracking, should be repaired immediately. Monitoring for self-heating is the subject of the next section.

6.4 Detection

Early detection of spontaneous combustion is important for the safe storage of coal and to minimise potential losses due to self-heating. The cost of monitoring large tonnage stockpiles is small compared to the total value of the coal within it. There are also safety considerations. Spontaneous combustion can result in sub-surface voids that are not apparent on the surface. These voids can make the surface unsafe for operators and equipment. Spontaneous combustion is often detected visually by seeing smoke or steam coming...
from the pile or by the melting of ice or snow at various locations on the pile in winter. In wet weather, a hot area can be identified by the lighter colour of the surface coal dried by escaping heat. By this time the self-heating has progressed to an advanced stage and urgent action is required to prevent the self-heating from progressing any further (see Section 6.5).

The two principal techniques employed for the early detection and monitoring of self-heating are:

- temperature measurement; and
- gas analysis.

The simplest method is to feel the ends of long iron or steel rods that have been driven into the suspect parts of the pile (Schmidt, 1945; Walker, 1999a). The rods are left to adjust to the internal pile temperature before being withdrawn. Thermocouples installed in pipes driven into the body of the stockpile and set in a grid pattern can monitor the temperature trends. This technique is generally limited to long-term stockpiles since the buried pipes would inhibit the day to day stacking and reclaiming of live stockpiles. A portable probe capable of measuring temperatures to a depth of 6 m, as well as sampling the gas emissions, is described by Grossman and others (1991). “Strenuous hammering” was required to drive the probe into a well compacted pile (density 1250 kg/m³). Calibrated thermocouples are generally preferred to mercury glass thermometers (van Vuuren, 1995).

Infrared detectors (hand-held or operated from a fixed position) have been employed, but these only indicate increases in the surface temperature or the presence of hot gases emitted through internal convection (Walker, 1999a). By the time heating has progressed inside a stockpile to the stage where increased surface temperatures are evident, there will probably already have been visual signs of combustion. This method can survey a large area in a short time, but care is required as the weather conditions, such as the sun, can affect the measurements (Cudmore and Proudfoot, 1988; Kok and others, 1989).

Analysing the gas within the stockpile can also help identify potential heatings. Carbon monoxide concentrations of 20 ppm or more at a pile depth of 1.5 m indicate that heating is in progress. More than 1% carbon dioxide at this level, together with reduced oxygen concentration, shows that an inert atmosphere is forming within the pile (van Vuuren, 1995). With an inert atmosphere and no air flowing into the pile, self-heating is less likely to occur.

<table>
<thead>
<tr>
<th>Table 4</th>
<th>Gas emissions in stockpiles at the Hadera power plant (Grossman and others, 1994)</th>
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<tbody>
<tr>
<td>Coal type</td>
<td>Pile density, kg/m³</td>
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<tr>
<td>South African</td>
<td>1250</td>
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<tr>
<th>Table 5</th>
<th>Gas emissions in stockpiles at the Ashdod coal terminal (Grossman and others, 1994)</th>
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<tbody>
<tr>
<td>Coal type</td>
<td>Pile density, kg/m³</td>
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<tr>
<td>Colombian</td>
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nd not detected na not analysed
Grossman and others (1994) used a portable probe to monitor the emission of gases within open air stockpiles (over 60,000 t) of imported bituminous coal in Israel. The coal was stored for more than 12 months at different degrees of compaction in a hot, dry climate. The initial temperature of the coal piles was relatively high at more than 25°C. The uncompacted piles at the Ashdod coal terminal emitted higher concentrations of carbon monoxide, hydrocarbons and hydrogen than the compacted piles at the Hadera power plant (see Tables 4 and 5). The presence of these gases increases the risk of fires; this will be of more concern for coal stored in confined spaces than open air stockpiles. However, where gravity reclamation is employed, the gas could accumulate in the tunnel, becoming an explosive hazard. Dangerous levels of carbon monoxide (400–600 ppmv) were found 1 m above the surface of the Ashdod stockpile. Since exposure to concentrations of 400 ppmv CO for more than 15 min is considered dangerous by most health standards, safety precautions must be taken when a worker attends a hot spot at near ground level (1–1.5 m).

6.5 Control

Regular monitoring of stockpiles is essential in order to identify potential spontaneous combustion problems so that appropriate action can be taken. Areas of a pile where the temperature rises continuously to over 40°C require further investigation, and a rise in temperature to over 60°C is a clear indication that self-heating is under way (Walker, 1999a). These temperatures are only guidelines as spontaneous combustion can begin at temperatures as low as 30°C for some US subbituminous coals, for instance. Both the spontaneous combustion susceptibility of the coal and the speed of the operation and, in practice, is not easy (Didari and Ökten, 1994).

Once self-heating is under way, there are two basic options:
- remove the hot coal and use it immediately. If the coal is hot enough to damage conveyor belts and ignite any unaffected coal, then it should be cooled with water sprays before being conveyed to the chutes and hoppers (Cudmore and Proudfoot, 1988); or
- remove the hot coal, cool by spreading into thin layers and then re-pile and re-compact it. The coal can be left to cool overnight when temperatures are lower or sprayed with water. However, wet coal can be difficult to handle.

A fire at the edge of the pile can be isolated by cutting a trench. The success of this procedure mainly depends on the speed of the operation and, in practice, is not easy (Didari and Ökten, 1994).

Open air stockpiles are easily accessible and normally present few problems in moving equipment to deal with an outbreak before the fire becomes too vigorous. Rail-mounted stacker-reclaimer systems (see Section 3.2) can be quickly moved to the site of suspected self-heating. Portal or semi-portal scraper reclaimers which remove coal from the side of the pile, or bucket-wheel stacker/reclaimers are particularly useful. Heavy earthmoving equipment, such as bulldozers and front-end loaders, can be used to excavate the hot coal, spread it into layers and re-compact it back into the overall stockpile profile.

The use of water to extinguish fires is generally not recommended. Not only will large quantities of water flush fine coal out of the stockpile, so increasing its permeability for subsequent air penetration, but there is the risk of explosive gases being generated if the coal is hot (Walker, 1999a). Water sprays, often used for dust control, can also exacerbate self-heating, since the heat of wetting is added to that generated by accelerating oxidation.

Dry ice (solid carbon dioxide) has been used successfully in controlling spontaneous combustion in stockpiles. Rogers and others (1997) note one incident in which 250 kg/h of dry ice was used to extinguish a fire in a 25,000 t pile. The dry ice was dug into the coal in order to achieve better coverage of the affected area. This would presumably work best in an enclosed or covered area, since wind effects would tend to disperse CO₂ if it were used on an open-air stockpile (Walker, 1999a). This would also be the case for other inert gases that are injected into the pile to prevent or control self-heating.

6.6 Comments

The self-heating of stockpiled coal is a complex process resulting from a number of factors. These include the properties of the coal, the ambient conditions, and the construction and management of the stockpile. There is no single property that can be employed to assess a pile’s self-heating behaviour. The most susceptible coals are the low rank coals, although all coals have the potential to self-heat. Live stockpiles typically have a lower risk of self-heating than coal stored in long-term piles.

Published information on stockpile fires is lacking. There is a need for greater openness, a move that would enhance safety and help prevent future economic losses by publicising potential problems before they can recur.

Stockpile fires are difficult to extinguish. Thus the adage “prevention is better than cure” is particularly appropriate. This can be accomplished by understanding the factors that contribute to self-heating, constructing the pile to prevent air ingress, and monitoring to detect any self-heating in its early stages. The cost and effort involved in monitoring stockpiles is generally small in relation to the value of the coal within it. Where there is an indication that self-heating is under way, the hot coal should be removed and cooled down. A rapid response in the event of a fire will prevent it from spreading. With proper stockpile design and management, even coals with a high propensity to spontaneous combustion can be safely stored.
Wind-borne fugitive dust emissions are not only an economic loss but can cause environmental problems in the surrounding areas. Coal dust is a nuisance, posing potential health and safety issues for employees and people in the neighbourhood. It can also cause damage to equipment. Regulations on air quality and penalties for non-compliance are becoming increasingly stringent. Laws to restrict PM_{10} (particulate matter with particles <10 µm in diameter) have been introduced and restrictions on PM_{2.5} (particulate matter with particles <2.5 µm in diameter) have been, or will be, imposed in places, such as the USA and European Union (Smith and Sloss, 1998). A range of measures are available for controlling dust emissions, but these vary both in their effectiveness and cost.

