Losses in the coal supply chain

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Abstract

This report examines the way coal can change as it passes along the coal chain. A great deal of the change is intended, through separation and sizing, to ensure the coal being mined matches the specification demanded by the customer. This report attempts to identify these changes and presents some of the issues faced by the coal supplier and user. Much of the change leads to a loss of mass in the coal. Some of the coal is left in the ground (intentionally and unintentionally), while elsewhere, full extraction might occur with the addition of non-coal materials from the surrounding rocks. In both cases, the mined coal often requires further processing.

Coal processing by separation at preparation plants refines coal further and is where most of the mass loss occurs. Value is added by reducing ash content and improving heating value, thus providing a much more saleable product for the market. As soon as the coal leaves the mine, mass loss can occur either through natural deterioration of the fuel, through spillage or dust, or in extreme cases theft. In all cases measuring the amount of coal as it passes through the supply chain is required to verify that the coal reaching the consumer is of satisfactory quality and quantity. This can be done crudely by measuring stockpiles, to more sophisticated weighing systems at various points along the supply chain, and even measuring the volume held in a ship. Measurement is subject to error which must be minimised. Biomass needs to be processed in much the same way as coal, such as removing mineral matter and taking care in avoiding contamination.

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Acronyms and abbreviations

$/t	US dollars per metric tonne
ACARP	Australian Coal Association Research Programme
ADS	air density separation
CHP	combined heat and power, also known as cogeneration
CIMFR	Central Institute of Mining and Fuel Research
CFRI	Central fuel Research Institute
CIAB	Coal Industry Advisory Board
CIL	Coal India Limited
crore	Indian quantity term for 10 million (equivalent to 100 lakhs)
CV	calorific value
DMC	dense medium cyclone
DPR	Democratic People's Republic (of Korea)
DUET	duel energy transmission
FGD	flue gas desulpurisation
FOR	free on rail
GJ/t	gigajoules per tonne
GPS	global positioning system
Gt	gigatonnes
HGI	Hardgrove Grindability Index
HHV	higher heating value
IEA	International Energy Agency
IEA CCC	IEA Clean Coal Centre
kcal/kg	kilocalories per kilogramme
kt	kilotonnes
M	moisture content as a %
MJ/kg	megajoules per kilogramme
Mt	million metric tonnes
Mtce	million tonnes of oil equivalent
Mtoe	million tonnes of oil equivalent
NOx	nitrogen oxide
NSRES	Norfolk Southern Rail Emission Study
OIML	Organisation Internationale de Metrologie Legale
PC	pulverised coal
PGNAA	prompt gamma-ray neutron activation analysis
RD	relative density
ROM	run-of-mine, also refers to raw coal
rpm	revolutions per minute
Rs	rupees
NSW	New South Wales
SCLCI	Swiss Centre for Life Cycle Inventories
st	short tonne
t	metric tonne
t/d	tonnes per day
t/y	tonnes per year
UK	United Kingdom (of Great Britain and Northern Ireland)
UN ECE	United Nations Economic Commission for Europe
USA	United States of America (also US)
W	coal mass
WCA	World Coal Association

Contents

1 Introduction

According to IEA (2012) data, global coal production has almost doubled since the 1980s, from less than 4 Gt in the 1980s to 7.6 Gt in 2011 (IEA, 2012). This growth has come from the rise in both thermal coal for power generation and coking coal (for metallurgical coke production). International trade in thermal coals has also maintained high growth, and accounts for an average 17% of global supplies. In 2011, 6 Gt/y of the 7.6 Gt/y of total production was used for power (and some steam/heat) generation (IEA, 2012). Most of this steam (thermal) coal is of bituminous or subbituminous grade. Just 0.9 Gt/y was brown coal (lignite). Added to this thermal coal production was 0.9 Gt/y of coking coal.

The supply chain for both steam and coking coal are broadly similar but, where some steam coals are used without a great deal of preparation before being delivered to the end-user, coking coals almost always undergo various stages of cleaning and separation due to the tighter specifications expected of the end-user. In some countries, high quality coking (and steam) coal reserves have been exhausted, or are more difficult to access, and so an increasing proportion of supplies are imported. As such, the coal supply chain is lengthening.

Losses might occur in terms of physical loss of the coal mass, or energy loss (in terms of MJ/kg) from degradation. Both types are discussed where applicable. For most of the supply chain, the mechanisms by which the coal mass loss depends on which stage is examined. Occasionally, *force majeure* can lead to sudden losses due to flooding and accidents at the mine face or along the transport infrastructure. During normal operations, losses can occur on a smaller scale than *force majeure*, but over time, these small losses can mount– it is these losses that this report focuses on.

When asked, some industry analysts admit there are few attempts to quantify coal losses along the supply chain. That does not imply losses are poorly understood or ignored. Major coal producers or exporters in countries like Australia, USA, South Africa, Colombia and so on pay great attention to their operations and logistics to ensure a smooth running of their businesses. However in terms of publicly available reports, few are published. This might in part be due to the fact that it is not deemed important. Losses from a natural gas pipeline or an oil pipeline for instance have serious implications due to the release of greenhouse gases, or the impact on wildlife and the environment. Few reports in the mass media have ever highlighted the catastrophe of a coal spill.

Losses none the less occur throughout the chain and to varying degrees. Interestingly, a great deal of the loss might occur intentionally, while others might be unintentional. Losses might occur as non-coal material and as saleable coal. The distinction between these losses is made in this report. Losses can be physical mass or by heating value (the latter may see little loss in mass). These issues are distinguished wherever it is appropriate.

Early on, freshly mined coal may require treatment at a coal preparation plant in order to make the coal as close to the desired product demanded by customers as possible. Losses arising from these processes are in fact mainly waste matter that has a low coal content, but is recorded as 'raw' or 'run-of-mine' coal by industry associations.

Coal preparation is discussed in more detail in Chapter 4, and describes the processes adopted to free the raw coal of excess mineral matter. These alterations to the coal also serve as a means of reducing transportation costs, as rail and conveyor or truck loads will carry more useful product and less waste. The cost of washing and preparation will therefore need to be balanced carefully with the needs of the customer and the economics of carrying out the extra task in the coal chain. Losses may be due to the extraction of ash, sulphur, mineral matter, and in some cases the removal of moisture.

Losses might be intended to avoid the risk of waste non-coal material, especially in high ash coals, or avoid the presence of fines. Not all discards are inert and value-free. Coal fines can provide a by-product, which may not be desirable to have present with the larger sized coal. Transportation costs for lump coal will be reduced if large amounts of these fines can be extracted, which would otherwise pose a dust hazard or run-off contaminant. For example, road and rail haulage costs on a per tonne basis can be reduced, as well as reducing airborne dust pollution.

Coal throughput can undergo loss from spillage, but can be recovered later, albeit not back into the original stream of coal that was being transferred. Other losses might occur from self combustion during longer-term storage, or in transit when it is being held within a cargo hold. Losses and changes in the coal supply chain are also impossible to measure accurately unless measurements of coal quantity and quality are measured en route. All these issues are examined to obtain a clearer understanding of the beneficiation of coal and transporting it to the customer.

In the most part, this report discusses the coal supply chain from the mine until it is delivered to the end-user. There is some brief discussion at the end of the report on losses during power generation, but it does not form the core theme of the study. This is due to the complication of coal transformation as it undergoes exothermic reactions during combustion at which point coal as a solid fuel loses its identity, and forms new gaseous and solid compounds. The process change for coking coal into coke products (and coke oven gas) prior to steel production is not included in this report for the same reasons.

Due to the variability in coal supply chains across the world, this report is at best a rudimentary overview of the coal supply chain. This is an introduction to explore some of the issues that make up certain elements of the supply chain where both large and small losses occur. There may well be need for further research required in many areas of this study.

2 The different patterns of coal supply

With world production fast approaching 8000 Mt/y, generalising the coal supply chain in terms of mass losses is an extremely difficult task. It is possible however to identify the broad issues that affect most supply chains.

In terms of extracting coal out of the ground, mining can be done either by opencast (surface) or underground (deep) methods. Within these two broad categories are a multitude of different techniques and mine designs to extract the coal depending on accessibility to the coal seam, the geology of the seam itself, and the machinery needed to safely extract and move the coal and the associated dry bulk. The coal is then transported to the end-user, the mode of transport of which will vary in type depending on the distance travelled and the amount that needs transporting.

Coal can come from a single seam, or several seams which might be located at different depths, or from different parts of the same seam. It may have variable characteristics even though it is apparently supplied from a single mine. Where the coal lies near the surface, open pit mining is preferable and more economic. For internationally traded coals, and for some which are internally used or traded, coals may be stacked and blended either before or after transportation, to meet required specifications. Currently, the coal supply to a particular end-user may come from:

- a single local mine, with or without a coal preparation plant (CPP). Where the coal is supplied without preparation, selective mining techniques may be used to minimise the variability in coals. This is commonly referred to as minemouth generation;
- a number of nearby mines, so that the coals will probably have broadly similar characteristics, as will be the case in Australia and South Africa;
- from distant mines, but in the same country. In countries like China, India, Russia and the USA, coals may commonly be transported over distances of up to 1500 km. The coal supply to the customer may then come from different mines and its characteristics will change accordingly with variations within seams and different seams within a mine;
- a mixture of indigenous coals, and coals which are imported from the international market, as in Germany and the UK;
- imported coals only, as in Denmark, Finland, Italy, Taiwan, Israel, Morocco, Japan, and South Korea, where end-users are located close, or within easy access to the coast where port, storage and coal transfer facilities are located.

Understanding the coal supply chain is made complicated by the various owners and operators of facilities that control the movement and storage of coal en route. As a result, the liability over custody of a coal shipment at any point may also change depending on the contractual agreements between sellers, traders and buyers. As a result, insurance and handling costs along the chain may fall upon different parties. Ship operators are usually dedicated companies operating fleets, some of the largest being owned by Greek, Chinese and Japanese companies.

There is sometimes greater integration between mine, rail and port operators, but not always. Inland transport operators are often a separate entity from the mine operator, such as the Drummond supply chain in Colombia. In South Africa, the major coal producers have interests in the mine operations as well as the massive export port, the Richard's Bay Coal Terminal (RBCT). Rail however is owned and operated by Transnet the state-owned rail company. The price of the coal is still reported as free-on-board at RBCT, or includes the seaborne freight and hence priced at the destination port. These prices mask the various ex-mine costs, inland rail costs of Transnet, the port, handling, storage and demurrage charges at the port, so on and so forth. Consequently, fully understanding the cost structure of these supply chains requires specialist knowledge.

On a day-to-day basis, these different companies coordinate operations well, but in terms of long-term development, investments are often staggered. Expansion plans in South Africa have lagged behind other major exporters, such as Indonesia for one reason or another, and this is partly due to the delinking between inland transportation with the mine/port facilities.

In Australia, organisations such as the Hunter Valley Coal Chain Coordinator (HVCCC) demonstrate how mine operations are almost seamlessly integrated with rail and port operations and investment.

The strategic and business goals are more integrated and so the operations has greater potential for efficiency through entire chain logistical planning, operation, and in the future possibly greater automation.

Although much of this discussion has thus far looked at coal exporting countries, around 85% of the world's thermal coal production is used within the county of origin, and 15% is internationally traded. This has implications for the nature and variability of the coals used at power plants across the world, and a number of patterns have emerged, for example:

- lower grade coals (with heat contents <16 MJ/kg) including most lignites/brown coals, and/or coals with a high ash content, are used at or near the minemouth. This is because transport costs are disproportionately increased by the amount of inert, noncombustible material present in the form of mineral matter and/or water. These coals are commonly quite variable in their characteristics:
- the high ash coals which are produced in coal exporting countries such as Australia and South Africa, where the higher grade, lower ash content, coal is sold internationally and the middlings products from the CPP contain 25–40% ash are used at nearby power stations;
- in the USA, the demand for mid western Powder River Basin (PRB) subbituminous coals has grown substantially from 264 t/y in 1998 to 423 t/y in 2008 (US BLM, 2012). This increase has been largely because the PRB coals have a low sulphur content, an attribute desired by many power station operators nationwide, and blending these with higher sulphur eastern US coals has enabled utilities to reduce/control SO_2 emissions. The blending of coals with very different characteristics has, however, presented some challenges in the past which have more or less been overcome;
- in China, coal is either used at minemouth power plants, or is transported over long distances by rail. Some of the largest power markets are in the southern provinces around Hong Kong such as Guangdong, the southeastern provinces around Shanghai, or the northern regions around Beijing. The coalfields however are located deep inland in Shanxi, Shaanxi and Inner Mongolia. Due to the considerable logistical exercise to transport coal from the coal producing regions to the farther coastal regions, coal imports from foreign countries now exceed 100 Mt/y.
- in Russia there are substantial transfers of coal westwards from the central Kuznetsk basin coalfield over vast distances (Crocker and Kovalchuk, 2008). These supply the Moscow area and other parts of western and European Russia, so many power plants there will be dealing with a mixture of local and more distant coals, and some will fire a mixture of coal and natural gas. Increasingly, coal is being sent by rail to the eastern coast for export;
- in India, coal is sent by rail long distances from the cluster of mines deep inland in the northeast apex of the country. Some of the main economic centres are located some distance from where the coal is mined, so rail infrastructure is therefore essential to this country. Indian coals are generally of low grade (but not necessarily low rank) due to their high and variable ash content. To encourage the use of coal washing, the government introduced a regulation to the effect that any coal transported more than 1000 km had to have its ash content reduced to <32±2%. There are reports of significant coal supply shortages in various parts of the country; this means that a number of power plant managers are likely to accept whatever coal they can get without worrying too much about its quality.

2.1 A representative coal supply chain

As the previous section shows, each country has a different approach to coal supply depending on the sourcing of the coal and how far the demand centres are from the indigenous and imported sources. Consequently, the coal supply chain can be simple or complex depending on the distance the coal has to travel (*see* Figure 1). Coal destined for more distant customers, such as those for foreign exports, will experience a much longer journey than that of a power station located adjacent to or close to the mine (minemouth).

Any coal supply chain can be simplified to the following stages: the mine, the coal preparation plant (CPP), inland and/or seaborne transportation, and finally the end-user. However, within this simplistic chain are many stages of stockpiling, different transportation modes, and where each link meets, and the various ways of transferring the coal from one to the other. Figure 1 shows how the supply chain can be extremely lengthy for exported coal but short for minemouth power stations. It illustrates all the stages of the supply chain that are examined in this report.