Wind erosion from stockpiles is a major source of fugitive dust. Dust can also form during the stacking and reclaiming of the piles, with stacking usually resulting in more dust. Stockpile management often entails considerable traffic on and around the pile to maintain the coal, creating additional dust. Equipment such as front-end loaders, bulldozers, and scrapers operating at the site can generate substantial dust. Trucks and conveyor belts are the main sources of coal dust during transport to and from stockpiles. This chapter will concentrate on dust emissions from the stockpiles, with the emphasis on preventative and remedial measures. More information on dust control during the transit of coal, including railroad cars, trucks and belt conveyors, can be found in the IEA Coal Research report by Schmitz (1994).

### 7.1 Factors affecting dust emissions

The severity of fugitive dust emissions from stockpiles depends on a number of factors:

- coal properties, including the moisture content, particle shape, interparticle forces and particle size distribution;
- stockpile design (geometry), layout and construction; and
- local climatic conditions, such as the wind speed, solar radiation, and rainfall.

One of the key factors in determining how much dust is generated is the surface moisture content. Coal dust severity decreases as the surface moisture content increases and vice versa. As a general rule of thumb, the dustiness is considered severe if the surface moisture of coal is 0–4%, mild if it is 4–8% and low at 8% and above (Coates, 1991). A critical moisture content can be reached at which dust removal can be prevented (see Figure 34); the value varies with coal type. This factor is exploited in wet dust suppression systems (see Section 7.2). The amount of moisture in the pile is also influenced by the weather (see Section 5.2), washing process and whether water is added to prevent dust emissions.

Coal piles with a high volume of fines can be expected to produce higher dust emissions since small particles are more easily removed from the surface. Typically, coal particles above 1 mm are too large and inert to become airborne (Schmitz, 1994). The smaller the particles, the further they travel. Figure 35 indicates how far different size particles dislodged from a 5 m tall stockpile by a 5 m/s wind can travel. Factors influencing the particle size distribution include the hardness and friability of the coal. Low rank coals are generally more friable than higher rank coals and so are more susceptible to dust generation (see Section 5.2). Very high rank coals are also susceptible (Handa, 1997). High moisture contents in these coals can, however, reduce their dusting potential, at least until the material dries.

Different stockpile shapes and their layout affect the area of exposure to the wind. The stacking method also influences dust formation and particle size segregation (see Section 3.1). These aspects are discussed more fully in the next section where it is shown how good stockpile design can help lower dust emissions.
The magnitude of fugitive dust emissions is influenced by the local climatic conditions, such as the relative humidity, rainfall, solar radiation, and the wind speed and direction. Meteorological conditions vary with the location of the stockpile, and even for one stockpile there are a number of microclimates. For example, the wind speed, which is generated as a result of the pile alignment with the direction of the wind, changes over the pile. For dust to become airborne, the wind must reach a certain speed in order to overcome the cohesion forces and aerodynamic drag forces on the particles. In work quoted by Hunt and Barrett (1989), in a windy environment with an average wind speed of 5 m/s, about 150 kg/m² of coal is lost per year. The respirable dust proportion is about 2%. Dust can therefore be expected to be a problem in hot and/or windy climates. Rainfall can increase the moisture content above the critical value, and so inhibit dust generation. However, too much rain can create handling problems (see Section 5.2) and, in some cases, flowslides (see Section 8.4). Weathering of the pile surface can generate dust and fines due to coal degradation. The lower rank coals are particularly prone to degradation. Thus protecting coal stockpiles from the weather is one way to alleviate dust emissions.

7.2 Prevention

The control of dusts from stockpiles is important from both an environmental and economic viewpoint. There are a number of measures that can be implemented to avoid or control dust emissions; these vary in both their cost and effectiveness. The measures taken can affect the quality and price of the coal, the efficiency of handling and other equipment, and can have consequences for the end use of the coal. The correct choice between, and proper implementation of, dust control measures is therefore essential in order to optimise the efficiency and cost-effectiveness of the stockyard.

The choice of system is best done at the planning stage. This is usually more cost-effective than piecemeal measures, or wholesale redesign, required to combat problems once the operation is under way. However, the choice of a particular system may be limited by additional factors, such as the flexibility of operations required or the need to avoid spontaneous combustion. Thus any solution will be site-specific.

The principal methods for combating dust emissions are:
- wind control (pile orientation and configuration, use of fences and berms);
- wet suppression systems (water, chemical wetting agents, foams);
- chemicals for binding the particles together (chemical binders or agglomerating agents);
- sealants for sealing the surface of the pile (chemicals and vegetation); and
- enclosing the stockpile.

The applicability of these methods for dust suppression during stacking and reclaiming operations, and for active and inactive (long-term) storage piles is summarised in Table 6. In addition, telescopic chutes and wind guards on stacking equipment, and gravity reclaiming systems can reduce dust emissions. Mechanical dust collection systems will not be covered since these are employed in enclosed systems such as covered belt conveyors, silos or bunkers.

Stacking systems

Stacking of stockpiles can account for a large proportion of the airborne dust. Virtually no stacking system is immune from this problem. Moreover, use of some of the most dust prone systems may be unavoidable at certain points in the stacking process. For instance, front-end loaders or bulldozers are often used to compact coals to inhibit spontaneous combustion. This entails considerable traffic movement on and around the pile, with dust generation almost inevitable. In such cases, rigorous management is required to minimise dust formation. This may entail the use of dust suppressant systems such as water sprays.

<table>
<thead>
<tr>
<th>Table 6 Applicability of dust control methods</th>
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<tbody>
<tr>
<td>Wind control</td>
</tr>
<tr>
<td>Stacking</td>
</tr>
<tr>
<td>Reclaiming</td>
</tr>
<tr>
<td>Active piles</td>
</tr>
<tr>
<td>Long-term piles</td>
</tr>
</tbody>
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Controlling the size and size distribution of the particles on the pile can help lower fugitive dust. Segregation invariably takes place as the coal is stacked (see Section 3.1). Conical piles are particular prone to it. Chevron stacking generally ensures that the surface remains smooth throughout stacking, whereas it is relatively uneven under the windrow method (Schmitz, 1994). Minimising the drop height can decrease particle fragmentation, and will also help avoid dust emissions during the stacking process. Boom-type stacker/reclaimers can be lowered to a location just above the pile. However, gantry-type systems have a fixed drop and thus high dust generation risks. These risks can be offset by fitting appropriate stacking chutes, such as telescopic chutes. These have been incorporated, for example, at the Superior Midwest Energy Terminal, WI, USA (Ethen and Shusterich, 1994).

Reclamation
Dust generation tends to be lower in the reclaiming of stockpiles than during their stacking. However, some systems can have an adverse effect on the surface roughness or profile of the stockpile, creating the potential for dust generation. For instance, the use of front-end loaders, bulldozers and scrapers (see Section 3.2) can result in surface roughness. Bucket-wheel slewing booms reclaim the coal from a number of levels, which results in several critical areas for dust generation. In addition, the ends of the stockpile are not always reclaimed if accurate blending is required (see Chapter 3). These resultant uneven remnants can be a source of wind erosion. Proper management and operational procedures are the main ways of minimising fugitive dust (Schmitz, 1994).

Gravity reclamation, whereby the coal is reclaimed through bottom reclaimers underneath the pile, generally generates the least dust. This is the system utilised at the Superior Midwest Energy Terminal, WI, USA, whereby the friable subbituminous coal (PRB) is reclaimed in a 503 m long tunnel system (Ethen and Shusterich, 1994). Safety precautions, such as fitting explosive vents, must be taken since dust generation in the reclamation tunnel is a potential fire and explosion hazard.

Stockpile layout and design
How the stockpile is laid out and its design can help mitigate dust emissions. Orientating the stockpile so that the narrowest side, or the side with the smallest surface area, faces the prevailing wind can significantly lower fugitive dust. This has the additional benefit of retarding spontaneous combustion (see Section 6.3). However, the wind direction changes during different climatic conditions, and so dust suppressants systems are often required as well (discussed below). Stockpiles should also be sited to take advantage of any natural shelters from the wind; these include other stockpiles and buildings. The air flow over the stockpile is influenced by the shape of the pile and the roughness of its surface (Hunt and Barrett, 1989). Steep slopes can significantly change the air flow over the pile. All the stockpiles at the Superior Midwest Energy Terminal, WI, USA, are regularly groomed and compacted at various times during the year. This gives the pile a smooth surface, reducing dust emissions, and retarding spontaneous combustion (Ethen and Shusterich, 1994).

Berms and fences
Berms (earth embankments) act as windbreaks, reducing both the wind velocity over the piles and its drying effects. The consequent reduction in the requirements for dust suppressant systems or other control measures make the installation of berms cost-effective in many locations. The berms can also host specially designed stacker and reclaimer systems or water spray systems. However, they are ineffective if too low and can take up valuable stockpile area (Handa, 1997).

As well as lowering dust emissions, berms can play an important role in the landscaping of the site; they can reduce noise pollution (see Section 3.4) and minimise the adverse visual impact of the stockpiles. For instance, the coal terminal at Ghent, Belgium, is surrounded by 5–8 m high grassed berms and fast growing poplars. Although only 250 m from a residential area, the site is generally accepted (Schmitz, 1994). A 12 m high berm was built around most of the Ashdod terminal in Israel and, on top of it, a 2 m high fence has been erected (Schneider and Grossman, 1997).

Fences placed upwind can, if high enough, reduce the wind velocity and turbulence before it reaches the pile, thus reducing fugitive dust. Fences placed downwind can inhibit dust transport. Although fences reduce the impact of the wind on stockpiles, they may also create dead zones close to them. Dust may be deposited in these areas, only to be redispersed when winds blow from a different direction (King, 1997). Hunt and Barrett (1989) recommend that the fence height should be about equal to that of the pile and its porosity about 50%.

The layout of the fences is important and should be designed to minimise the effects of the prevailing winds. Practical situations of site layout, and available funds, will impose limitations on the design. For example, fences can only be built where they can be structurally supported and where mobile equipment does not run into them. Mathematical models (Chang and others, 1995) and computer packages (Chan and Zhu, 1995) are available for analysing the effectiveness of different fence designs and layouts.

The ideal place to put a fence may not be where the stockyard operator wants it, and where he would like to place it may be where it will do the least good. This is illustrated, to a certain extent, at the Nadins coal mine, UK (King, 1997). The fences erected were found to offer good protection in wind directions from which strong winds seldom blew (north and south), but lesser protection in the prevailing westerlies and frequent easterlies. The 6 m high fence of knitted polyethylene netting material consisted of three separate runs around the conical stockpile and its loading area (see Figure 36); gaps had to be left for vehicular access. Monitoring showed that the presence of the fences reduced dust emissions by about 30 µg/m³, giving an overall dust suppression efficiency of about 40±10%. Without the gaps, only 20 µg/m³ would have been added to the dust levels, and the overall efficiency of the fence would have risen to about 75±10%.
Dust suppressants

There are many dust control and suppression agents available for inhibiting fugitive dust from stockpiles. These include water, wetting agents (surfactants), foams, binders, agglomerating agents, and chemicals for long-term sealing of the pile surface. It is difficult to compare the effectiveness, and the treatment cost, of the different agents. Companies rarely offer any quantitative evidence of the performance of their products, relying instead on providing case studies where the agents have been most effective (King, 1997). This makes choosing the most suitable control agent somewhat difficult since each coal and situation is different.

Chemical agents often serve a dual function – as well as reducing dust emissions, they can prevent the oxidation of coal and hence the potential for spontaneous combustion. Lehto and others (1998) found that the rate of oxidation can vary dramatically with the amount of water added and with the choice of chemicals used for dust control. Dust suppressants have a number of drawbacks. These include such factors as cost, an often limited experience in use, and environmental limitations, such as ground water contamination. In addition, there may be an aversion on the part of the coal users to the addition of chemicals whose precise nature, and consequences for its end use, may not be certain.

Water

As noted in Section 7.1, the surface moisture of coal is a key factor influencing fugitive dust. Spraying the stockpile with water to maintain or increase the surface moisture levels above the critical value is one of the simplest dust suppressant methods. This solution is often the cheapest in the short-term, but it may not always be the most effective. In arid environments, where water is scarce, spraying with water may not be an option. The main disadvantages with water spraying are:

- the effect of water is short-lived. Once water has evaporated, the dusting conditions return. Thus regular spraying is required;
- adding excessive water reduces the heating value and economic value of the coal, and can have consequences for its end use. Care is required to ensure that the contract specification for the moisture content is not exceeded, incurring financial penalties;
- water can accelerate surface weathering. The coal breaks down, so releasing more fine particles that can form dust;
- wet coal can result in subsequent handling difficulties (see Section 5.2);
- provision for dealing with water runoff should be made (see Chapter 8); and
- strong winds can blow the water sprays off course.

Water spraying can be carried out during stockpile construction to prevent dust emissions. But then the overall moisture content of the pile will be high, and the coal may exceed the contract moisture specification. If water is only added to the fully built stockpile, then although the surface layers will be high, the overall moisture content remains low. But dust emissions could be high, depending on the prevailing weather conditions, during its construction. This could then result in emission regulations being exceeded during the construction phase. Thus a complete strategy for dust control for the whole stockyard that includes the stacking and reclaiming of stockpiles, as well as the storage period, should be considered and implemented, preferably at the planning stage.

Water sprays rely on the impact between the fine particles...
and larger water droplets. The water encapsulates the dust particles, and causes them to agglomerate. Water, however, has a relatively high surface tension, limiting its ability to wet the dust particles, especially very fine respirable dust. Wetting agents can be used to reduce the surface tension (see below). The probability of impact can be increased by raising the relative velocity of the particle and water droplet, decreasing the size of the water droplet, or imparting a charge on the water droplet that is opposite to that of the dust (Coates, 1991; Schmitz, 1994).

The application of water to the coal surface with water cannons can be an effective method for suppressing dust emissions, especially for short-term stockpiles. For the water spray to reach a high stockpile and cover it completely, a high mast and high pressure cannon is required. Water cannons have been successfully employed at the Superior Midwest Energy Terminal, WI, USA. The terminal is adjacent to Lake Superior and is situated just 3.6 km from the business district of Superior (Ethen and Shusterich, 1994). It stockpiles subbituminous coal (PRB), delivered by train. Water sprayed at conveyor belt transfer points has limited dust emissions during the stacking process. However, the somewhat dry climate can, after a period of time, dry the surface of the stockpiles. On the east side of the stockyard, a series of water cannons were mounted 37 m above the ground on the shuttle conveyor tower (see Figure 37). With a 2.2 m/s prevailing wind, the effective radius of each cannon is 366 m. The west stockpiling area extends a further 152 m from the shuttle tower than the east stockpiling area. When strong westerly winds blow, portable cannons on the westernmost perimeter berm are utilised. The coal berm height averages about 18 m and, with a 2.2 m/s prevailing wind, the wetting radius is 183 m. One water cannon has been added on top of the radial yard coal stackout conveyor, and another on the reclaim conveyor number 3 to control dust emissions generated by routine vehicular traffic.

An on-site weather station is employed at the Los Angeles Export Terminal, CA, USA to automatically control the water cannons and high mast water misters, instead of relying on the subjective judgement of the operators. The wind direction and velocity, temperature and humidity are monitored. When the wind and weather conditions that promote dust develop, the weather station triggers the combination of cannons and misters calculated to off-set those conditions. The water used for dust control is captured and sent to two settling ponds for filtration and recycling (Harder, 1998).