The supply chain is varied and depends very much on the distance between the mine and the location of the end-user. Freshly mined raw coal, typically referred to as *run-of-mine* (ROM) production, can be blended with coals from other seams. Coal is crushed, sized, cleaned and prepared before stockpiling. The trail of a single tonne of coal from a particular seam is therefore lost early on in its journey to the power station or industrial consumer, making this research a considerable challenge. Furthermore, the transportation of coal (either by road, rail, conveyor, or ship) means it changes hands several times. As mentioned earlier, the responsibility of the consignment transfers from the supplier, to the shipper or directly to the end-user, a process which requires auditing to ensure that the tonnage and quality is as contracted. Coal contracts are not discussed in this report, but it is accepted that measuring and quality assessments are required as part of the contractual requirements. This auditing can be done by the supplier, the buyer, or a third party verification company, and reporting procedures

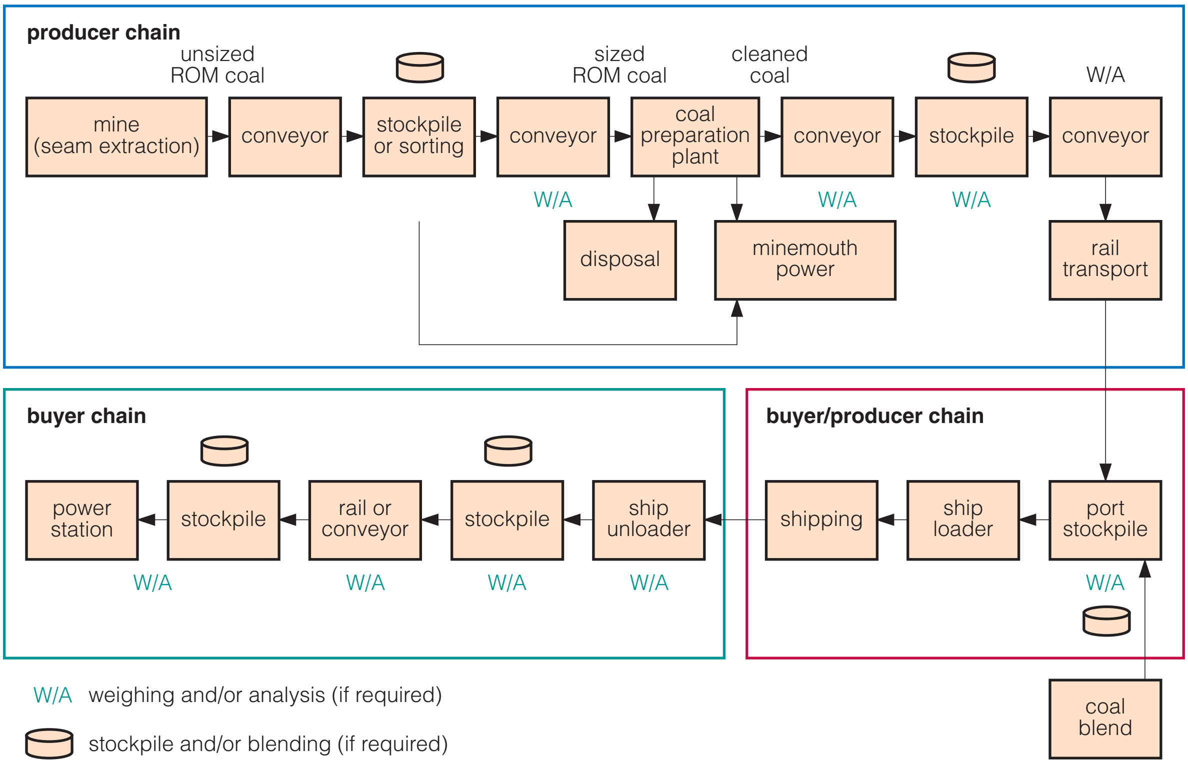

Figure 1 Coal supply chain for a typical export coal

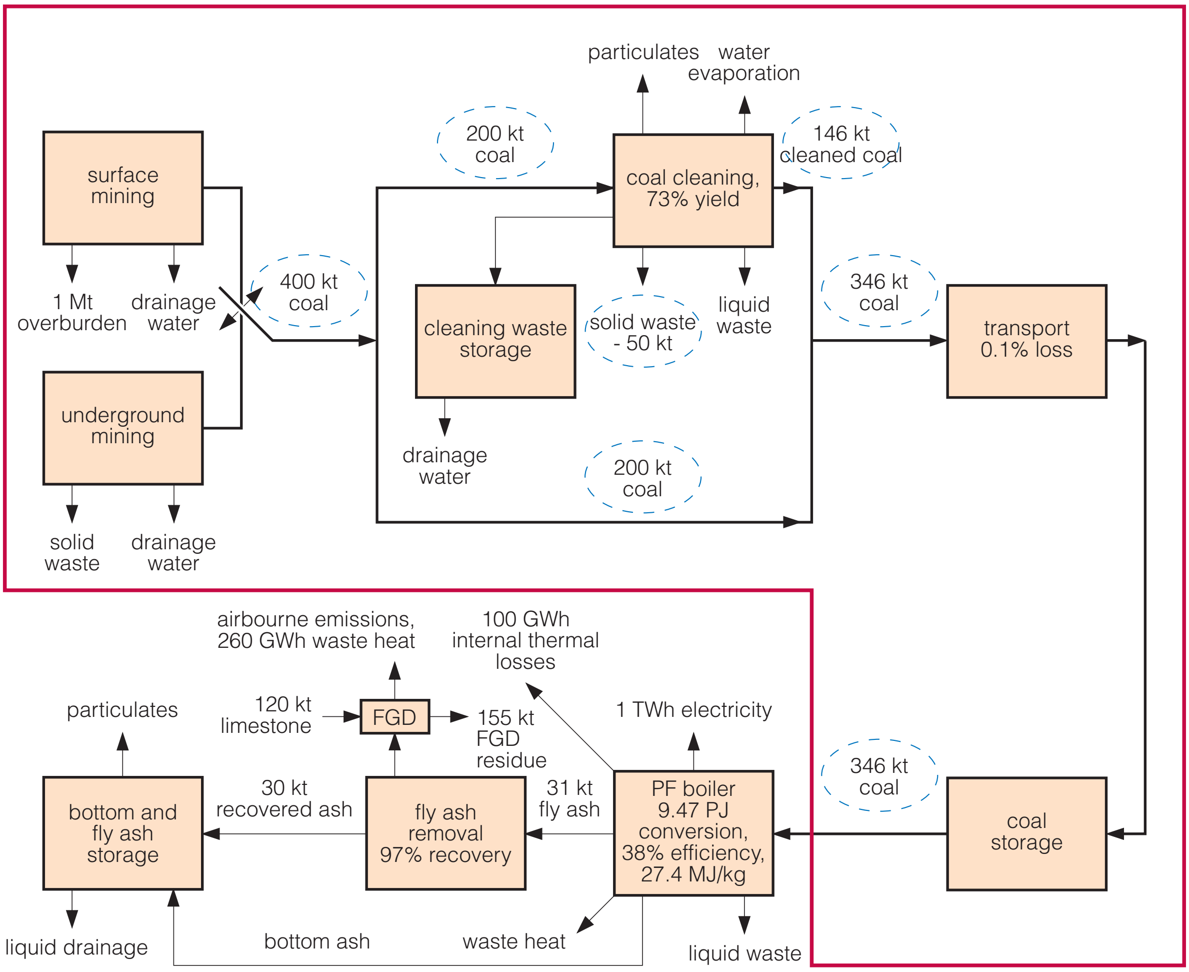

Figure 2 Coal cycle for electricity generation, showing emissions, effluents and residues (Couch, 1995)

ensure that the physical coal tonnage and quality resembles the agreement between buyer and seller. In doing so, each incumbent along the supply chain is responsible for safe throughput of the commodity, eliminating the risks of excessive dust, explosion, and acidic runoff wherever it arises.

Auditing requires several stages of sampling and weighing to ensure that the buyer receives the correct volume and specification of coal. Weighing and analysis are carried out at several stages, most crucially when the coal consignment is being transferred between modes of transport at stages when the liability for the coal delivery is also being changed, such as when the coal supplier hands the coal over to the shipper at the port and the ownership of the coal might then transfer to the trader or end-user of the coal. Samples might be taken either while the coal is conveyed or while the coal is static in the stockpile, in which case fast throughput is desired. Coal that is stored in stock for too long can undergo changes, whether gaining moisture, drying, or even self combustion.

2.2 Quantifying losses in a coal supply chain

When looking at the coal supply chain, it is important to recognise that at each stage different personnel are responsible for the throughput of coal. However each manager, whether it is the mine operator, the coal preparation plant manager, the shipper or the end-user, need to understand the coal entering their systems to ensure the smooth running of that plant or operation. Figure 2 shows supply from a small mining operation, quantifying the losses that occur throughout the short chain, and detailing some of the specific areas where they occur. The Figure shows a mine which outputs 400 kt of raw coal; some 200 kt of the 400 kt of mine output can pass through the washery plant. Of this washed coal, a 73% yield can be achieved of suitable product. This therefore provides an output of 146 kt, meaning 54 kt is extracted, of which 50 kt could be reusable waste (hence the negative entry). Liquid waste is assumed to be discarded. Of the 346 kt of coal, just 0.1% might be lost during transportation according to this Figure 2, however as this report goes on, losses could be higher if the conditions are such that dust, degradation, and weathering are considerable.

Nevertheless, based on this model, the losses are amount to 54.2 kt, out of a washed product stream of 200 kt. This translates to a loss of 26%, most of which arises from the coal preparation and washing stage.

3 Losses in mining and preparation

In modern operations, mine machinery consists of large mechanised cutting tools which extract large volumes wherever the coal seam geology is allows. This might include longwall machines for underground mines or dragline systems for opencast mines. Other extraction methods might be employed where seams are thinner, fragmented, and less accessible. Here, truck and shovel methods might be employed for opencast mining, and in underground mines continuous mining is common. There is therefore a multitude of extraction solutions to cope with the infinite variation in geology faced by the mining company. Whichever condition is faced, coal losses can occur in all mines to some degree.

According to Couch (1998), mine waste inevitably gives rise to losses in the production process. Coal losses can be large, and occur at two major stages, extraction and preparation. During mining, some coal may remain in the ground, and so be lost due to incomplete extraction. On the other hand, coal may be mined but inadvertently discarded with waste rock or overburden (particularly during opencast mining). There is more discussion on this later in this chapter. Some of the major losses of mass occur during coal preparation through the waste solids and liquids. Non-combustible mineral matter content of coals can be in the range 5–50% which affects the heating value of the coal and ash deposition in a power station boiler.

3.1 Methods of coal mining

Understanding losses at the mining stage requires some introduction to the different ways coal is mined. Mining methods are determined by the depth at which the coal lies, the two methods are surface (opencast) mining and underground (deep) mining. Surface mining accounts for around 80% of production in Australia; while in the USA it is used for about 67% of production. In China, deep mining is the most common form, while in Indonesia surface mining is predominant.

Different types of surface mining exist depending on the seam geology and the manner in which the seams are accessed and recovered. Such terms include strip mining, opencast, open pit, highwall opencast mining, opencast mountaintop removal, auger and highwall mining. For the purposes of this report, the term for all surface mining will be called opencast for simplicity. As a general assumption, opencast methods recover a higher proportion of the coal deposit than underground mining as almost all of the coal seams can be exploited; perhaps 90% or more of the coal can be recovered this way. Some exceptions occur, such as where the seam might be located below environmentally sensitive areas, or occurs close to or below population centres. Large opencast mines can cover an area of many square kilometres and use very large pieces of equipment, including:

- draglines, which remove the overburden;
- bucket wheel excavators for removal of large coal seams (typically for lignite); or smaller capacity for reclaiming coal from stockpiles;
- electric/hydraulic shovels, in combination with excavators (hoes) and bulldozers;
- large trucks, which transport overburden;
- conveyors to move the coal.

Hard rock overburden is first fractured using explosives and then removed by draglines or by hydraulic/electric shovels and other earth removing equipment. Once the coal seam is exposed, it is drilled, fractured and systematically mined in strips or whatever is practicable given the seam geometry. Coal is then loaded on to large trucks or conveyors for transport to either the coal preparation plant or even direct to the end-user.

In (deep) underground mining there are two main methods: room-and-pillar and longwall mining. In room-and-pillar mining, coal deposits are mined by cutting a network of ‘rooms’ into the coal seam and leaving behind ‘pillars’ of coal to support the roof of the mine. These pillars left in situ can be up to 40% of the total coal in the seam so the reserve is effectively reduced to just 60% of the physical total that exists. This coal can sometimes be recovered at a later stage, typically when the operation is in retreat, but in many cases, the pillars are left in place to maintain ground and roof stability.

Longwall mining involves the extraction of coal from a horizontal section of seam using mechanical shearers that move laterally across the face on a rail that is the usually width of the working seam. A longwall face requires careful planning to ensure favourable geology exists throughout the section before development work begins. The coal ‘face’ can vary in width from 100 to 350 m. The shearer and roof support systems are programmed to be self advancing in sections, whereby the hydraulically-powered supports temporarily hold up the roof and advance forward in sections as the seam is cut away. As the supports advance forward, the roof is allowed to collapse behind. Access to and from the forward migrating working area and coal conveying is by a series of dedicated tunnels.

In underground mines, armoured conveyor belts feed ROM coal into receiver hoppers, where a mechanised coal handling system takes coal to the surface for preparation. ROM coal may be blended with coal from another source on surface stockpiles. Over 75% of the coal in the deposit can be extracted from panels of coal that can extend 3 km through the coal seam.

With regard to opencast mining hardware, coal is transported by either truck or conveyor. The former is typical of operations where numerous shovels are in operation, sometimes working with staggered, thin or steeply dipping seams where vehicle mobility is important. Vast quantities of waste material can arise from overburden removal in open pit operations called ‘spoil’ or from a washery plant.

Where the seam is flat and thick, bucket wheel excavators (BWE) requiring fewer operators are connected with conveyors which access the stockpiles often for delivery directly to a minemouth power station. This is most often associated with and softer and extremely thick deposits associated with lower rank coals like lignite (brown coal).

Technological advancements have made coal mining more productive than it has ever been. To keep up with technology and to extract coal as efficiently as possible modern mining personnel must be highly skilled and well-trained in the use of complex, state-of-the-art instruments and equipment. In some cases, remote coal operations are monitored and controlled many kilometres away using GPS systems that can track each vehicle movement to ensure maximum safety and operational efficiency.

3.2 Coal losses and dilution with surrounding rock during seam extraction

In both underground and opencast mines, coal that is left in the ground (apart from that which is left in pillars) can be considered to be lost, particularly if the coal can be extracted and is potentially saleable. However, many parts of a seam might be too costly to access, let alone extract, and so remain in the ground. Some of this raw in situ coal will comprise of mostly coal and mineral matter that might later require separation in the preparation plant, so it is never clear how much (saleable) coal would be lost.

Dilution is a different concept where unwanted additional material, perhaps through over digging, enters the coal supply. As a result, more material is shifted and transported than desired, therefore adding to costs and reducing product quality. Additional undesirable mass can also come in the form of water, which is often unavoidable if the coal lies at or below a water table, or is used for cutting and dust suppression. So, whether it is mineral matter or moisture, there is a loss in the coal ‘heating value’ for every tonne that is extracted. When looking at the physical mass losses within the coal seam, sterilisation of reserves can occur with room and pillar production, or where production stops and operations withdraw abruptly.

In the deep underground mines using room and pillar methods, recovery in some industrialising nations can be extremely low. In addition, a significant amount of coal is burned inside the mines of the Jharia basin alone. Over the last century, a large number of mines have been closed with no appropriate mine closure method. India's total coking coal reserves available up to a depth of 1200 m appear to be based on virgin reserves alone. Reserve and resource assessments of specific deposits do not take into account the coal that is locked in pillars, particularly of closed and abandoned mines. Reserves also do not include seams of 0.5 metres thickness from the coal inventory being deemed too thin for extraction. For every 10–30 t of coal extracted, 90–70 t is left in situ. Naturally, mineral rich material will be selected for the pillar supports and the coal extracted, but often this is simply not possible. These losses are an example of coal that is intentionally left in the coal mine. It consist of potentially marketable but inaccessible coal using the current means of extraction. This does not necessarily deem these as inaccessible using future means of production, perhaps through underground coal gasification (UCG) but losses resulting from this process is beyond the scope of this report. UCG is covered as a topic in Couch (2009).

Holtham and others (2005) published a useful document on the reconciliation of tonnage in Australian coal mines. The report sets out to improve the procedures that ensure coal extraction is properly verified against the planned production estimates, enabling better planning for equipment purchase, deployment, maintenance, personnel, load capacity of conveyors as well as the essential task of ensuring cutting machinery, lubricants, and spare parts are all available ahead of production. Not least is the planning for the coal preparation plant that must accommodate the correct throughput for efficient operation (*see below*). Part of this planning and monitoring should ensure that the CPP does not receive material that is too far off specification that the CPP can handle.

During the mining phase, dilution can be a problem where unwanted matter enters the coal stream, effectively reducing the heating value of the coal. The throughput mass may contain inert material

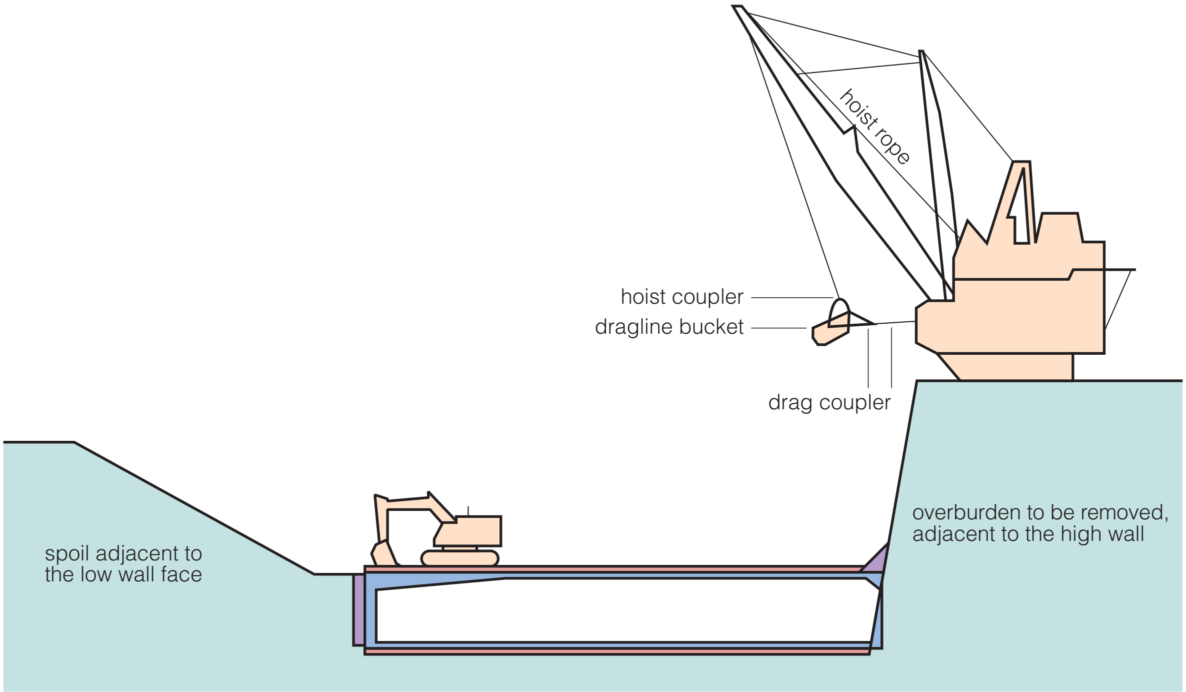

Figure 3 Sources of dilution and losses in a typical opencast coal seam (Holtham and others, 2005)

quite useless to the customer, therefore reducing the heating value and efficiency of the fuel. Where a mine seeks to maximise recovery of the recoverable coal reserve, dilution could increase creating greater challenges to the operator of the coal preparation plant. More problematic dilution occurs if the mineral matter is interspersed within the coal material, either due to folding or faulting during coalification of the seam.

The major areas of loss and dilution at the mine is where the coal and rock/overburden boundary are disturbed during mining. The sources of losses and dilution are shown in Figure 3 where 'losses' are the black areas where coal is left in situ, and sometimes not recovered, and 'dilution' due to surrounding rock and dirt being loosened or unintentionally mechanically removed and so entering the extracted coal shown in orange. The figure shows the losses and dilution that can be experienced during opencast mining, but this figure can also apply to underground coal seams. This occurs at various locations, chiefly the top of the seam (roof), the base of the seam (floor), or ribs (edge of a pillar). Seams which suffer from faulting or the intrusion of veins will be subject to the same problems described above.

Scott and Wedmaier (1995) obtained privileged access to data for a variety of opencast mines in Australia. An average of 7% of mineable coal was reported to be lost during open cut mining, with losses greater in New South Wales (8.5%) than in Queensland (6.5%). Scott and Wedmaier (1995) three areas where loss and dilution occur: at the seam roof; the seam floor; and the various exposed coal edges.

General experience suggests that at the roof of the seam, more losses occur than dilution during opencast mining, while the floor experiences more dilution than losses. This occurs mainly during overburden removal here seam roof damage, loss and dilution can occur due to:

- blast damage: overburden, interburden and parting blasting operations;
- equipment choice: type of overburden removal equipment, while the type of coal mining equipment would affect the floor of the seam;
- choice of clean-up equipment, as well as extent of clearing, some coal would end up in spoil;
- excessive equipment traffic on top of coal, breaking up the roof of the seam;
- geometry of the top of coal and the geology of the floor (planar or irregular);
- relative colour and hardness of roof materials compared with that of coal;
- ease of separation of roof and floor materials versus the coal;
- the presence of clay veins or other rock intrusions;
- operator visibility (day versus night, dusty conditions);
- presence of water (dry versus wet);
- operator experience.

In the study of opencast mines by Scott and Wedmaier (1995), 94% of the mines surveyed considered that seam roof loss was being incurred by overburden removal equipment. Extensive roof loss was exhibited where dragline operations occur, possibly due to the scale of the bucket size and the proximity to the digging area of the operator, affecting the accuracy of material removal. Use of closer proximity equipment such as electric and hydraulic shovels produced lower losses. A dragline operator who is 50 metres above the coal roof performing clean-up duties will find the task more difficult than a dozer operator located four metres above the working face. A lower proximity operator can feel the materials better, through the feedback of resistance through the equipment, and will find it easier to differentiate materials under wet and low light conditions. Blast damage from overburden, interburden, or parting blasts also weakens the top of the seam contributing to coal loss during the clean-up process. Blasting also mixes roof materials with the coal, while the bond between the coal and interburden or over burden material may limit the separation of the materials. Coal can therefore get ripped up during removal.

Controlling the accuracy of blast depth and radius presents problems. Blast proximity permeates the path of least resistance, and can lead to blast damage. Blasting is almost always for overburden weakening only, coal is normally very soft in comparison and does not require such measures. Operations generally drill to the coal surface, but then retract away and the hole is back-filled with drill cuttings to limit the exposure of coal to the blast. Cuttings are however weaker than the rock, and fine, and in the presence of water can even turn to mud. The cuttings, whether dusty or muddy, are the path of least resistance which lead directly to the coal seam, and so care must be taken. Over confinement of the blast can also drive high pressure gases into the coal seam causing fractures and dilution of rock particles into the coal seam. Care must be taken therefore on the methods of blasting, to avoid disturbance of the coal.

Rope shovel, excavator and front end loader overburden removal requires haulage equipment to travel across the seam roof. This can weaken the top of coal. Spillage of overburden from the haulage trucks combined with dozing or grading vehicles mix dilution materials with the upper plies of the coal seam, contributing to dilution.

Exposure of the coal edge to overburden removal equipment can lead to losses. Some two-thirds of the mines surveyed in the Scott and Wedmaier (1995) report considered that the coal edge was lost from blasting and spoil placement, the latter being particularly problematic when using draglines. Coal characteristics affect the dilution and loss of coal. If the coal and surrounding rock is of similar colouration, particularly in conditions of poor visibility (night or wet conditions) coal can be lost as part of the overburden removal process, and dilution incursions may occur. This is where a distinct difference in relative hardness is a useful guide, where an experienced operator can ‘feel’ whether the tyne is in coal. Ease of separation of material is therefore essential. The strength of the floor material is important as floor heave, a problem amongst clay based materials, can cause the upheaved material to be mixed with the coal. As such, dense medium separation is necessary in the coal processing stage.

Having identified all the areas and mechanisms of coal loss (or dilution) due to overburden removal and coal extraction, quantifying these losses depends on the multitude of variants of operating equipment and procedures and training employed at each mine around the world. Wittmers (2011) illustrated the losses experienced by opencast mining seams in South Kalimantan. Here the coal is higher in moisture content and has a lower heating value compared with other export coals from say Australia, Colombia, South Africa or Russia. Around 30 cm of the seam is lost in the roof and floor layers, therefore totalling 60 cm of coal being lost and not recovered (*see* Figure 4). The coal at these margins is probably perfectly marketable, and the low heating value still within the acceptable limits of traded coal. Instead of dumping, this coal could be fed into a washery system, which could yield a low-ash coal of equivalent quality to the rest of the seam, or priced accordingly to reflect a small discount.

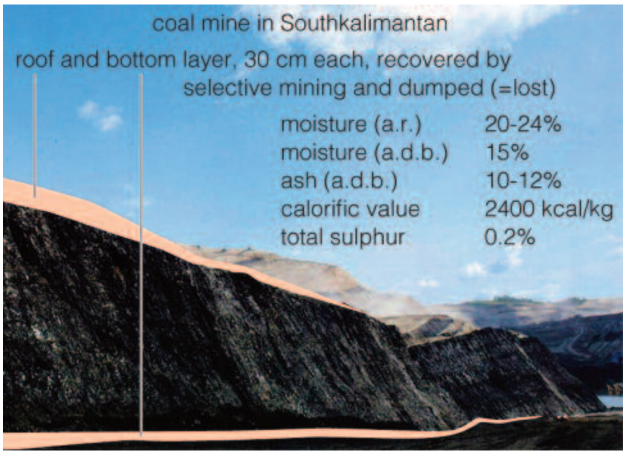

Figure 4 Roof and bottom layer losses at the coal seam (Wittmers, 2011)

Wittmers (2011) estimated that the yield of such coal could be as much as 86% of the feed coal. This is an example of a particularly poor level of loss. When mining thinner seams, perhaps as small as one metre, losses of a few centimetres is quite likely, and so the extent of these losses is very much dependent on the particular seam being worked, the conditions and depth of the seam.

Johnston and Kelleher (2005) reported on Goonyella Riverside opencast mine in Australia which is one of the largest coking coal producers owned by BHP Billiton Mitsubishi Alliance (BMA). Capacity of the operation is 13 Mt/y of saleable product. To achieve this 180 million cubic metres of overburden was moved to uncover 18.5 Mt of raw coal. After the coal was uncovered in a trial area, surveys were performed to quantify the coal lost during dragline uncovering and seam extraction phases. During the survey, cores were taken from 25 in-pit drill holes. The quantity and quality of in situ coal was compared with a reserve model, and the two estimates agreed within 1%. Total losses from one location occurred in four areas, the low wall coal wedge, top of coal edge, top of seam and floor of the seam (*see* Table 1).

Table 1 Distribution of total loss in the ramp 13 North Strip 22 Goonyella Lower seam trial (Johnston and Kelleher, 2005)

Loss area	Percentage of total loss
Low wall coal wedge	27.42%
Top of coal edge	6.45%
Top of seam	48.39%
Floor of seam	17.74%

In both opencast or underground seams, water ingress can be a common issue where the coal seam is below a water table or sea level. ROM moisture can be higher than in situ moisture as broken coal attracts surface moisture, something that will be experienced in regions prone to high rainfall such as in Indonesia and Colombia. Additional mass for increased moisture therefore has to be accounted for when calculating and measuring ROM tonnage.

$$W_{ROM} = W_{IS}\,(100 - M_{IS})/(100 - M_{ROM})$$

W_{ROM}	the mass of ROM coal
W_{IS}	in situ mass including in situ moisture
M_{ROM}	ROM moisture %
M_{IS}	in situ moisture %

4 Turning raw coal into saleable products

The next step in the coal supply chain is to assess whether the ROM coal is suitable for the end-user or requires preparation and cleaning. Coal preparation consists of a series of separation processes where cleaner coal matter is separated from dirtier matter which is more mineral rich. Density differences between the coal and mineral matter is the key to preparation.

To the uninitiated, coal preparation is a bewildering and complex process, but is in essence a straightforward series of processes that separates lumps and particles of different sizes, before separating coal from mineral matter by their different densities. In essence, the CPP more or less aims to separate out coarse, intermediate, and fine mineral matter to output a transportable coal product of a suitable size and ash and sulphur quality that is saleable and attractive to the market.

It is rare for coal to be transported in unmanageable lumps of say 500 mm or larger except perhaps in rural non-commercial mines serving local communities. For coal entering a CPP, the coal might have coarse mineral matter removed, while oversized coal material is crushed. Smaller mineral matter particles and lumps may still be present amongst the cleaner coal which needs to be removed, here the CPP becomes an essential part of the supply chain.

To understand the potential loss of mineral matter before the coal is distributed to the open market, by means of an example; the *New South Wales* (NSW) coal industry publishes data on raw and saleable coal on a mine by mine basis. NSW is an efficient producing region and one of the leading coal export regions in the world with large mine operations and dedicated rail and port facilities that ship coal worldwide.