Wetting agents

Water is scarce in many areas and its cost is increasing. To reduce the amount of water used, wetting agents (or surfactants) can be added. These chemicals reduce the surface tension of water, enabling finer water droplets to be produced, and increase the water’s ability to wet the hydrophobic coal. Wetting agents are typically added to the spray water at concentrations of 0.05% to 2% (Coates, 1991). They are generally longer lasting than water treatment alone, but can be more expensive. However, the number of treatment points on the way to the stockpile can often be reduced. The amount of water needed is decreased, with consequent cost savings.

There are a substantial number of wetting agents available. Their appropriateness for a particular coal dust can only be established by laboratory or field tests (see Section 7.3). These tests can determine the most cost-effective wetting agent and treatment concentration. The tests also need to establish their environmental acceptability, particularly in terms of biodegradability and aqueous toxicity (Schmitz, 1994).

Foams

Foam systems usually require less than 10% of the water added by wet suppression systems (Coates, 1991). Foam is

![Figure 37 Schematic of the water cannon dust suppression system](Ethen and Shusterich, 1994)
produced from water, air and a foaming agent; wetting and binding agents may also be present. Instead of water droplets, a large amount of foam microbubbles are produced. These burst on contact with the dust particles, creating numerous fine droplets which encapsulate and bind the particles together. The foam is best applied at transfer points during transport to the stockpile or during crushing. This is where the foam and coal can be well mixed to increase the suppressant effect.

Foams, if properly applied, are better at controlling the moisture content of coal than systems using water and wetting agents. A foam system, introduced at the W A Parish power plant, TX, USA, was effective in controlling dust emissions during transport of the friable subbituminous coal to the stockpile, while minimising water addition. It was a priority not to add unnecessary water to the coal. A complication was the high humidity and high rainfall at the site (Weiss, 1994).

**Agglomerating agents**

Agglomerating agents (also termed binders) act by binding the particles to each other or to larger particles. They include oils, oil products (such as asphalt), lignins, resins, and polymer-based products. Usually these agents are sprayed on to the coal at a transfer point on its way to the stockpile.

Some of the agents are applied as foams to improve cost-effectiveness. Field trials at two UK coal mines showed the importance of matching the dosage rates of the agglomerating agent to individual conditions in order to achieve effective dust control (King, 1997).

The main advantage of an agglomerating agent is its longevity. Effective dust control may be obtained over several transfer points on the way to the stockpile or for a significant period in the stockpile. An effective binder often reduces or eliminates the need for dust control during subsequent handling of the reclaimed coal (Coates, 1991). A disadvantage, though, is their cost. The cost of dust suppression chemicals (binders and surfactants) ranged from about US$0.03 per ton of subbituminous coal to over $0.06 per ton at the Sherburne County power plant, MS, USA. When the cost (including the effect on heat rate and increased boiler fan power) of the water used with the chemicals is included, the total cost of the dust suppression sprays was between 6 and 12 cents per ton of coal (Lehto and others, 1998).

Oil and oil products are particularly suitable for dust suppression when freezing problems occur. Unlike water, their use can increase, rather than reduce the heating value of the coal. However, if the oil becomes too concentrated in the coal, its lower flash point can cause fires when the coal enters the mill (Schmitz, 1994). Moreover, environmental problems could result if runoff from the stockpile contaminates the ground water. There are also questions about the environmental effects of some of the other agglomerating agents. For instance, polysulphides may be toxic to aquatic organisms if allowed to enter the surface water (Zinkan, 1998).

Agglomerating agents available that are claimed not to lead to environmental problems include the Dustcoat series (water-based emulsions and polymer emulsions) (Herrmann and Evensen, 1994) and Coalgard (an oil emulsion). Coalgard is biodegradable and has been utilised at the Kota power plant, India, to suppress both dust emissions and spontaneous combustion in stockpiles (see Section 6.3). The effective dosage rate depends on the level of coal fines. A typical dosage for 5% coal fines is 3 litres of Coalgard in aqueous spray for every 100 t of coal. About 5–10 litres of water is added per tonne of coal depending on the coal moisture content. The treatment can last up to 3 months, and can be reactivated with a light water spray (Handa, 1997).

**Sealants**

The stockpile surface can be sealed using crusting or coating agents (chemical binders), which are usually sprayed onto the pile with a water cannon. After drying, a water insoluble crust is formed. This reduces erosion from the wind and rain, water entry, and pile runoff. Their application also lessens oxidation which, in turn, reduces heating and spontaneous combustion. Depending on the agent used, the crust formed may be hard enough to be walked on without breaking, but it is not strong enough to support vehicles or equipment. Crusting agents are generally only suitable for long-term stockpiles because of the expense and inconvenience of reaplication (Coates, 1991).

The agent should produce a crust that is flexible enough to allow the pile to ‘breathe’ and thus avoid mechanical stresses. A range of crusting agents are available, but their suitability for a particular coal can only be assessed by laboratory tests or field trials (Schmitz, 1994). Stockpile characteristics that need to be considered include its age, moisture content, compaction and configuration. Polymer-based products (such as polyvinyl acetates, acrylics and latex), resins, lignosulphonate (a by-product of the wood pulp and paper industries), lignins, waste oils and bitumens have all been used as crustung agents. Drawbacks to lignins and waste oils are water solubility and heavy metal contamination, respectively (Coates, 1991). Novel approaches include the application of grass or fly ash to the pile. The roots of the grass can bind the surface, inhibiting dust emission, and improve the visual appearance of the pile. Grass has been planted, for example, on stockpiles at the Avedstre (Denmark) and Dünrohr (Austria) power plants. The application of fly ash (with a CaO content >20%) and water forms a cement-like coating on the surface (Coates, 1991).

Depending on the agent, a crust may remain intact for several months. For instance, an application of Soil-Sement (an aqueous acrylic vinyl acetate polymer emulsion) on a stockpile at the Rockport power plant, IN, USA, was effective for 6–9 months (Chakraborti, 1995). The frequency of reaplication depends upon the agent and the weather conditions. Piles should be regularly inspected to check for damage to the crust. Isolated weak spots or cracks can then be patched with a reaplication of the crustung agent. This helps to extend reaplication times and reduce the overall treatment costs. Costs per application are typically lower than for agglomerating agents since only the surface, and not the whole bulk, is treated. However, once the surface is broken by reclamtion, retreatment is necessary to maintain dust control.
Dust emissions

A type of pile management, which is termed the ‘crater concept’ by Hatt (1997), involves coating the sides of the pile with a crusting agent such as latex. The outside of the pile is inactive and the main activity of stacking and reclaiming occurs within the pile walls. In some cases it may be more practicable to work in a horseshoe shape crater where one wall has been removed. In both cases, the wall around the active portion serves as a wind break to minimise dust emissions from the pile.

Enclosures

Complete or partial enclosure of piles can limit dust formation. In addition, covering the pile keeps the coal dry, restricts oxidation, prevents the generation of leachates and runoff due to precipitation, protects personnel and equipment from severe weather conditions, and reduces noise pollution. At new power plants, the trend is for coal stockpiles to be covered, but this does reduce pile capacity (Walker, 1999b).

Circular stockpiles are generally cheaper to cover than longitudinal piles (Gerstel and others, 1998; Walker, 1999b). Scraper reclaimers are typically utilised inside the structure since boom-mounted bucket-wheel reclaimers are too large. Figure 38 illustrates the stacking and reclaiming system installed within the dome-covered circular stockpile at the Mai-Liao power plant in Taiwan. The system provides a storage capacity for 180,000 t of coal (equivalent to a ship load) and has a diameter of 120 m. The roof is made of aluminium attached to a concrete retaining wall (Bulk Solids Handling, 1998). Covers have also been constructed in concrete, air-supported fabrics and galvanised steel. The choice of material partly depends on the span and access requirements.