Using these data, a simple comparison of the mass of raw coal production and saleable coal production can be made. The percentage of saleable to raw coal is often called 'yield'. In addition to this comparison, it is necessary to distinguish between domestic and export thermal (or steam) coal markets. Export quality coal is invariably a more clean and refined product.

Table 2 shows the production output from mines (producing chiefly export quality coal) in New South Wales and shows how yields of all saleable coal in NSW averaged 76–78% as a percentage of the raw coal. More coal yield was obtained from underground mining (79–83%) than from opencast mining (73–76%). In these circumstances, underground mining appears to give rise to less waste material and perhaps less coal loss. In some ways it gives clues to the process of mining using different techniques for different conditions. Underground mining could be considered more selective and more accurate, generally avoiding surrounding rock to minimise cutting teeth wear and any unnecessary load on the armoured conveyor belt.

To support the Australian example are data from South Africa, another large producer of coal, which suggest 20–30% mass loss of raw to saleable coal. In 2002, South Africa's run-of-mine coal production was reported to be 285 Mt; while 220.2 Mt was considered of saleable quality, suggesting 77% of ROM coal was saleable (Prevost, 2002). So the loss of material, some of which is coal amounted to 64.8 Mt. However, a total of 63.2 Mt of coal discards were generated. This would suggest that 1.6 Mt was lost elsewhere outside the coal processing plant, perhaps accounting for 0.6% of the ROM production. These South Africa data demonstrate an interesting trend in how ROM discard tonnage increased in 2002. The recorded discard loss was higher due to a rise in coal processing which resulted from an overall decrease in ROM coal quality. This quality change came about as production shifted from the Highveld, Vryheid, Utrecht and Nongoma coalfields and increased in the Witbank, Waterberg, Ermelo and Klipriver coalfields. This could be an increasing problem where operators worldwide are facing depletion of existing reserves. Interestingly, there is still a trend towards lower rank coals especially from Indonesia, so clearly the issue is not

Table 2 New South Wales Coal Industry Statistics (TIRE, 2011)

Production, Mt	2004-05	2005-06	2006-07	2007-08	2008-09
Raw coal, all mines	156.31	161.14	170.32	177.17	181.98
Raw coal from underground	51.91	52.23	57.24	61.32	63.07
Raw coal from open cast	104.40	108.91	113.08	115.85	118.91
Saleable coal, all mines	122.06	124.61	131.33	135.15	138.46
Saleable coal from underground	43.19	42.30	46.20	48.97	51.61
Saleable coal from open cast	78.88	82.31	85.13	86.18	86.85
	2004-05	2005-06	2006-07	2007-08	2008-09
% saleable from all mines	78.09	77.33	77.11	76.28	76.08
% saleable from underground	83.20	80.98	80.71	79.87	81.83
% saleable from opencast	75.55	75.58	75.28	74.38	73.04

straightforward and the degree of coal washing will depend on in situ coal quality and customer demands.

Ewart (2012) described how almost all the coal consumed domestically in Canada, Colombia, and Indonesia is supplied on a raw basis. There would be some minor losses in transport, but for all practical purposes these are negligible. However, coal losses for export quality steam coal differs from country to country with the percentage in parentheses referring to the average yield of saleable coal to raw coal:

- Australia (15–40%) – NSW: in 2007 there were six NSW mines exporting steam coal on a raw basis with the rest of the mines (around 35) shipping washed products with wash plant yields varying from 60% to 85%. Reject coal with a heating value of 16 GJ/t or contains >35% ash can still be reused for power generation, but is subject to a royalty of 5% (of the value of the waste coal) or half the rate of ad valorem tax on standard coal (typically 6.2–8.2%), which ever is less.
- Australia (15–46%) – Queensland: in 2007 there were four Queensland mines exporting steam coal on a raw basis with the rest of the mines (around 16) shipping washed products with wash plant yields varying from 53.5% to 85%. Some of Queensland's operation produce steam quality coal on the back of some coking coal operations.
- Canada (45–55%): most export thermal coal is washed with typical wash plant yields varying from 45% to 55%.
- Colombia (negligible): most coal is shipped raw. Cerrejón washes about 10% of their export coal (about 3 Mt/y).
- Indonesia (3–35%): about two thirds of the mines export exclusively raw coal while the remaining operations export either a washed product or a blend of washed and raw coal. Average yields for the washed or partially washed products range from 65% to 97% depending on the amount of coal washed.
- South Africa (10–40%): almost all export coal is washed or partially washed with wash plant yields typically varying from 50% to 90%.

In the USA, most bituminous coal from underground mines is processed, although some were subject to sizing only. Surface-mined coal, chiefly the subbituminous coals in the Mid West was crushed (65–80% crushed, screened and sized) and 20–30% was washed (Ducatman and others 2010), and so losses were likely to be fairly low in this region.

China has the greatest potential for coal losses. According to Cheng (2008) there were 961 coal preparation plants with a total capacity of 838 Mt/y in 2006; by the end of 2008 there were 1708 coal preparation plants and a total production capacity of 1.38 Gt of coal plus an unknown number of small plants (capacities of less than 90 kt/y) (CCRI, 2010).

The findings also show a low degree of plant yield in Canada at just 45–55%. This could be due to the highly friable nature of some Canadian coals, leading to large amounts of discarded fines, which can be dewatered after centrifugal separation using thermal drying. Although not in the above list, India had 16 coking coal washeries, most of which were 40–50 years old. These washeries operate at a yield level of 30–45%.

Yields from process plants across the world therefore vary due to the coal quality and the desired product to be output. As such coal preparation plants are designed and adapted to suit. A proportion of these discards may go onto be reused if they are benign, or if they contain an adequate heating value and acceptable ash content, they can be combusted in an appropriately designed power plant. Wastes can otherwise be dumped in settlement pools from where they may be reused after further processing.

4.1 The process of coal separation from mineral matter

Bethel and Barbee (2007) and Ghosh (2007) summarise some of the most widely used methods of coal preparation deployed by the world's major coal producing countries. Separation occurs through several stages, using a mix of size based operations and density based operations. Some processes are mechanical, using agitation while other processes are fluid based that 'float' the coal away from more dense mineral matter. Once the coal is separated to a sufficient requirement, it must then be dried, usually using centrifugal methods.

Raw coal must be separated to ensure each separation process receives the correct sized coal in order for the whole process to work efficiently (Bethell and Barbee, 2007). Coal lumps larger than 15 cm (6 inches) would not enter a separation plant, although crushing would be carried out in order to make the coal more transportable and easier to handle. Large raw coal lumps may pass through a crushing/sizing stage, typically a rotary or roller type, to reduce larger coal lumps to a maximum 50 mm (size of a tennis ball) above which coal preparation plants are less able to handle the material effectively.

At this early stage, hardness differences between mineral rock matter and coal can determine separation if rotary breaker cylinders are used. These cylinders use little mechanical force on the material itself, but rather use the effect of gravity and agitations to break coal along fissures and fractures.

This method of separation is common in ore processing as well as biomass separation. A large cylinder made of perforated screen plates is fitted with internal shelves. The long steel cylinder with a diameter of around two metres tumbles the feed material with a similar action to a rotating cement kiln or a domestic washing machine. As the cylinder rotates at about 10–18 rpm, the shelves lift the feed and, in turn, the feed slides off the shelves and drops onto the screen plates below, where it shatters along natural cleavage lines. The coal breaks down and exits the long drum through the screen plate perforations. The mineral matter and refuse move through the drum which is angled at a decline, and are rejected at the discharge end. This is a system common with biomass preparation and is useful for friable coal.

Direct mechanical crushing uses compression and movement within steel drums with breaking and sizing teeth and can come in a variety of sizes and duties. Lighter machines perform coal crushing tasks, while heavy duty machines deal with large rock and mineral matter. Manufacturers of such machines include Maclanahan and Metso.

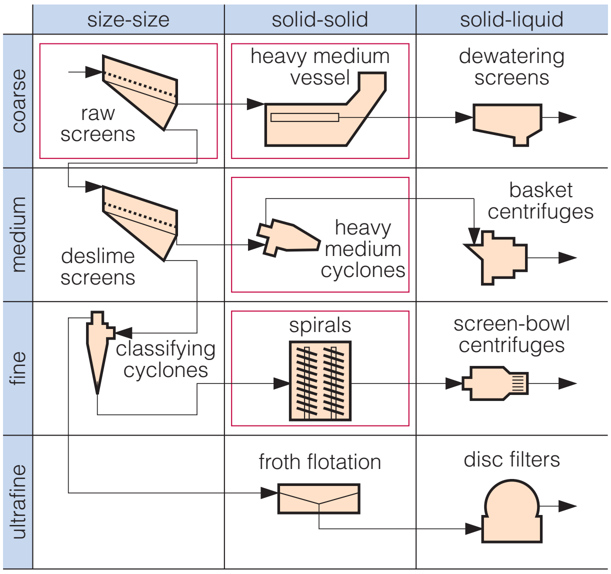

Figure 5 Representative flow chart for coal preparation (Kennedy and others, nd)

Eck (2007) describes how modern circuits crush coals to 5 cm (2 inches). Crushing coal to this level, rather than the traditional 15 cm (6 inches), enables greater separation of rock material and maximises coal recovery, therefore reducing losses. In doing so, the crusher must be carefully matched to the coal to avoid increasing the level of fines being generated, which could add to losses and costs as fine separation further downstream is far more costly. Not all operations fit perfectly into these ranges but the various methods of separation lend themselves to achieving sharper separations with coal particles of a broadly uniform size. Kennedy and others (nd) illustrate a typical coal preparation process which has three broad stages of separation for three sizes of coal (*see* Figure 5) but is by no means definitive, only representative. Washing operations occur within three distinct size ranges, these are:

- coarse coal 10–150 mm in size (a tennis ball ±5 cm);
- medium/intermediate coal 0.5–10 mm (a pea ± 0.5 cm);
- fine coal, or fines below 0.5 mm (size of a grain of sand);
- a further category of ultra fines has been termed for coals <0.15 mm.

The first stage of preparation separates coals by size, using the physical diameter of the coal that enters the preparation plant (usually after crushing and clipping). Screening of crushed but coarse material can be achieved on a large metal mesh over which coal passes on a slope or horizontally. In Figure 5 these are referred to as raw screens. The surface is mechanically agitated using high powered motors that vibrate a metal mesh surface either a single direction (back and forth or sideways) or in a circular or oval motion. Steel punch plate is the typical decking material for this, but polyurethane panels are also being used that exhibit considerable wear performance. Since coal is relatively soft, the wear on the mesh material is fairly low.

Separation of coarse to intermediate lumps at up to 25 mm (0.5 inches) is becoming common with the use of multi-slope high-capacity banana screens which are used worldwide. Banana screens are so named as they are a curved mesh surface that are at an incline which is steep at the top and shallow at the exit, akin to a 1–2 metre wide children's play slide with perforations. Banana screens can screen more than one size using multiple slopes, use an upper screen which sieves coal with a coarser mesh, and a second slope underneath with a finer mesh down to 1 mm particles.

Varying levels of sophistication can be employed, but many plants still use single deck banana screens. Other methods of coarse separation include Romjigs and Batac, which use dry density separation by either mechanical agitation creating loose stratification in the material bed along the mesh, or the use of air pulses to suspend lighter density material in a vessel. Either way, mineral matter for certain coals can be separated at this stage.

When moving to the next stage of coal separation for intermediate fractions, mechanical only processes are combined with wet suspension methods that utilise the differences in material densities, between coal and more dense mineral matter. Coal with particle size larger than 1 mm is usually separated from waste material using a dense medium separation process. This process takes advantage of the density differences between the coal (typically RD 1.30–1.50) and the gangue materials (RD >1.75).

Fluids with a density similar to coal are used to ‘hold’ coal in suspension, and mineral matter, which invariably sinks is then easily separated using a variety of techniques. The fluid is generically called a ‘dense medium’ and one such medium is a liquid called magnetite. Coals with a similar density to mineral matter are difficult to separate, especially where mineral matter is present within the coal, a problem faced in Indian coals.

According to Martin and Robson (2012), coal floats on top of a liquid medium of a known Relative Density whilst the gangue sinks to the bottom. This gravity process is often sped up by utilising Dense Medium Cyclones (*see below*). Magnetite (Fe_3O_4) is the preferred ferromagnetic mineral used to create the dense medium suspension required in the beneficiation process. There are a number of reasons for this:

- magnetite has a RD >4.9, and can be used to create stable suspensions from RD 1.30 to 1.80 which is the preferred operating range for the majority of coal beneficiation plants;
- magnetite is magnetic and hence can be recovered by magnetic separators and re-used in the process;
- magnetite is relatively inexpensive when compared to other high density materials such as ferro silicon (FeSi).

Dry magnetite powder is mixed with water and pumped into the magnetite circuit. Crushed raw coal (<50 mm) reports to a desliming screen where the fine coal (–1.4 mm typ.) is rinsed off and is sent to the fine coal and ultrafine coal circuits. Using the example by Martin and Robson (2012), the 1.4–50.0 mm is passed through the magnetite suspension and pumped to the dense medium cyclone(s) for separation. Once separated, the coal product and the reject material (which is rich in mineral matter but may have coal bound to it) report to screens where the magnetite is recovered using water for simple rinsing and draining. On the first part of the screen, magnetite is drained and reports back to the correct medium sump for re-use in the circuit. On the second part of the screen, magnetite adhering to the coal particles is rinsed off with water from the process. This rinsed dense medium is recirculated to a dilute medium sump where it is pumped to magnetic separators that recover the magnetite and bleed fine coal out of the system.Dense or heavy medium separation methods come in a variety of forms, two of which are bath/vessel system and cyclone system (*see* Figure 5). In the USA for example, bath-type dense-medium (DM) vessels for separating 1.2 cm (0.5 inches) materials is common (Bethell and Barbee, 2007). DM baths provide low cost yet effective separation. South African coals are near gravity density and so use the slightly more efficient drum method for coarse coal cleaning, however some circuit designs favour coarse (3 inches) and fine dense-medium cyclone (⅜ inches x 1 mm). Australian plants also use DM cyclones and generally combine intermediate and coarse coal separation.

In the USA, intermediate coal fractions (0.5–10 mm) are also separated by dense-medium cyclones (*see* Table 3). These are conical vessels mounted statically on their side. The ends are truncated and at each are outlet pipes. The high pressure feed pipe is fired tangentially along the cyclone inner surface. Like the barrel of a rifle, the flow takes a spiral form, with dense material flowing to the outside of the cyclone and ejected at the bottom, while lighter cleaned coal is maintained within the centre of the fluid vortex and being less dense than the fluid, is passed out of the upper wider end of the cyclone (*see* Figure 6).

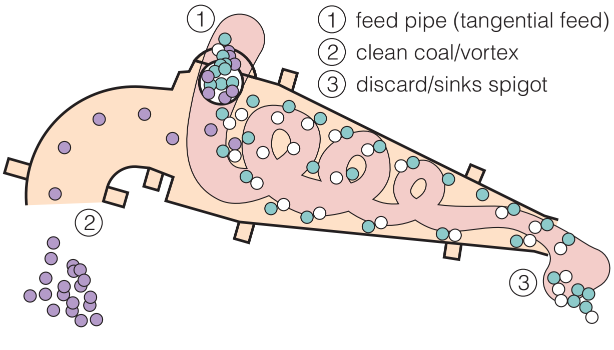

Figure 6 Dense medium cyclone (Parnaby, 2012)

Cyclone diameters can be as large as 2 m wide and capable of handling 500 t/h, such as those in operation in Australia. The separation of fines is poorer especially where cyclone units need to treat large topsize material. South

Table 3 **Preferred coal preparation technologies for major coal producing countries** (Ghosh, 2007)

	Comminution	Coarse washing	Medium washing	Fine washing	Dewatering
Australia	Crush to 50/60 mm	Mainly by DMC (diameter1000 mm or more) Drums or baths in some plants Jigs at few plants.		Spiral + Jameson or microceltechnology Limited use of froth flotation for metallurgical coal	Coarse and medium size-vibrating or scroll type basket centrifuges Flotation products-vacuum filters and screen bowl centrifuges Tailings-high rate gravity thickener and belt press filter
China	Crush to 100/50 mm	Mainly jigs (60%) Dense medium separator (Drewboy, vertical lifting wheel separator)	2-product dense medium cyclones (diameter 660–1300 mm) 3-product dense medium cyclones (diameter 1000–1400 mm)	Mainly flotation Column flotation (for very fine coal)	Mainly high frequency screen Centrifuge (vertical & horizontal) Pressure filter Fast diaphragm filters Plate-and-frame filters (slime recovery)
USA		Dense medium vessel	Dense medium cyclones (diameter<1000 mm)	Water-only cyclone Spirals Combination of both froth flotation (very fine coal after desliming: 35–40 µm)	Coarse size fraction - basket type dryers Fine size fraction - screen bowl centrifuges - combination of vacuum filter and thermal dryers
Russia		Heavy media baths & cyclones Jigging Flotation High-angle separators (water-only cyclones) Spiral separators Pneumatics (for thermal brown coals)			High frequency screens Centrifuges (settling & filtering) Belt press filters Continuous disc filter (operating under pressure)
Canada		Dense medium vessel	Dense medium cyclones (diameter <1000 mm)	Water only cyclone Spirals Combination of both Froth flotation (very fine coal)	
South Africa	Crush to 80 mm	Mainly large diameter pump fed dense media cyclones Dense medium separator (Wemco Drum, Drewboy) Jigs at few plants.	Smaller diameter cyclones	Limited use of froth flotation Mainly spirals	
India	Crush to 100/75/50 mm	ROM jigs (moving screen jig) Coarse coal jigs Dense medium separator Barrel washer	Small coal jig Dense medium cyclones (diameter 600–1000 mm)	Flotation Spirals Water only cyclones	Vacuum filters High frequency screen Centrifuge Belt press filter

African plants make use of two dense-medium cyclones, a large diameter for >10 mm, and a small diameter for 1–10 mm.

Fines are commonly separated in vertically orientated spiral cyclones, especially in the USA. These systems have few or no moving parts, and comprise of spiral columns which use gravity flowing water. Fines separation enables extraction of both fine coal and fine mineral matter, and within this system the two fines types can be further separated to ensure a clean coal fines stream. The recovery of fines is simple, but not always economical, so the potential for losses is considerable since much goes into settling ponds.

After coal has undergone various washing and separation processes in the CPP, the coal is wet so dewatering is carried out for almost all the fractions, from fines to 50 mm. Mechanical dewatering such as coarse coal centrifuge or screens is the most common procedure for the bulk of the mass, while water and heavy media magnetite separation is performed using magnetic drums. After dewatering it is assumed that natural air drying, especially in hotter climates, is a suitable method.

4.2 Losses from fine coal separation

ROM coal can yield a fines proportion of 10–20%. Coal preparation would typically involve screening using wet methods to provide tailings. According to Miller (2005), 20–50% of material that is delivered to a coal preparation plant may be rejected. Couch (1998) estimated that 600 Mt/y of residues produced from coal washeries in ten of the (then) top 17 coal producing countries. The *Swiss Centre for Life Cycle Inventories* (SCLCI) uses a value of 1167 Mt/y for global tailings production from hard coal.

Commercial factors that encourage the reclamation of fines that are otherwise lost is determined by the value of these fines. Provided the costs of recovering the fines are low, it can make sense to use them. However, they are often processed into a separate product, and not reintroduced into the hard lump coal product. In one example, Lewitt (2011) states that OAO Severstal saved 25 million roubles through recovering low ash coal slurries for use in power generation. The cost was around a third of that for buying and transporting coal from the open market. It was expected that this resource could be available for 30 years (OAO Severstal, 2004). Occasionally, recovering organic coal from residue deposits is not in itself profitable, but can provide some mitigation of the costs incurred for land reclamation (Department of the Environment, 2009).

Furthermore, where costs may be a factor, regulations governing the mining, preparation, and residue disposal can force the requirement for coal recovery. For instance, regulations that limit the disposal of materials can be such a driver. Planning permission for expanding tailings impoundments can be denied, and so a possible option for the operator is to recover material that has settled to release storage capacity. In some countries, legislation exists to ensure reclamation is done during the colliery closure process, although this activity may not necessarily be carried out by the bodies responsible for mine operation. For example, in the UK, The Coal Authority oversees mining activities, whereas local planning authorities oversee land reclamation.

4.3 The scale of loss from preparation

In this section the potential amount of deposited coal preparation residue is considered at a global level. According to Ghosh (2007), at a hard coal production level of 5000 Mt (possibly referring to 2004-05), there were considered to be 2500 coal preparation plants operating in the world beneficiating more than one third of world production; this would infer a washed coal throughout of at least 1500–1700 Mt/t. The losses occurring could be considerable. It is thought that between 217 Mt and 1090 Mt of discard material could arise from the global coal industry as this following section explains.

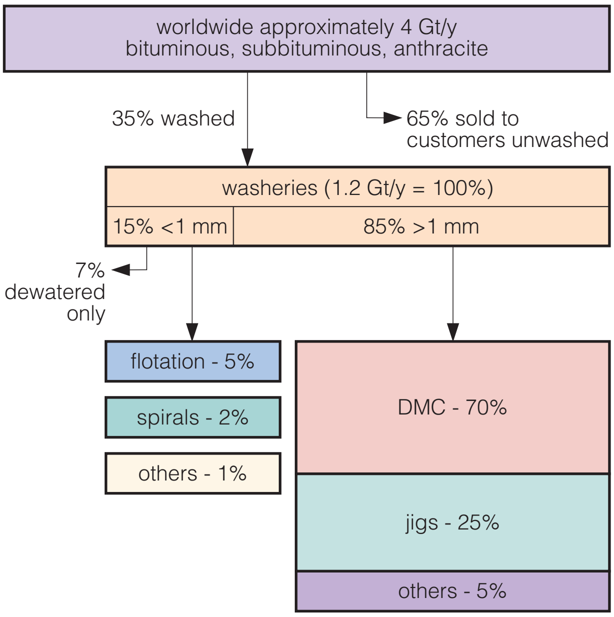

Figure 7 Flowchart of coal preparation residues, and throughput (Wittmers, 2011)

Wittmers (2011) presented a paper on the importance of coal washing/preparation as illustrated in Figure 7. The flow chart shows a fairly good representation of the status of modern coal washeries in the world today, and summarises all the relevant major methods used. The quantities are dated, with global production of 4 Gt, equivalent to the world production in 2003 with 2010 figures exceeding 6.2 Gt (IEA, 2012).

Assuming global hard coal production of 6.2 Gt, and the Wittmer's assumption of coal being washed at a rate of 35%, washed coal mass could be as high as 2.17 Gt. According to Miller (2005), 20–50% of the ROM material that is delivered to coal preparation plants may be rejected. This would suggest that with a 2.17 Gt mass of coal passing through the world's washeries, 0.43–1.09 Gt of material will be rejected. It is almost impossible to know with any accuracy how much of this is coal, as material with a potentially useful heating value will be lost with non-coal rejected material.

Recent research makes the process of determining the amount of fine particle discharge easier to understand and quantify. This is partly due to the fact that coal fines are an area of interest for many suppliers as a potential source of useful by-product. Processes to separate fine coal from fine mineral matter have long been tested and can be implemented with extremely simple and effective methods, namely the water only spiral systems which use centrifugal force as the separator. More expensive froth flotation systems are also used widely, and provide even greater effectiveness in fine recovery. These would normally be adopted for producing useful by-products, while washing run off which might otherwise contain both coal and rock be taken off to slurry ponds.

According to Lewitt (2011) fines associated with ROM coal are typically in the range 10–20% of a washery reject, the rest being middlings and coarse rock 'deshaling' waste. Using Lewitt's assumption, this reject mass could be as much as 217–434 Mt globally. This compares well with figures derived from Wittmers (2011) of 430 Gt to 1090 Mt for total discards. The *Swiss Centre for Life Cycle Inventories* (SCLCI) assumed a value of 1167 Mt/y for the mass of global tailings produced from hard coal production.

Table 4 lists a sample of countries that cover 90% of world hard coal production, and these producing countries gave rise to 374 Mt/y of washery rejects or discard material. Much of this was inert material, but it is not clear how much was coal. For the purposes of comparison, if these washery reject levels were added to the hard coal production for these sample countries (5.5 Gt/y in 2010), then the rejects account for 6–7% of production.

Assuming much of this is stable mineral matter, some of this washery waste is used as backfill in underground mines or for land reclamation. In Germany, coal production wastes are either injected into underground workings, or landscaped. Tailings are not regarded as waste. In other countries, coarse residues are used, while the fines are deposited. In South Africa, some settled fines are re-mined and incorporated into the coal supply to pulverised coal fired power plants.

According to the Australian Coal Association, 80% of all coal mined in Australia is washed including

Table 4 Global coal production and washery capacity

Country	Bituminous and other hard, Mt/y	Lignite, Mt/y	Washery capacity, approx Mt/y
World	6233	830	3000 approx
China (inc Hong Kong)	3019	0	1380
USA	917	65	636
India	532	33	139
Australia	353	67	335
Indonesia	336	0	17
South Africa	255	0	66
Russia	248	76	95
Kazakhstan	105	6	na
Poland	76	57	38
Colombia	74	0	4
Canada	58	10	47
Ukraine	54	0	
Vietnam	45	0	12
DPR Korea	32	0	na
UK	18	0	18
Germany	13	169	13
Czech Republic	11	44	
Venezuela	9	0	
Spain	8	0	
Philippines	7	0	
Turkey	4	68	
Botswana	1	0	
Romania	0	31	

almost all the hard coal (Lewitt, 2011). Queensland and New South Wales between them account for around 97% of Australia's coal production. It is has been estimated that about 15% of the coal slurry produced annually in the USA is disposed of in this way (Ducatman and others, 2010) leading to the loss of any potentially useable organic content. The rate of fine coal discard to impoundments has been estimated at 70–90 Mt/y (Greb and others 2006).

Washing of fines and slurry is recognised as a key problem due to the very low floatability of Indian coal, which cannot be separated easily using conventional methods. By 2006, the central coking coal washeries produced about 1.6 Mt/y of fines in slurries, but due the absence of flotation circuits the plants were not able to process the coal. The slurry material was discharged to impoundments as tailings, and *Central Institute of Mining and Fuel Research* (CIMFR, formerly Central Fuel Research Institute, CFRI) were anticipating this rate could rise to 4.75 Mt/y. Treating the –0.5 mm fines from Indian coking coals therefore requires techniques that accommodate their negligible floatability.

In Vietnam anthracite has been mined for over 160 years. There are five preparation plants with a total processing capacity of 12 Mt/y and the largest of these has a capacity of 6.1 Mt/y. In 2004, around 9 Mt were washed in preparation plants while the remainder was prepared by just screening, crushing, and blending. In 2005, Vietnamese coal preparation plants produced 6 Mt of dry rejects and 4.5 Mt of coal slurry. The coastal location of the preparation plants near the China Sea presents significant disposal problems and with three further washeries planned for installation would increase this problem (Bach and others, 2006 ; Bach and Gheewala, 2008, 2010).

4.4 Low rank coal and preparation

For low rank coals, additional moisture is best avoided, and the upgrading of such high moisture content coals may require additional dewatering or drying at additional cost. Dong (2011) reviewed some of the dry cleaning/separation methods such as air jigs, magnetic separation, aerodynamic separation, and FGX. Many of these dry methods of separation include fluidised bed separation, relying on the lighter density of coal compared with mineral matter to create the separation opportunities. Using air as a medium to suspend coal and mineral particles, in much the same way a DM vessel or cyclone works, is commercially available. Interestingly, these are mechanical systems that require more capital investment than liquid based systems.

The previous section raw coal mining and product preparation can be a large part of the supply chain for a minemouth power station. For export coal, mining and preparation can be a relatively short section of the chain, albeit constitute a significant proportion of losses (especially from mineral matter loss).

5 Verifying coal quantities and qualities in the supply chain

This chapter looks briefly at the aspects of measuring and verifying coal throughput as part of the auditing regime that occurs within coal contracts between seller and buyer. Measurement of the mass or quality of coal as it passes through the supply chain is necessary to verify that the coal that is sold is reaching the consumer satisfactorily. Responsibility and liability for the coal along the supply chain passes from coal supplier, to the shipper, and finally to the end-user at specific points along the supply chain.

Verification through sampling and surveying is often necessary to ensure coal consignments are correct throughout the journey to the consumer. A producer might carry out the same verification to ensure that the output from a particular seam or working face is in agreement with the planned production estimates with respect to in situ reserves. Further along the line, measuring tonnage and quality is necessary to ensure that the preparation plant receives the appropriate feed of coal for product blending, and so on. Throughout the transportation chain, auditing can be done by measuring stockpiles, weighing regularly at various points along the supply chain, and even measuring the volume held in a ship to ensure that any coal loss is either compensated for or made up with the appropriate quality coals.

5.1 Reconciling planned production with actual output

For the owner of a coal mine operation, estimating tonnage, moisture and ash of the raw coal delivered to the transportation system requires a number of assumptions. A detailed mine survey should establish the seam area, thickness, ash content and *relative density* (RD). Once a seam is identified for working sections, the volume and RD should be established to obtain an estimate of the tonnage that exists in the seam, and that which can be recovered.