In any enclosure, attention must be paid to the requirements for ventilation (dusts and methane) and for fire and explosion protection. At the Piñon Pine power plant, NV, USA, space was left to enable a truck to drive around the interior perimeter of the dome with a fire hose when hot spots occur (Weed and Lopez, 1995). At sites where moveable coal handling equipment is utilised, ample openings are needed to allow access without potential damage to the structure. In these cases, aerodynamic studies should be carried out to insure that fugitive dust emissions are acceptably small.

7.3 Monitoring and test methods

Monitoring dust levels around a stockyard can identify problem areas and can be employed to determine the effectiveness of dust control practices. Accurate measurements may also be required to confirm that ambient air quality standards and regulations are being met. Instruments are available for measuring either dust concentration or dust deposition. However, particulate measurements are notoriously difficult to standardise, and measurements taken from one instrument may well produce different values than those determined in another type of instrument. This is partly because instruments are often designed for a specific particle size range, such as respirable dusts (PM$_{2.5}$ and PM$_{10}$) or coarser particle sizes. Information on the most common measuring devices, including their advantages and disadvantages, can be found in the IEA Coal Research reports by Schmitz (1994) and Sloss (1998).

Successful monitoring of coal dust requires adequate measurement points, orientated towards the prevailing wind direction. It also requires information about meteorological conditions, and the coal handling operations. Thus separate instruments for measuring the meteorological conditions, such as the wind speed, temperature, humidity and rainfall, may be needed.

Figure 38 Dome-covered circular storage system (Bulk Solids Handling, 1998)
By knowing the dustiness potential of the coal, appropriate control measures can be implemented. The test method must be appropriate to the particular dust problem. Dust generated from a falling stream of coal within an enclosed chamber provides a measure of the dust arising during stockpile stacking. Alternatively, the dust created in a rotating drum is determined. Wind tunnels can be used to measure the dust generated by the action of wind on the stockpile. If temperature and humidity control, as well as wind speed, are included, then the wind tunnel can simulate the effects of wetting and rewetting. Laboratory-based wind tunnels and a portable version to allow field measurements have been developed (Schmitz, 1994).

Since the time and cost of comparative field evaluation of dust control measures can be prohibitive, laboratory testing can be used to assess whether a particular solution is effective. For instance, King (1997) evaluated the effectiveness of a sealant (crusting agent) and two agglomerating agents in a laboratory-based wind tunnel. The system allowed the optimisation of the mixture and application rates to be determined.

One disadvantage with all the test methods is that they do not simulate the real conditions occurring at the stockpiles. Computer packages have been developed to predict dust emissions from stockpiles and their dispersion patterns (Parrett, 1992), and the effectiveness of dust control measures. For example Fastflo, developed by CSIRO in Australia, has been used to evaluate the effectiveness of different fence layouts to control dust emissions (Chan and Zhu, 1995).

### 7.4 Comments

Increasingly stringent air pollution regulations are encouraging stockyard operators to incorporate dust prevention and control measures in their operations. There are a range of methods available to achieve this, but the methods vary widely in both their cost and effectiveness. The optimal solution will be site-specific. The cheapest solution may not necessarily be the most cost-effective. Particular sites may not be allowed to operate at all without specific dust control measures. In other cases an apparently low cost solution may be offset by increased costs elsewhere; for instance if the solution reduces the heating value of the coal or affects plant efficiency. Requirements for dust control can change if the coal source changes. With end users looking for cheaper coals, some flexibility, where possible, should be built into the system. Knowing the likely dustiness of the new coal in advance will allow the stockyard operators to take the appropriate measures.

These days, water pollution from stockyards is a subject of increasing concern to stockyard operators. This is the subject of the next chapter, along with flowslides (which can be caused by heavy rainfall and poor drainage).
### 8 Runoff and flowslides

Water management is becoming a sensitive issue in countries where water is in short supply, and because of environmental concerns. Increasingly stringent pollution regulations are encouraging stockyard operators to incorporate systems for handling runoff from stockpiles, as well as storm, dust control and washdown water. The rising cost of water treatment and disposal of the waste products is an incentive for operators to try and achieve as close to zero discharge as possible. The collected water can then be recycled for use at the site. After briefly discussing the composition of stockpile runoff, the chapter then examines its collection and treatment. Legislation on waste water discharge for various countries is covered in the IEA Coal Research report by Adams and Fernando (1998).

Heavy rainfall and poor stockpile drainage can lead to flowslides which can pose a danger to personnel and can damage equipment. Thus it is important to assess the probability of a flowslide occurring so that appropriate precautions can be adopted to minimise the hazard. The causes and prevention of flowslides is discussed in the second part of this chapter.

#### 8.1 Runoff composition

Coal pile runoff may pollute the ground water and soil. It is produced when water percolates through the pile or runs off the surface. Rain, snow, spraying for dust control, piles left to drain in order to meet the moisture specification, and even underground streams that surface under the pile all generate runoff. The amount of water that penetrates the pile is dependent on its construction and management, while the amount of runoff depends primarily on rainfall and, to a lesser extent, the permeability of the soil. If the rainfall is very heavy, large quantities of fines can be washed out, and gullies can be created that require treatment in long-term stockpiles to prevent dust emissions and spontaneous combustion. Furthermore, heavy rainfall and poor drainage can lead to flowslides (see Section 8.4).

The composition of the coal pile runoff is influenced by:
- the composition and size distribution of the coal;
- the drainage patterns in the pile. These affect the contact time between the coal and the infiltrating water; and
- the amount of water that percolates through the pile.

Spontaneous heating may also influence the composition of the percolating water; for example, because of pH decrease due to pyrite oxidation (Schmal, 1989). Generally, the effluent is characterised by high levels of suspended solids, a variable pH and heavy metals content. Table 7 shows the range of a number of characteristics of runoff from US coal stockpiles.

Leachate composition can vary widely, as shown in this table. Acidic leachates, for example, tend to contain high levels of many metals such as iron, manganese, aluminium, zinc and cadmium; acidic leachates result from the oxidation of pyrite. The acidity of the runoff also depends on the availability of neutralising materials in the coal. Bituminous coals tend to generate runoff that is usually acidic. Subbituminous coals tend to produce neutral to alkaline runoff. Leachate from high sulphur coal typically has a low pH and high concentrations of sulphate, iron and soluble salts. Coals containing high levels of chloride can give rise to saline waters. Runoff from piles treated with dust suppressants (see Section 7.2) may contain additional chemicals. More information on the composition of the runoff can be found in the IEA Coal Research report by Adams and Fernando (1998).

Although coal pile leachates have been characterised extensively, there is little information on their potential to contaminate ground water. Work carried out by Zelmanowitz and others (1995) indicated that coal piles stored directly on soil surfaces may pose a risk, particularly where leachates are acidic and coarse textured soils exist.

#### 8.2 Runoff collection

Increasingly stringent water pollution regulations are...
encouraging the collection of runoff from stockpiles. The water collected can either be re-used (for example, for dust suppression) or treated prior to discharge.

The siting of coal stockpiles can limit contamination caused by runoff. According to Stultz and Kitto (1992), a potential site should be evaluated to include:

- analysis of the soil characteristics;
- bedrock structure;
- local drainage patterns;
- potential for flooding; and
- climatic data, such as the precipitation records.

Protection from tidal action or salt water spray may be needed in coastal areas. The potential effects of water runoff must be considered. Site preparation includes grading for drainage, compacting the soil and providing for collection of site drainage. Drainage ditches are usually constructed around the perimeter of the piles (see Figure 39). Drains beneath a pile should be avoided, if possible, since they may produce an air current up through the pile and thus assist spontaneous combustion. The ground for the piles should be slightly sloped to provide natural drainage to the drainage ditches and be sloped away from the reclaiming area (Chakraborti, 1995). In addition, the collection system ought to prevent the runoff from draining into clean areas. The drainage system must be designed to collect the runoff and rain water from the entire stockpile area and be able to cope with storm water.

Installing an impervious liner, such as compacted clay, under the stockpile area can help in collecting the runoff and preventing contamination of ground water. In Israel, a plastic liner was installed at the Ashdod coal terminal (Schneider and Grossman, 1997). A protective layer, such as compacted sand, is usually added to prevent damage to the membrane layer. Fly ash and bottom ash, mixed with an activator, has been successfully used to protect the reinforced polypropylene membrane layer at the Morgantown Generating Station, MD, USA. Utilising the on-site stockpiles of fly ash and bottom ash that was unsuitable for use as a concrete mix material enabled significant cost savings to be made. As well as producing direct cost saving, power plant operation and maintenance expenses were reduced (Muncy and Miller, 1997).

The stockpile area at the Los Angeles Export Terminal, CA, USA, is built on an hydraulic fill of sand and silt (Harder, 1998). The high water table required placing the stockpile reclaim tunnels and conveyors close to the surface and laying an impermeable membrane water barrier under the stockpile area. Protecting the membrane is a 0.6 m topping of cement-treated base, overlain by a 0.6 m buffer of rejected waste coal. When stockpiles are low, a bulldozer blade could easily slice through the cement-treated base and thereby contaminate the shipped coal. Damaging the membrane itself would threaten ground water contamination. A global positioning system helps the bulldozer operators avoid this and other damage to vulnerable obstacles such as the reclaim shafts.

### 8.3 Runoff treatment

Runoff is transported to settling ponds to maximise the recovery of coal fines. These ponds may be located close to the corners of the stockpile area and away from the stacking and reclaiming activities (see Figure 39). Chakraborti (1995)

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**Figure 39** Runoff collection system at the Rockport power plant, IN, USA (Chakraborti, 1995)
requires building a shallower pre-settling pond ahead of the settling pond to minimise the amount of coal fines collecting within it. This reduces the frequent need to clean the settling ponds. A high proportion of the fines should be recovered from these primary ponds before the residue is pumped to secondary treatment, if necessary, prior to disposal or reuse. The recovered material can be returned to the stockpile provided it has not been degraded by contact with other wastes.

Different coals produce effluents with different characteristics. Some effluents may require additives to remove the suspended solids and to adjust the pH. Raising the pH precipitates soluble heavy metals (White, 1993). The runoff from the PRB subbituminous coal stockpile area at the St Clair power plant, MI, USA, contained very finely divided coal with a low apparent density. Most of the solids were small enough to pass through a filter and did not settle out. The runoff from the second stockpile area, where both PRB and eastern bituminous coal were stored, had entirely different characteristics. Effluent from the bituminous coal contained red sludge (an iron compound), which acted like a natural coagulant causing the fines to settle out. Tests showed that adding alum to the runoff from the first (PRB coal only) stockpile area would remove the fines. Alum is relatively non-toxic and cheap; the chemical treatment costs were less than US$50 per million gallons (Seaton, 1997). At the Bolsover Works, UK (a smokeless fuel plant), a cationic polymer flocculant is added to the runoff to precipitate the very fine low density solids (Duce, 1995).

Requirements for runoff treatment can change if the coal source changes. The self-treating qualities of the runoff from the stockpile area storing both PRB and bituminous coals at the St Clair power plant were lost when the bituminous coal source changed. The runoff no longer had sufficient iron to coagulate the solids in the settling ponds (Seaton, 1997).

In some cases filter presses and other mechanical equipment may be required. At the Port of Bristol, UK, the effluent from the settling ponds is pumped to a thickener. After monitoring the pH and automatically adding acid/alkali solutions to maintain the neutrality, flocculating polymers are added. The thickener underflow is then dewatered in a multi-roll filter. The filter cake is disposed of off-site (Reading, 1993).

Chemical processes for treating waste water can be expensive and may result in large quantities of inorganic sludge materials for disposal. Bioremediation techniques have the potential to generate biodegradable by-products and may provide an opportunity for metal recovery. Bioremediation of acidic stockpile runoff has been successfully demonstrated (Groudev, 1997; Ibeanusi and Wilde, 1998). The latter authors investigated the batch treatment of acidic runoff at a power plant near Aiken, SC, USA. Treatment in tanks containing a mixed culture of specific strains of *Bacillus* and *Pseudomonas* with growth nutrients elevated the pH from <2 to >7, and lowered the heavy metal concentration to within or below the US EPA drinking water standards (see Table 8). Conversely, Rastogi (1994) describes how the addition of bactericide pellets to the base of coal stockpiles controlled runoff acidification.

| Table 8 Metal concentrations in treated and untreated runoff in relation to EPA standards (Ibeanusi and Wilde, 1998) |
| --- | --- | --- | --- |
| Metal, mg/l | EPA standards | Treated runoff | Untreated runoff |
| Aluminium | None | 0.50±0.20 | 492.8±5.01 |
| Arsenic | 0.05 | 0.03±0.10 | 7.4±0.13 |
| Cadmium | 0.01 | 0.0 | 1.6±0.01 |
| Chromium | 0.05 | 0.0 | 3.0±0.00 |
| Copper | 1.0 | 0.0 | 1.6±0.01 |
| Iron | 0.3 | 1.0±0.01 | 486±0.18 |
| Lead | 0.5 | 0.2±0.01 | 17.2±0.15 |
| Nickel | 0.1 | 0.2±0.01 | 1.6±0.01 |
| Selenium | 0.01 | 0.0±0.00 | 4.8±0.07 |
| Zinc | 5.0 | 0.03±0.01 | 21.6±0.21 |

The choice of treatment system will, of course, depend on economics, the governing factors being the costs of primary and secondary treatment and off-site disposal of wastes that cannot be returned to the stockpile. The cost of the secondary treatment is directly affected by the effluent disposal regulations. The acceptable level of contamination for recycled water may not be the same as for water disposed as an effluent. The treatment facility can then be designed to meet both these water quality criteria (White, 1993). In addition, the capacity of the treatment system should be designed to cope with storm water.

### 8.4 Flowslides and their causes

Stockpiles of coal may be prone to instability resulting in slope failure. Wetting of the surface layer can result in erosion gullies and shallow slipping with small flows depositing saturated coal at the toe of the slope (see Figure 40(a)). However, the hazards involved are minimal compared with those from deep seated sliding that result in a major flowslide, illustrated in Figure 40(b). Flowslides ranging in size up to 10,000 t and slipping and flowing up to 60 m in 10 to 15 seconds have occurred (Eckersley, 1990). The slipped material adopts a flat final slope, and may expose a steep scarp which subsequently slumps back to the angle of repose. Consequences of failure have included increases in operating costs associated with cleanup, loss of production if debris clogs conveyor lines or stacker/reclaimer tracks, damage to coal handling equipment, and danger to personnel, particularly those on the ground. In addition, coals showing a tendency to stockpile instability are at a potential marketing disadvantage when in competition with coals that do not show the same behaviour.

A survey of stockpile flowslides indicated that the most significant conditions leading to collapse (Eckersley, 1990; Quinn and Partridge, 1995) are:

- saturation of the stockpile base due to heavy rainfall infiltration;
- redistribution of moisture within the coal at placement;
- loose stacking of the coal; and
- particle size distribution.
The survey also showed that the failures generally occurred in relatively fresh coal, that is coal placed within the previous two weeks. Significant height increases at a given operation can substantially increase the hazard potential unless appropriate precautions are taken (Eckersley, 1990). Although the survey found that the flowslides were restricted to coking coal, some thermal coal piles may have the characteristics listed above rendering them prone to instability. Fretwell (1995) reports flowslides occurring at the Lamma power plant, Hong Kong.

Saturation of stockpiles results from the percolation of moisture to the base, and/or the infiltration from heavy rain (see Figure 41). The water is trapped above the low permeability subgrade. As the water table within the stockpile rises, the potential for a significant and deep seated slip increases. The height of the water table is particularly sensitive to the drainable moisture content, which is influenced by the subgrade permeability and gradient, and the coal characteristics. The permeability and moisture retention characteristics of the coal are influenced by the particle size distribution and, for unwashed coals, the clay mineral content (see Section 5.2). Studies carried out by Eckersley (1994a) found that there is a threshold moisture content below which no saturated zone developed. This value was between 8–10% for the coking coals studied. Although there is an association between heavy rainfall and flowslides, rain is not necessarily a prerequisite. Coals stockpiled while relatively wet have slid (Eckersley, 1990). For instance, the coals may have become wet whilst being transported in open-air railway cars, or are being stockpiled to allow drainage of excess moisture.