Production over a period of time must then be reconciled against planned performance targets. Simple measures of production can take a variety of forms, such as weighing the coal as it leaves the mine on conveyor by a weightometer, and/or the mass moved by trucks. Moisture and ash content are also included. This then provides a ROM production yield. Coal can then be transported to the customer, or pass to the coal preparation plant. As mentioned in the previous chapter, further losses can occur as rejected material can ‘slim’ the coal tonnage with the removal of fines and coarse rejects. Throughout these processes, some mass balance must occur. The sum of the rejects and the saleable coal should be more or less equal to the mass of the coal entering the preparation plant, plus any additional moisture resulting from the coal preparation process.

5.2 Measuring output using truck quantities

In opencast operations, a simple way to reconcile mine output tonnage with mine stockpile tonnage is to monitor the amount of coal that is moved by the trucks (Holtham and others, 2005). Truck measurements can be done in a number of ways, either by using estimates of truck loads, or the actual weighing of the load in the truck as each load is carried. The means of tonnage measurement is by ‘truck factors’ – a proxy for the amount of coal a particular truck design can carry in a single pass, either by loading to capacity, or to a specified number of bucket loads, or similar measure. These factors could be calculated by a variety of simple methods:

- theoretical or nominal capacity as specified by the truck manufacturer;
- values calculated by the total production for a period and the number of truck loads moved;
- analysis of output from onboard truck weighing devices;
- data from fixed weighbridge.

Individual truck loads will vary considerably and so the use of truck factors will require some statistical smoothing to standardise the factor. Truck factors may need to be adjusted constantly. They do not necessarily require physical measuring equipment, rather procedural diligence to ensure consistency in each truck load. Truck factors are prone to variation especially in wet weather, or when there are changes in dilution from the ROM coal. The accuracy of the truck factor can be checked by the regular weighing of trucks and making appropriate adjustments. Weighing systems such as truck (weighbridge) scales, coal hopper scales, and conveyor belt scales can all be utilised.

5.3 Measuring materials during conveying

Weightometer readings taken from belt conveyors as the coal leaves the mine area to stockpiles or the CPP are another useful measure for reconciling tonnage with other methods. Weightometers or belt weighers measure the load on rollers that support the conveyor. These systems provide a continuous estimate of the tonnage being carried. Some weightometers measure whether any load is being carried and sophisticated meters measure the load within an error range of ±0.5%. A typical weightometer consists of an electronic load cell to measure the mass instantly, weighing at a single point, and when combined with the belt speed (such as a tachometer) can determined the mass flow rate.

The *Organisation Internationale de Metrologie Legale* (OIML) International Recommendation for belt weighers (OIML, 1997) divides weightometers into three groups, 0.5, 1, and 2 which refer to the maximum levels of error that are allowed for each class, these are ±0.5% error, ±1.0%, and ±2.0%. For instance, for 100 t of mass moving over a class 0.5, the reported tonnage must be within 99.5 to 100.5 t. A class 2 weightometer must report 98 to 102 t. Typically, the error for a newly installed system may be less than half of these specified by the OIML, but unless the weightometer is well maintained and calibrated regularly, it is unlikely such levels of accuracy can be maintained. Errors in belt scales can result from belt tension fluctuations and from off centre belt loading.

Resometric belt weighers differ from the conventional load cell system that most belt weighers adopt. A digital force transducer is calibrated to account for the conveyor belt weight. As the force varies with the moving load carrying belt, the resonant frequency changes in proportion to the load, and this change is processed electronically providing accurate weigh readings.

Since most belt weighers operate at a fixed calibrated angle, variations in the angle of a conveyor, such as those attached to mobile stockpile stackers or reclaimers, can be compensated by using specialist measuring systems. The Astatic Mass Zero compensation system can be fitted to such variable angle equipment. As such the mass of coal can be measured on the boom of a ship unloader, the conveyor, or the stacker if the coal is likely to be stockpiled at the port for any period.

5.4 Measuring the mass and volume of stockpiles

Stockpiles are located along the entire coal supply chain and serve a variety of purposes:

- to serve as a buffer between material delivery and processing, acting as a strategic stock against a short- and long-term interruption;
- to homogenise and/or blend coals to provide an even feedstock or the required quality;
- to act as transfer points between different transportation intersections.

At the mine, stockpiling is done by stacking or dumping from either mine haulage trucks or conveyor booms. Stockpile areas are subject to coal spillage on the floor and airborne dust. Spillage and losses can also occur during stockpile reclaiming when done by hydraulic shovels, grabs or bucket wheel reclaimers (similar to those used for bucket wheel excavators for overburden removal at high capacity lignite mines).

Coal auditing is done to assess both quantity and quality. One reason is to determine whether the consignment meets the contract specification agreed between the buyer and seller. While quality is one parameter, volume surveying is another auditing measure that can be carried out while the coal is being stored in stockpile.

Tonnage mass of a stockpile is measured using simple volume and density measurements. Book inventories are maintained from recorded weights of coal going into and coming out of the stockpile. When the book inventory deviates markedly from the measured inventory, the book inventory is adjusted. Sometimes the adjustment is an addition to the inventory, but often the book is less than that measured mass (Rose, 1992; Voorhis, 1988). As such, these losses may or may not be made up with additional coal blending.

When looking at stockpiles, the shape and size can vary, but typically stockpiles are either conical or peaked embankments with circular ends. These shapes are created by the gravity settlement of any dry bulk goods in a granular form. The same stockpiling shapes and size will apply to grain, ore, cement, and other construction material.

Determining volume can be done using ground or aerial surveys. Pile surfaces should be smooth (no washouts or gullies) and the measuring points taken at regular intervals. Because stockpiles come in all shapes and sizes aerial images, known as photogrammetry, have been a common method for surveying large stockpiles for more than 20 years with an accuracy of 5% for even large stockpiles of 50,000–500,000 t (Craven, 1990).

For ground surveys, the stockpile profile is surveyed using a theodolite which employs a laser for distance measurement. Measurements of the vertical and horizontal angles enables each apex to be accurately positioned on the pile surface. This is done many times to establish a three dimensional profile of the surface. Since large stockpiles can deform the ground over the area of its footprint, holes can be drilled down to the substrate and depth determined using a laser so that the material below ground level can be determined. Volume accuracy is also affected by the smoothness of the stockpile, the number of samples taken, and the location from which the sample is taken. Naturally this affects the calculation for larger stockpiles. Numerous laser based instruments are available capable of determining large stockpiles. The accuracy of stockpiles can be measured to ±2%.

Measuring the mass or tonnage of the stockpile is simply a function of the volume multiplied by the density, taking into account moisture content of the bulk coal. The density will also be affected by compaction of the pile and particle size will determine the level of air spacing between particles. As a reminder, the volume of a cone is ⅓πr2h (r = radius; h = height) while density can be simply calculated by sampling of the product (*see below*).

5.5 Measuring the density of coal stocks

While visual inspection and measurement of volume is more or less straightforward, density can be more complex as density variations occur within stockpiles depending on the degree of compaction which is determined partly by the height of fall from the stacking boom, the piling irregularities that might arise from arranging the mass with a dozer, the particle size of the coal product, and the moisture content. Variations in bulk density of the stockpile can create error in mass calculations. Stockpiles are subject to considerable compaction from the action of dozers on the stockpile surface. Empirical methods have also been published where calculated bulk densities are within 5–7% of measured values (Standish and others, 1991; Yu and Standish, 1991). This suggests that calculating coal volumes can be fairly accurate, but throughput could feasibly be subject to error if relying on calculations alone, and so will require verification with further measurement up the coal chain. A 5% underestimate could lead to a missing 50 kt of coal on a capesize shipment of coal and, at times of high prices, amount to a discrepancy of $500,000.

Nuclear depth gauges are the most common method of measuring density. This can be measured at different locations and depths within the pile. Vertical and horizontal measurements are determined to ensure the near exact location of each density reading. Calibration errors can occur since coal composition can affect readings. Stockpiles with coal blends or mix can create difficulties (Craven 1990). Forming the hole to take the readings itself causes compaction and increases the density of coal close to the hole leading to error of ±3%. Access holes should be backfilled to reduce the risk of spontaneous combustion.

5.6 Verifying seaborne shipments

For seaborne traded coal, there are various points at which coal can be weighed and mass can be calculated. Visual inspection and expert surveys are also commonly performed on coal entering a country (or indeed leaving a port), by a vessel inspection while the coal is loaded on the ship.

Ocean vessel draft surveys have been the internationally accepted method of establishing the weight of bulk cargoes. Draft surveys involve taking readings (*see* Figure 8) which may involve descending down a rope ladder or moving around the ship in a small boat. The surveyor must also take samples of seawater that the ship floats in. Deductions are made for the volume of liquids that are carried onboard such as fuel oil and water as well as deductions for stores. Finally the nominal displacement of the ship needs to be established based on calculations of the original shipbuilder for weight of steel and materials used for the construction of the ship.

Correction factors are used to improve the accuracy of the draft readings. As no two ships are the same, and export and import ports located in different parts of the world, even water density and deformation in the ship's heel, trim and hull need to be accounted for. Changes in the content of the buoyancy tank and storm water intake can also affect the outcome. Subjective reasoning plays a part in some of this error. According to Stewart Surveyors, these errors could give rise to disputes between sellers, vessel operators, buyers and surveyors. Such errors may be less significant in smaller shipments, but in shipments of perhaps Panamax or Capesize vessels, errors could lead to a discrepancy of $750,000 to $3 million, depending on the price of coal, and whether the commodity is steam coal, coking coal, or indeed any high value dry bulk.

Figure 8 Illustration of ship draft markings (Wikipedia, 2012)

5.7 Sampling coal for analysis

While much of this discussion has been on the measuring the mass of coal passing through the supply chain, quality and heating value are equally essential criteria to be audited. In the early stages of assessing coal in a reserve deposit, core samples from drilling are used. These will provide a vital part in the assessment to determine which parts of a coal deposit are worth extracting, and of the subsequent timing and sequencing of the mine operation that follows. Selective mining is one of the techniques that can be used to improve the quality of mined coals. This is an 'expert' system/procedure which will not be discussed in this report but which is an important preliminary step in coal reserve exploitation.

Whether the coal is in situ or in a stockpile, it is one of the most complex materials to analyse (through sampling) because of the number of contaminants/impurities that are present in the composition, as well as its tendency to particle segregation. Sampling is further complicated by the equipment available, the quantity to be represented by the sample mass, and the degree of precision required. In addition, the coal may be a blend of different coal types. How the coal was blended can have a profound effect on the way a representative sample is obtained; depending, for instance, on whether it is intimately mixed or not. Biased results can be introduced by the sampling procedure as well as by sample preparation and analysis. The main sources of bias during sampling can be avoided by:

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

Sampling is commonly carried out from ROM coal on a conveyor belt, and from belts at various stages in the supply chain including the feed into a boiler. It is also carried out on the coal stored en route between the mine and the end-user power plant or industrial user, particularly where the coals are traded. The purchaser needs to be assured that the coal delivered is of adequate quality, and there will be adjustments made to the amount paid if the material is off-specification.

Even when online analysis is undertaken of the coal carried on a conveyor belt, the device is calibrated (and recalibrated) against the laboratory analysis of samples so that sampling procedures are still important. 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 larger lumps.

When sampling to determine whether a coal consignment meets the contract specification, it is important to take samples and divide into three – one each for the supplier, the buyer, and for independent analysis in case of dispute. Mechanical sampling systems that are capable of collecting unbiased samples from moving coal streams can be categorised into two types:

- 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;
- 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.

Sampling coal when it is sticky is a problem since it can 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. 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. Technological advances in mechanical sampling systems, and a comparison of cross-belt and cross-stream systems is given in Reagan (1999).

5.8 Determining coal quality from laboratory analysis

Because coal has been mainly used inside its country of origin, many different standards for coal testing, analysis and sampling have emerged, and although they are broadly similar in principle, there can be significant variations in detail. Some (such as the German standards) are biased towards assessing the coking behaviour of a coal, rather than its combustion characteristics. Among the principal standards used are those of:

- the American Society for Testing and Materials (ASTM);
- Standards Australia (AS);
- the British Standards Institution (BSI);
- the Standardization Administration of the People's Republic of China (with the prefix GB);
- German Standards (with the prefix DIN);
- Russian National Standards (with the prefix GOST);
- the International Organisation for Standardisation (ISO).

The data obtained from coal analysis may determine which parts of a coal seam are extracted (using exploration data). It will provide vital data relating to the design and operation of a CPP, and the information will establish the value of the coal product, and thus, broadly, the price at which it may be marketed and the use to which it is put.

For the power plant operator several aspects of the analysis provide important information which will affect the economics of running the plant. This is because the quality of the coal being used will affect its heating value, the amount of ash deposition and corrosion in the boiler, and the costs associated with flue gas cleaning. Prior knowledge of the exact composition of the coal being fed can help the boiler operator to minimise the overall and long-term operating costs of the individual units. The main components which may cause operational problems are associated with the mineral matter present, or sometimes, in the case of low rank coals, of organically bound impurities. If the coal composition and its properties are varying as it is fed into a boiler, this can cause additional uncertainties and the provision of information from on-line analysis can be of value.

However, both the laboratory and online methods of analysis have limitations (Nalbandian, 2011). The principal limitations being that laboratory conditions do not always represent the operating conditions of the plant in which coal is used (such as PCC boilers). Coal samples can oxidise between the taking of the sample and its delivery to the laboratory. Lower rank coals are generally more readily oxidised and as a result, more care is necessary in this respect.

Proximate analysis provides the basic quality measurements of a coal, and includes measuring a sample, or a series of samples for the percentage content of moisture, ash (A), volatile matter (VM), fixed carbon (FC), sulphur (S), and calorific value (CV). These values can be presented in any of the bases listed as follows:

- as received (ar): includes total moisture (TM);
- air dried (ad): includes inherent moisture (IM) only;
- moist, ash free (maf): excludes ash but includes moisture;
- moist, mineral matter free (mmmf): excludes mineral matter but includes moisture;
- dry basis (db): excludes all moisture;
- dry ash free (daf): excludes all moisture & ash.

One of the critical values to arise from proximate analysis is the calorific values (CV) often referred to as the heating value. This can be calculated in a variety of units as follows:

kcal/kg – kilocalories per kilogram
MJ/kg – megajoules per kilogram
Btu/lb – British Thermal Units per pound

The CV of a coal can be commonly presented in either gross or net. The gross CV or higher heating value' (HHV) is the CV under laboratory conditions. It includes all the energy *available* within the fuel, including the latent heat of vaporisation which assumes the water produced from combustion is condensed and useful. The gross CV (GCV) involves burning a weighed sample of coal in a strong sealed vessel called a bomb calorimeter. It has a thermal jacket whose temperature is carefully controlled by a microprocessor system which also fires the 'bomb' and measures the resultant temperature change. The test continues until equilibrium has been reached. The GCV is calculated from the temperature rise in the water in the calorimeter (Carpenter, 2002).