Loosely stacked coal is prone to structural instability. Saturation results in significant loss of volume and therefore significant stress redistribution towards the stockpile toe may occur (Eckersley, 1990). Flowslides have arisen where it was necessary to extend stockpile capacity beyond the range of the stacker by pushing the coal over the edge of the pile.

Fine coal particles within the pile can migrate under the influence of water flow, particularly in loosely stacked piles. These can concentrate in relatively impervious layers, resulting in local water saturation and reduction of shear strength (Quinn and Partridge, 1995). These effects are most noticeable in materials with higher fines levels and lacking intermediate size particles (1–10 mm). Generally, coals with a higher fines content have a lower permeability, retain more water, and are less able to absorb movement before failure. Eckersley (1990) suggests a 10% coal passing size ($d_{10}$) falling within the range 0.07–0.3 mm can indicate susceptibility to flowslide. Accumulation near the toe region of very fine particles washed out of the pile is likely to impede drainage and thereby worsen the risk of deep seated failure. The coal fines content is usually limited at power plants due to their poor handleability; this may be one reason why flowslides are less common in thermal coal piles.
The total moisture content and moisture distribution throughout the stockpile are of practical interest, not only for instability problems but because of the associated handling problems (see Section 5.2). Moisture movement also influences the amount and characteristics of the runoff from the pile (see Section 8.1). Moisture movement in stockpiles has been investigated by Eckersley (1994a,b,c) in both the laboratory and in an instrumented 15,000 t coking coal stockpile. He found that the initial total moisture content needed to exceed a threshold value (8–10%) for significant moisture redistribution to occur. This threshold value can be determined in a laboratory column drainage test. Moisture movement was analysed using the THEWET numerical model. The analyses showed that simple gravity drainage can be used to effect significant moisture content reduction for coal initially wetter than the threshold value and that the analyses could be used to predict the period of stockpiling required to meet the contract moisture value. If lateral seepage is impeded (for example by not removing the remnants of the previous stockpile before placement of new coal), then the chances of water pressures becoming sufficiently high for flowsliding are increased.

8.5 Prevention and control of flowslides

Strategies for reducing flowslide hazards include modifying the stacking method and the overall stockpile installation. However, operational and other factors may preclude major changes to existing operations. For instance, limiting the amount of coal fines may not be an option. As a general safety precaution, pedestrians and mobile equipment should be excluded from stockpiles thought to be susceptible to flowslides or whose coal characteristics have been recently modified, and especially for the week following heavy rain or the placement of particularly wet coal (Eckersley, 1990). It is also recommended that personnel in the vicinity should leave the safety of their vehicles or loaders only when at a safe distance from the pile.

The height of a stockpile is one factor influencing the flowslide potential. After prolonged heavy rain, the high and uncompacted stockpile at the Lamma power plant, Hong Kong, has slid over the retaining walls and on to the stacker/reclaimer feed conveyor rendering it inoperative (Fretwell, 1995). The height of the stockpile is therefore minimised in the rainy season but this is limited by the busy shipping schedules. When there is a combination of high stock levels and heavy rain, the access roads are closed to minimise the risk to personnel. If the coal does slide it is cleaned up and put back on the pile. Additional storage areas are being sought to overcome this problem.

Reclaiming coal from the toe of the pile by front-end loaders is inherently hazardous for coal prone to sliding and so is best avoided (Eckersley, 1990). Mechanical removal at the base of the pile can increase the natural angle of repose. While the coal is wet the sides are fairly stable, but as the coal dries out, the adhesion of the particles becomes weaker and the unstable sides can collapse.

Controlling the moisture content of the pile can decrease the potential for flowsliding. Achieving the proper combination of particle size, porosity, permeability and field moisture capacity allows the infiltrating water to quickly flow down to the saturated zone and be discharged from the pile (Nolan, Davis and Associates, 1991). However, this must be balanced against creating too permeable a structure which will allow diffusion of oxygen into the pile with consequent detrimental effects (see Chapters 5 and 6), and enhancement of acidic runoff (see Section 8.1).

Compacting the coal and building the pile with proper drainage slopes can limit water ingress and facilitate surface runoff. Compaction also increases the effective friction and reduces the tendency for the saturated coal to suddenly lose strength and flow. Where compaction is not a practical option and the coal is prone to flowsliding, it may be worth compacting selected areas to bias any instability away from critical features such as conveyors (Eckersley, 1990). However, the type of coal stockpiled affects the ability to reach certain compaction rates (see Section 6.3).

Building the stockpile with a more convex longitudinal profile and no flat topped centre can facilitate runoff. A slightly concave cross-sectional profile can direct the surface runoff away from the uncompacted side slopes (Nolan, Davis and Associates, 1991). For compacted piles, the top can be slightly crowned to permit even runoff.

Sealing the stockpile may be useful in high rainfall areas (see Section 7.2), but is not practicable in working stockpiles. Although enclosing the pile keeps the coal dry (see Section 7.2), it limits the size of the pile and can be expensive. This is probably not an option at, for example, terminals that are handling a number of different coals and blending them to customer specification.

Trials have indicated that slotted drain pipes installed in the stockpile base can accelerate the removal of water and thus reduce the height of the saturated zone and pore water pressures (Eckersley, 1990, 1994b). Drainage of the stockpile toe is particularly beneficial in preventing initiation of minor instabilities that can develop into overall retrogressive failure. It is important that direct movement of vehicles and handling plant on coal just above the drains is avoided, since crushing of coal beneath the wheels and tracks results in a large reduction in permeability. Thus the effective operation of stockpile drains may be precluded where coal is loaded out by front-end loaders and trucks. An alternative approach is to spread a layer of coarse coal to form the stockpile base and act as a drainage layer. Drains may be beneficial in stockpiles where the moisture content of coal is being reduced by gravity drainage, but care is required to avoid spontaneous combustion in coals prone to this process (see Chapter 6).
Good stockpile management is an important part of the coal supply chain from mine to customer. Virtually all coal producers and consumers make use of stockpiles at their facilities. These days, more coal is being produced and traded internationally, providing a wider choice of sources to the consumers. Coal producers are having to compete in a tough market with competition driving prices down. All this has forced a greater focus on stockpile management. Issues such as the optimum stockpile size, stockpile turnover periods and timely stock management have all assumed greater significance. Past practices may no longer be sufficient to cope with the needs of today’s coal industry.

The value of coal stored in stockpiles can form a significant part of the end user's costs. For instance, coal represents 60–80% of a power plant’s operating costs. Capital tied up in the stockpiles gives no return on investment and one way to reduce costs is to optimise coal inventories. However, there is a fine balance between security of supply and the cost of the stored coal. The optimum inventory will be different for different sites because each location is governed by a unique set of factors. For example, power plants that import their coal need to carry larger inventories than mine-mouth power plants. There may also be safety or environmental issues. The amount of brown coal stockpiled at the mine-mouth power plants in Victoria, Australia, is kept to a minimum because of its liability to spontaneous combustion. Responsible auditing is required to reconcile the actual amount of coal in the stockpiles to the book inventory. By knowing more precisely how many tonnes of coal are present in a stockpile, one can write off coal used more quickly and/or reduce inventories that are too large.

Coal consumers are becoming increasing stringent in their demands to both quality and price. However, taking advantage of cheaper coals available on the market often involves buying a coal of poorer quality. This means that the stockyard operator has to solve any coal quality problems that may occur. Quality control may involve blending coals either within the pile, or after the coal has been reclaimed. Better blending is certainly becoming a key factor in optimising power plant performance. Most of the improvements at power plants to achieve cost savings have involved refinements to the design and operation of the plants. It is only now that attention is being paid to the savings that can be made from improvements in coal handling, including stockpile management. Achieving the correct coking coal blend is particularly important at steel works. Transhipment facilities, such as the EMO terminal in the Netherlands, are beginning to offer blending services in addition to straight transhipment. These therefore have an advantage over other transhipment facilities that cannot offer this service since the end user avoids the necessity for blending facilities, with all the costs implied, at their site.