The net CV or 'lower heating value' (LHV) is the useful calorific value in boiler plant, in that the water vapour produced from combustion of the fuel is not 'useful' and therefore condensed later in the process. As such, the latent heat of vaporisation is subtracted from the GCV. Even though the measure is under laboratory conditions, it is important to have a benchmark measure whish uses the same equipment and conditions worldwide. It may also be necessary to test for GCV to calibrate online analysers for consistency and accuracy.

Ash analysis provides a measure of the incombustible material present, and the composition of the ash can provide some guidance about how it will behave in a PCC boiler. There are a number of different standards used (Carpenter, 2002). However, the conditions encountered in the boiler are markedly different from those used during the analysis with much higher temperatures and variable oxidising conditions. There may also be interactions between various ash forming components which differ from laboratory conditions. This is why ash behaviour in terms of its slagging and fouling characteristics cannot be precisely predicted from the ash analysis results.

5.9 Determining coal quality from online analysis

The use of laboratory tests is essential to ensure that the coal being passed through the supply chain is as specified in the contract between the supplier and buyer, or any third party handling the coal, even if the conditions differ from that in the boiler. Physical samples removed from the coal chain can be time consuming, and so the adoption of 'online' analysis can provide a useful and extremely fast method of proximate testing of a coal. The same issues arise in designing an online system, where scanning a small sample of coal, relative to the thousands of tonnes passing through every hour, requires accuracy and must represent the full tonnage passing through as much as possible, with little bias or error.

The previous discussion has shown that obtaining samples that are representative of the many thousand tonnes of coal in a stockpile or consignment can be an exacting task. By its 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 and, perhaps more importantly, coal-fired boiler operating conditions (Nalbandian, 2005).

Online analysers are the only system which can show variations in coal quality as they are delivered. In systems where coal can be analysed directly on the conveyor belt, errors due to sampling and sample preparation are minimised. However, online analysers are expensive and their cost-effectiveness depends on the site and application. The chosen samples must represent the range of coals which the machine might be expected to encounter in service. Analysis of coals different and beyond the range of the initial calibration will necessitate re-calibration. The calibration may also drift over time, requiring the analyser to be frequently re-calibrated. Online analysers have been employed:

- to monitor the incoming coal at a site to determine whether it meets the required specification. In addition, the analysis data will provide information of direct relevance to controlling the operating conditions in the boiler plant which form a key component within an 'expert' system for combustion purposes;
- 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;
- 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 online analyser to control the feeders beneath the stockpiles involved; and, for monitoring coal during reclamation to check it meets the desired specification.

Some of the main types of coal analysers are described in Nalbandian (2005) and Woodward (2007) and include a variety of equipment that detect ash-only or multi-elemental analysers, such as:
- *dual-gamma gauges* (LET or DUET) are used as ash-only gauges. They measure the natural gamma emission from potassium or thorium in the conveyed coal and calculate the ash content by combining this with a measurement of the weight of the load. In *dual energy gamma-ray transmission* systems, the 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 at different points. These may provide a better measure of the ash content but varying chemical composition, especially Fe_2O_3 content, can lead to up to 3% error. Triple energy gamma-ray transmission systems have been developed. Although natural gamma systems may not be the most accurate, they are generally less costly than other methods;
- *prompt gamma neutron activation analysis* (PGNAA) provides the elemental composition 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 Si, Fe, Ca, Al, K, Na and Ti). A separate ash analyser is included in some PGNAA systems. The heating value (if a moisture meter is present), ash fusion (slagging factors) and oxygen content can also be indirectly determined based on the ash composition. 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;
- 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.

In China and India, many coal preparation plants lack online analysers, and the few that do use ash-only analysers. In the USA, PGNAA analysers are more popular and most are used for measuring coal feed into a preparation plant. 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.

There are situations, such as small operating units, where the use of online 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 and require no artificial radiation sources and are relatively inexpensive. 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 accuracy of ash determination by this method is relatively unaffected by variations in ash composition or normal variations in moisture content, but a large number of measurements have to be taken over the whole of the coal stockpile.

6 Coal loss in storage and transit

Measuring tonnage and quality of coal throughput throughout the supply chain is important to ensure that the coal, whether blended or not, meets the correct specification. As the coal passes through the supply chain is loaded into trains, barges and ships, the onus of responsibility and liability also passes to the custodian of the coal, from seller, to shipper and then end-user (*see* Figure 1, page 9). Losses can be experienced in transit between the mine and the preparation plant, but also at any point after the coal has left the preparation plant for distribution to the market.

6.1 Deterioration and oxidation in stockpiles

Figure 1 illustrates the numerous points at which a coal may be stored and transported from the mine to the power station. While the coal is in stock, there can be some deterioration of coal. The period in which coal is stored in stockpiles can vary. In periods of severe shortage, stockpiles can have a fast turnover, with stocks lasting from just a few days – as experienced in India in the summer of 2012 – while stocks can last for months during periods of surplus production and lower demand – as seen in China in the latter half of 2012.

In South Africa, stockpiles average 40 days of supply for power stations operated by the state utility Eskom (GBSA, 2012). As Eskom keeps stockpiles for longer periods, coal deterioration can occur during seasons when there is stock accumulation. Similarly, from a supplier’s point of view, one of Indonesia’s leading producer of export coal, PT Adaro, has some of the largest opencast mining operations in the world where coal can be stockpiled for 30–40 days prior to shipment to the world market.

Normally, in modern power utilities stock accumulation occurs just prior to high demand seasons, as fuel buyers prepare the power plant coal supply for colder and darker winter periods, or for increased output in summer months (for cooling equipment). Stock build can occur unintentionally when competing fuels such as natural gas displace coal generation forcing coal generators to run at lower loads. Where stock levels are high, and the turnover of coal in the stockyard is low, coals are susceptible to greater weathering and atmospheric oxidation.

Weathering can result from a variety of reasons. The good wetting properties of coal means that excessive rainfall can wash away fine coal dust, although controlled wetting with water sometimes mixed with appropriate chemicals prevents dust pollution and helps reduce loss. Rainfall can also wet the coal stockpile, elevating the moisture content of the coal. Combined with sub-zero temperatures, moisture in the coal can freeze and increase the degradation of friable coal.

The organic nature of coal means weathering and oxidation leads to reactions with macerals and minerals with oxygen and moisture at ambient conditions. Macerals consist of phytogenetic organic substances, consisting of plant remains with distinctive chemical and physical properties. While coal consists of the woody material, macerals might be leaves, shoots, spores, pollen, and so on.

Weathering is the physical degrading of the material for example by frost action and can break down a coal physically and hence increase the exposure to oxidation. Oxidation alters a coal’s property and structure and so the subsequent quality change can alter the coal’s behaviour during controlled combustion in the boiler. The changes within the coal are not reversible, and so can lead to the economic devaluing of that particular shipment of coal, and may require further blending, adding cost and volume to the stock, or an adjustment to the price agreement to reflect the change.

According to the Indonesian PT Adaro Guide to Stockpile and Storage (Adaro, 2012) coal degradation is largely dependent on air humidity and wind conditions. The Adaro Envirocoal brand is high in moisture, and loss of part of this moisture from the coal on stockpile faces causes breakdown or weathering of the surface coal particles. This breakdown tends to affect the outer ‘skin’ of the surface coal, a bulk of the stockpile remains unaffected. Frequent application of water in the form of a mist to maintain moisture condition of the coal reduces degradation. However, in everyday practical terms, keeping all coal stockpiles in such as vast production facility may be impractical, so a certain amount of degradation is accepted, with occasional fog spraying to reduce dust pollution.

Adaro makes reference to US studies on the effects of long-term storage on coal quality. All open coal stockpiles absorb moisture from rainfall and suffer from CV loss. Excess moisture drains through the base of the stockpile although some moisture is retained in the stock. It is possible that the saturation point of coal is lower than the moisture content, hence the coal has a capacity to absorb and retain more under certain conditions. CV loss from oxidation in the stockpile is considered to be small according to Adaro. Given that subbituminous coal has a greater risk of self combustion than most other coals, clearly it is a manageable problem.

6.1.1 Quantifying loss from self-combustion

As far back as 1912, heating value losses were studied and estimated for coal stockpiles (Porter and Ovitz, 1912), but these measured heat value losses are for static stockpiles that probably do not experience large throughput of coal. Also, the granularity of the coal may have been different in the early 1900s. Today’s stockpiling consists of high throughput and cycling of coal supplies, and may reach the power station in a matter of weeks.

Quantifying these losses (in mass terms) is impossible to generalise since the conditions of loss depends on the coal type and the way the coal is stored. In energy terms, it is reasonable to assume losses are probably no more than 2%. In the 1960s, the UK Central Electricity Generating Board reported on stockpiling and suggested good practice involved the layering, compacting and sloping of the ends and sides of the pile. After a number of years, losses (on a dry ash free basis) in the heating value was 0.65%, equivalent to the losses incurred in just a few weeks experienced by US coals on barges stacked in looser conical piles. Subbituminous coals can lose 1.5% of their heating value during transit between the mine and the power station (Lehto, 1995).

Presumably losses are a function of the time coal is left in stockpiles, and so a faster throughput of products, and particularly during periods of high demand, such losses are reduced. The rate of oxidation rate is dependent on coal rank, with low rank coal being are more susceptible to oxidation than high rank coal, hence most of the observations have been for subbituminous coals. Based on figures in the 1990s, losses of PRB were encountered within ten days from the open air stockpiles. Losses were also experienced in enclosed storage of Montana coals. After two years, long-term stockpiles can lose as much as 1 $/t of value (assuming prices of the day) due to the loss in heating value from oxidation. In Brazil, low rank coals in stockpiles for ten months resulted in a 5.6% loss in heating value (from 28 MJ/kg to 27.4 MJ/kg).

Freshly mined high volatile coal when stored in bulk undergoes low temperature atmospheric oxidation due to the presence of methane and other volatile matter on the surface. This exothermic oxidation causes the rise in temperature of the coal and if the heat is not removed, a stage comes when coal begins to burn on its own. This is called *spontaneous combustion* which leads to outbreak of fire in the stored coal, and can take place rapidly as in a furnace or slowly in a stockpile. Low-rank coals are most susceptible to spontaneous combustion. Self-ignition or spontaneous oxidation is usually predominant in fresh coal. If the material is mined within one to four months prior to storage it is less susceptible to self-ignition. Coal already stored longer than six months with exposure to air is not usually liable to self-ignition.

Some coals stored over a longer period absorb oxygen, and for every 1% increase of oxygen content the heating value of coal can potentially decreases by 1%. Oxidation can be at a low level, say 50°C, or at a high level of more than 200°C. If the temperature rise due to oxidation does not exceed a critical value (500°C for lignite and about 800°C for bituminous coal), spontaneous ignition does not take place, but the quality of coal is affected (Nalbandian, 2010). Whatever the level of combustion, changes to the coal stock are inevitable. The web resources www.coalspot.com published a brief on the oxidation of high volatile coal. Spontaneous oxidation can cause:

- a decrease in calorific value;
- a decrease in carbon and hydrogen and an increase in oxygen %;
- a reduction in size grading (due to crumbling, the coal lumps gets broken down into small pieces);
- fire, if the temperature exceeds the critical value.

As the maturity of coal increases, its tendency to catch fire during storage decreases. Furthermore, for every 10°C increase of storage temperature the rate of oxidation doubled. High heat losses can occur in loosely compacted stockpiles, and in addition windy condition can accelerate air movement and so is not unknown for exposed coal to lose as much as 19% per year of heating value for subbituminous coal in measurements of Spanish coal (Miranda and others, 1994). Compaction of smaller particle coal can therefore reduce these effects, along with protection from winds.

6.1.2 Hazards of stockpiling lower rank coals

Indonesian coals are high in moisture and, as previously mentioned, can degrade at the surface due to natural drying. However, the addition of moisture is sometimes required to suppress self combustion. MTD (2009) reported on coal storage problems for Indonesian coals, where coal stockpiles would reach 50°C temperatures and would need to be cooled using water monitors. However, water monitors created vertical faces which increased the surface area, and paradoxically improved air flow as hot air rose through the pile, and cool air passed down the vertical sides creating good circulation of O_2. Using water for coal cooling is not always appropriate according to Adaro (2012).

Losses were therefore incurred in an effort to reduce the heating as coal was removed with front end loaders, spread in thin layers to cool the coal, and the pile compacted with sloping edges. This resulted in reduced tonnage, reduced heating value, while the ash and moisture contents rose. Ways to avoid self-ignition or spontaneous oxidation included:

- Cooling by ventilation or by water spraying to avoid increase of coal stock temperature. The former is recommended by PT Adaro by removing the heated coal, and laying in a flat 20–30 cm layer to allow the coal to cool. The latter can be hazardous, but may be appropriate under some circumstances.
- Storing the coal in smaller lots of stock pile (<200 t/pile) to enable better cooling to prevent heating up of coal stock.
- Reducing access to air, by storage in compressed piles (packing coal tightly and compacting by running dozer /loader compactor over stock pile) or storage in closely covered air tight enclosure.
- Reducing the fine powder content in the coal.
- Height of stock pile limited to less than three metres for high volatile coal and less than two metres for lignite.
- Coal which is stored for six months is more stable. Coal which was mined and supplied within four to five weeks is however more risky.
- Conical heaps are to be avoided. It increases the surface area and the risk of fire.
- The storage location should be such that any external source of heat is to be avoided (for example steam pipes, flue ducts).
- Follow the practice of ‘first in, first out’ stockpile management. The old coal should go for consumption and fresh coal should go for storage. Regularly check the pile with long portable thermocouple temperature indicator the pile temperature. Water hydrant points to be provided near

to the pile. When fire is noticed in pile with small emanation of smoke, large volume of water should be sprayed. Spraying very small quantity of water will not quench the fire instead it will further enhance the fire due to water gas reaction: ($C + H_2O \rightarrow CO + H_2$)

The problems associated with oxidation are often found while the coal is stored in transit, particularly in a cargo hold of a barge or ocean vessel. These issues and ways to alleviate the hazards are discussed later in this chapter.

6.2 Losses through spillage and dust

The friable nature of some coals means dust can be generated throughout the coal supply chain, whether it is during mining, transportation, storage or various handling processes. One obvious method of loss is from spillage and dust pollution. Spillage can occur at the mine during coal moving, leading to coal covering the floor of the mine and spreading throughout the site. However, during transit, spillage can occur at either the transfer points or during transportation.