The method and equipment used for stacking and reclaiming stockpiles affects the performance of the facility and hence its effectiveness. The available equipment is also a factor in whether blending could be introduced at a site. Systems that only offer the ability to stack and reclaim have their uses, especially where coal quality is consistent. At sites where blending is required, the windrow and chevron-type stacking systems provide a better blending efficiency for longitudinal piles. Travelling bridge and portal scraper reclaimers, for instance, give a better blending efficiency than bucket-wheel stacker/reclaimers. Where it is important to maximise throughput and where blending is not an issue (for example at import/export terminals), higher capacity bucket-wheel stacker/reclaimers are advantageous. As with any operation, it is important to match the equipment to the requirements of the facility. Failure to conform with coal quality specifications results in financial penalties and may even lead to rejection of consignments. Good management involves maximising the utilisation of the equipment and minimising rehandling operations, whilst still meeting specifications.

Stockyards operating a large number of stockpiles are complex operations requiring integrated information management and control systems. Knowledge of the location and quality of the different coal types and grades at any moment of time is a fundamental requirement of stock management. There are a number of systems available that are capable of keeping track of the coal quality and tonnage in the stockpiles and while the coal is being moved. These systems may incorporate a computer module for determining the cheapest blend that will meet the required specification. Computerised control systems have been installed on some stacking and reclaiming equipment leading to automated operation; but this may only be cost-effective at facilities handling large tonnages of coal.

With coal quality management coming under mounting pressure, good sampling and analysis procedures are essential. Sampling procedures must be accurate and precise to ensure that a representative sample is provided for the subsequent analysis. If the initial sample is not properly taken than the resultant analysis will be meaningless. Sampling a stockpile in situ presents difficulties in obtaining a representative sample since sampling from the middle of large piles can be difficult. For this and other reasons, sampling is best carried out, where practical, while the coal is being transported on belt conveyors. Mechanical sampling systems are generally preferred over manual systems; but they can be expensive and so will not be cost-effective for facilities handling small tonnages. In addition, they cannot be applied to all situations. The sampling costs are strongly influenced by the number of samples required, and the extent of sub-sampling and sample preparation carried out. Thus the sampling system must be designed to meet the required situation. Some quite simple systems can be effective and inexpensive. There is the question of whether the milligram or gram samples used in the standard analysis procedures or in many bench-scale tests can provide a truly representative sample of the hundreds of tonnes of coal in a stockpile or
Real-time information on coal quality can help operators to manage stockpiles more efficiently. On-line analysers can show the variations in certain coal quality parameters (such as ash, sulphur and moisture contents) as they are occurring. However, they can be expensive and their cost-effectiveness is dependent on the site and application. Few, if any, on-line analysers are installed at coking plants. Certainly, on-line analysis is more difficult to undertake where the coal supply comes from a number of different sources because of calibration problems. Despite frequent disappointments and questions about their accuracy, on-line analysers are gradually approaching the levels of precision and reliability needed for confident usage.

Good stockpile management also entails preserving the coal quality within the pile, that is, preventing oxidation and weathering. Most coals, particularly the lower rank coals, are susceptible to oxidation and weathering in open-air piles, leading to economic loss. The extent of the deterioration depends on the properties of the coal, the ambient conditions, the construction and management of the pile, and the residence time. Oxidation and weathering of coal is of more concern in longer term stockpiles than short-term ‘working’ piles. Sampling and analysis of the coal after it is reclaimed from longer term piles is therefore recommended. Knowledge of the reactivity of the coal to oxidation and the rate of deterioration can help to determine cost-effective stockpiling times. However, methods for predicting the behaviour of coal are hindered by a lack of understanding of the fundamental chemistry of coal oxidation, and the interactions of the many and complex parameters affecting the oxidation and weathering reactions. More research is required in these areas.

Stockpiles should be managed to meet health, safety and environmental obligations. This includes managing stockpiles to prevent spontaneous combustion. Published information on stockpile fires is lacking. There is thus a need for more open discussion, a move that would enhance safety and help prevent future economic losses by publicising potential problems before they can recur. Since stockpile fires are difficult to extinguish, monitoring to detect any self-heating in its early stages is recommended. The cost and effort involved in monitoring is generally small in relation to the value of the coal within the stockpile. Where there is an indication that self-heating is under way, the hot coal should be removed and cooled. A rapid response in the event of a fire will prevent it from spreading.

Coals that are susceptible to self-heating should be identified well in advance so that measures can be taken to ensure their safe storage. Bench-scale tests, such as crossing point temperature measurements, provide a relative ranking of the self-heating propensity of coals. Although they have been criticised, they do have the benefit of being simple to use. A major limitation with models for predicting spontaneous combustion is their lack of validation on large-scale stockpiles. A full description of the chemical and physical processes leading to self-heating is complex and is still not fully understood. Thus a number of assumptions have had to be made when formulating the models. Field trials have been used to compare actual events with modelling predictions, with varied success. The trials have often employed small stockpiles. The effects of scaling up to commercial-sized stockpiles, especially the effect on convection and other heat and mass transfer processes in the models, needs to be investigated. Validation of the models in field trials is both an expensive and difficult experimental task, but essential if the models are to be utilised with any confidence.

It is also important to assess the probability of slumping and flowslides occurring and their possible consequences, both to personnel and equipment. Appropriate safety precautions can then be adopted to minimise the hazards. Flowslides are much more common in coking coal stockpiles.

Techniques to minimise oxidation and spontaneous combustion propensity, and help prevent flowslides are well-established. In general terms, measures preventing oxidation and spontaneous combustion involve restricting the entry of oxygen or, in the case of spontaneous combustion, providing adequate ventilation to remove the generated heat. Building the stockpile to facilitate surface runoff and inhibit water ingress reduces the potential for flowsliding. The measures chosen will, of course, be site-specific and are dependent on the purpose of the pile. Sealing the piles, for example, is only cost-effective for long-term stockpiles, while enclosing them is only appropriate for short-term working piles.

Increasingly stringent pollution regulations are encouraging the incorporation of dust and runoff prevention and control measures in stockyards. The cost of water treatment and disposal of the waste products is increasing. Thus there is an incentive for operators to try to achieve as close to zero discharge as possible. Wherever it is practical, the collected water should be recycled for use at the site, for example, for dust control.

There are a range of methods available for dust control and prevention; these vary widely in both their cost and effectiveness. The cheapest solution may not necessarily be the most cost-effective; an apparently low cost solution may be offset by increased costs elsewhere, for instance if the solution reduces the heating value of the coal or affects plant efficiency. Changing the coal source can change requirements of the new coal and its leachate characteristics in advance with varied success. The trials have often employed small stockpiles. The effects of scaling up to commercial-sized stockpiles, especially the effect on convection and other heat and mass transfer processes in the models, needs to be investigated. Validation of the models in field trials is both an expensive and difficult experimental task, but essential if the models are to be utilised with any confidence.

Noise from mobile equipment can be one of the most difficult environmental problems to solve. The use of electrically powered equipment should be encouraged since these are quieter than diesel powered equipment. Fitting diesel engines with muffling devices and enclosing belt conveyors will reduce noise levels. Berms (earth embankments) with trees and vegetation surrounding the
stockyard can have aesthetic and noise abatement benefits, as well as reducing dust emissions from the stockyard.

The underlying purpose of stockpiles is to meet the need to store sufficient quantities of coal of an appropriate quality to meet the demands of the next stage in the process, be it transhipment, coal cleaning, combustion or coking, and at the lowest possible cost. Experience has shown that with good stockpile design and management, most coals can be safely stored in an environmentally acceptable way.
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Management of coal stockpiles


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