Losses in transportation may come from the uncovered moving of coal using trucks and rail where wind and agitation can cause losses. Dust and spillage can occur regularly during the transition between two different storage modes, whether it is the static stockpile in a port or minemouth, to the rail car or hold of a ship.

Figure 9 Opencast mining operation in India (MoC, 2011)

Figure 9 is an example of a growing number of larger-scale opencast operations in India (MoC, 2011), and demonstrates how coal spillage can cover large areas of a mine. This is by no means restricted to Indian coal mines, but applies to mines across the world, even by the most advanced operations.

Temporary stockpiles might be located ad hoc around the mine site to ensure the passage for mine vehicles is clear and safe. However, as the seam face migrates to other areas, much of this discarded coal will probably be beneficiated wherever the piles contain saleable coal, or end up as landfill.

6.2.1 Coal loss from conveyors

Fine airborne particles are a particular problem, not just from a coal loss point of view, but as a hazard due to the risk to respiratory health, explosion, or reduced visibility. Coal spillage is a nuisance, and clogging from spilled coal, especially if it is wet, leads to stoppages of the throughput. Since conveyor systems are used throughout the coal chain, many of the issues and solutions might apply to any point between the seam face and the end-user.

In terms of minimising dust, one technique involves wetting the surface of the stockpile to inhibit the airborne suspension of dust. One drawback of course is the addition of moisture, which reduces the heating value of the coal and adds load to the transportation system, but this may be an acceptable loss given the considerable nuisance excessive dust can cause in windy conditions.

Wet suppression involves little more than water spray that forces dust particles downward due to gravity as the wetting properties of fine coal are generally good. Water spray is effective at dumper areas and transfer points. Costs can be fairly low. Foam suppression is effective and lays a heavy spray of foam that blankets dust before a cloud can rise. Foam reduces the static charge of particles and increases molecular attraction between them and larger coal particles. This method requires foam surfactants, water and compressed air, but the water requirement is considerably less than that needed using wet suppression. The wet methods materially add to the coal mass, effectively altering the weight/mass ratio and cohesiveness of the material. Wetting the dust material either within a mass or as it begins to become airborne increases the mass of the particles such that further dispersion is minimised. The cohesion of the material as a result of using suppressant solution makes it difficult for air currents to pick up smaller particles.

Residual suppression consists of binders, humectants and surfactants that can be applied to the coal on the conveyor belt prior to dumping into a stockpile. As such, the entire stock can be treated and need only be treated once, after which the coal is treated effectively for the rest of the supply chain. This also aids compaction in the stockpile, a desirable benefit for reducing self-heating during storage.

Studies of water systems with chemical systems suggest that 2–4% surface moisture is added to coal by water spray systems, compared with 0.15–1.0% for chemical systems. In effect, the alleviation of dust decreases the heating value of the coal, so the gain in (retaining) finer particles could also lead to a small loss in value. However, the benefits of operating in a dust free environment outweigh this.

Foam technology adds typically less than 0.2% of moisture. Added moisture increases the usual problems for boilers and steam generating cycles, but issues that are often ignored include the problems in belt slippage and the increase in wet and sticky fines that can accumulate within chutes and around transfer points. These can accumulate and form clumps which could affect friction in moving parts, obstructive to the drier coal particles. The author of the paper cited two examples for lignite mines in Germany where such method are deployed for dust suppression.

Excess water present in newly mined coal can cause spillage on conveyor systems. Wet coal can be mined where deep mine faces are subject to water migration and where normal pumping is difficult at low points of the active mining area. Wet coal causes slippage in the coal load on conveyor belts resulting in large spills resulting in production stoppage and clean-up. Normally most of this coal is recovered, but the main problem is the stoppage time and impact on continuous productivity. Transfer points between conveyors are parts of the coal supply chain that are simple, and assumed to perform faultlessly, but as a result are not considered a source of concern. Design of the transfer points is constrained by the predetermined location points of the conveyor systems, resulting in possibly less than optimal transfer design. Conveyor systems are typically rubberised belt systems for long distances or (for ROM coal) the belts are generally armoured steel chains to accommodate larger pieces and mineral matter.

With the rubber belt system, coal is generally funnelled onto the chute with some care, while armoured belts have to be robust enough to have large coal lumps spill onto them from a height of up to several metres. To avoid any obstruction, coal spillage from the armoured conveyor should be regularly cleared to allow a clear advance for the long wall system, as such losses are fairly minimal.

Dodds-Ely (2011) describe the construction and operation of rubber conveyor belts. Rubber belts with ‘multi-ply’ textile reinforcement are the most commonly used type within the dry cargo industry and usually consist of two elements. The basis of every conveyor belt is the carcass, which typically contains layers of extremely strong, but flexible fabric embedded in the rubber. It is the carcass that provides the inherent characteristics of a conveyor belt such as its tensile strength and elongation (elasticity or ‘stretch’ under tension).

Dust generation around coal conveyor transfer points has always been a problem. Conventional systems use expensive enclosed skirting systems, baffle boxes, or dust collectors. Whenever a stream of coal hits a stationary chute wall, or is required to abruptly change speed and/or direction, the forces generated from impact can degrade the material and can cause fracturing of the particles. This degradation reduces material particle size that may or may not matter to the operation. One option is to install a seal around the transfer point in both directions of material flow, and then use dust collection systems to circulate the atmosphere and capture the visible and respirable dust.

According to a US engineering company Flexco Engineered Systems, that specialises in material handling transfer, controlled material flow can reduce the dust build-up by the reduced impacts and energy changes in the material flow during the transfer (Flexco, 2010). Reduction of the visible and respirable dust levels reduces the demands on the dust collection system. This is called an ‘engineered transfer point’, where the transfer of coal is designed carefully, taking into account the velocity and direction of both conveyor systems rather than having the coal from one conveyor effectively ‘collide’ with the onward conveyor belt.

The idea of the engineered transfer point is to take the material from the discharge belt, deliver it to the receiving belt in the direction and speed of the receiving belt, do away with dust and eliminate the need for traditional dust suppression equipment such as distilling boxes and skirting systems (Blankenship, 2006).

Despite the benefits of engineered transfer points, conventional methods still provide many systems across the world with an adequate solution to dust and spillage reduction. One example is the Lambton power station (Ontario Power, Canada) which installed a system for its 2000 MWe power stations that has 48 conveyors feeding coal to the plant. The reason for the design was the possible future elevated dust levels expected from coal switching. The existing transfer system was 36 years old and so due for replacing but, instead of repairing and replacing the dust collection system which would have required a large capital outlay, some money was saved by adapting one of the transfer points with reduced material turbulence and less impact on the transfer chute on the receiving belt. There were two conveyors capable of transferring 19 kt/d running as a replacement for each other during frequent down time due to spillage. However, as new skirt boards were installed, the spillage and loss was reduced so the need for the extra conveyor was minimal, therefore increasing the life of both conveyors. Before the installation of the skirts, spillage would amount to 2–3 feet every day around the tail pulley, and required 15 hours of clean-up every 12 days.

Spillage in other power stations with coals with different properties suffer from pluggage due to high moisture. While this does not necessarily lead to coal loss over a long period of time, say between maintenance schedules, losses might occur at any point in time over hours or days, requiring extra material to be made up. At any single transfer point the losses are likely to be negligible, but if coal was being transported a great distance with numerous transfer points the losses could add up.


Figure 10 Joy Mining Machinery 12CM27 Continuous miner (KCE, 2012)

In a paper written by Mogodi (2010), the Anglo Coal Zondagsfontein colliery in Mpumalanga Province suffered losses from a mismatch of conveyor capacities. The mine is an underground operation using bord and pillar methods at two seams (numbers 2 and 4), and started operation in 2010. The process uses continuous miners, an example is shown in Figure 10, and each of the eight continuous miners use cutting drums to spray water and cut the coal face. The machinery also has built in a crab like claws that scoop the coal within the miner which transfers the coal to a shuttle

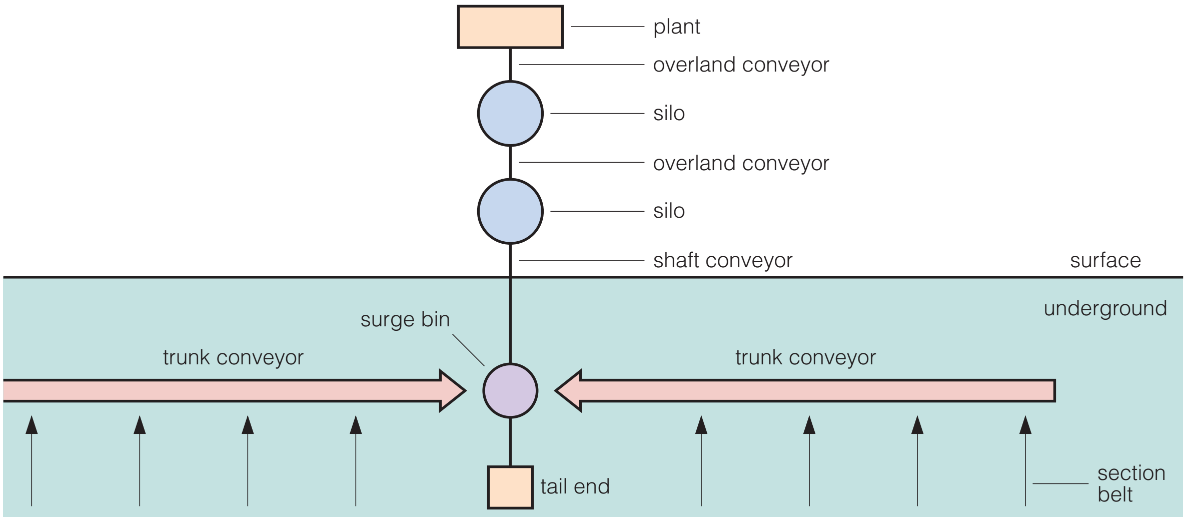

Figure 11 Coal clearance system using a surge bin to minimise spillage and loss from linking conveyors (Mogodi, 2010)

car. The shuttle car then moves a short distance to a feeder breaker to crush the coal to an appropriate size which then transfers coal to a conveyor belt, described as a 'section' belt. Numerous coal faces may have section belts, which than transfer the coal to a 'trunk' belt' which then transfers again to a 'shaft' belt' which as main artery through the coal mine to take coal to the surface. Where the shaft belt has a capacity of 4200 t/h, eight section belts feeding at rate of 1000 t/h each is clearly not adequate to accommodate full capacity production without some sort of spillage and buildup. In addition to the increased overloading and wear on the shaft belt, there is the risk of spontaneous combustion of coal, methane explosion, and coal dust explosion. Solutions to this might include increasing the belt speed of the shaft belt, but this increases belt wear and power consumption. High speeds however give rise to increased float dust and spillage as coal is almost lifted off the belt at higher speeds.

Reducing the feed from the section belt and trunk conveyor by slowing these belts is possible, or the installation of a surge bin, which effectively contains the flow of one belt while measuring the output to the speed and capacity of the shaft belt (*see* Figure 11). Spillages between two conveyors is minimised although surge bins have the problem of being immobile installations. If one component fails, the entire operation must be halted as all conveyors may pass via a single surge bin. The surge bin is a high cost solution, and may not be suitable for all mines, but it does indicate the problems faced by underground mines when the conveyor specifications lead to the risk of spillage and coal loss, which itself may be insignificant, but the associated hazard and halt on operations can have major impacts on mine productivity.

One development of interest to minimise spillage is by Germany's Buerkle GmBH. Coal sampling is carried out regularly, and the German company has devised a non-spill sampling system comprising of a stainless steel stand with attached funnels which empty samples into separate containers. The real purpose of this is to increase accuracy rather than reduce losses, as the losses are more likely to spill into the conveyor.

6.2.2 Reclaiming and loading coal during transit

The transition between different stages of the coal supply chain whether it is between the stockpile and the rail car or ship, is done in a variety of ways which are common for most dry bulk commodities. Differences occur depending on the granularity of the commodity – for instance coal reclamation from a stockpile may differ from biomass or grain, but will differ again from ore or aggregate. With respect to coal, the main bulk handling methods come in various modes and are as follows:

- Stockyard equipment, which includes slew or bridge type bucket wheel machines of various designs to suit both circular and longitudinal stockpiles, as well as dozers and tractors. Other equipment includes wheeled scrapers which are large wheeled vehicles that level off the apex of peaks in stockpiles. All wheeled vehicles have high stability designs, with long wheel bases, large profile tyres, and a low centre of gravity.
- Ship unloading and loading equipment: grab type ship unloaders either mobile, fixed, or floating, the designs are numerous, but the grab technology is more or less simple and universal. Some ship unloaders can also utilise screw thread type reclaiming or bucket wheel style collection using vertical booms rather than the horizontal booms that are used in mines.
- Other material handling types: railway wagon tipplers, truck dumpers, and unloading stations with hoppers to receive bottom opening wagons and belt conveyor (covered or uncovered).

Spillage commonly occurs from grate buckets or any dry bulk unloading system. Provided the excess spills back into the cargo or stockpile then there is no loss, but if the grab, dumper bucket, conveyor or similar mode changes direction prior to the settlement of the load, then spillage will occur on the ground or into water. If spillage is in the latter, recovery of the coal is likely to be impossible.

Coal dust causes the most problems at various stages of the mine operation, for instance handling, unloading, and storage activities. Particulate matter that is generated is not only lost, but adds extra problems such as settlement on buildings, increases equipment maintenance and can shorten the life of coal handling equipment as fine dust can penetrate parts of machinery that larger diameter coal cannot. Many countries have adopted standards for fugitive dust emissions and health and safety regulations associated with reducing respirable dust levels. Added moisture through either exposure to weather or water spray for dust suppression adds weight to coal but reduces the heating value per tonne of coal delivered. Adding moisture in the form of a fine spray can reduce dust pollution from coal. Friable coals can produce high levels of airborne dust causing problems such as health and safety, possible violation of environmental emissions, fire and explosion, increased maintenance expenses, and fuel loss during transit (Blazek, 1999). Three types of dust control methods have been identified:

- Containment includes the installation and maintenance of skirtboards, belt scrapers, baffles, and conveyor hoods to contain and limit airborne dust. According to Blazek (1999), even well engineered systems have limited success with low rank coal dust and have no impact on dust control during transport and storage.
- Mechanical dust collection systems, such as baghouses, can target areas with particular dust problems. Water spraying is not necessary and so no moisture is added to preserve the original heating value of the dry coal. Collection efficiencies can reach almost 100%, but maintenance costs are high. These systems also have high installation costs, the collected dust must be treated to avoid the risk of fire or explosions, and the system does not control dust generated downstream of the collection point or at the coal pile.
- Dust suppression systems use manifolds where a dust suppression solution can be sprayed to control airborne dust levels. A typical system will include a wet surfactant system, foam surfactant, and residual suppression that uses binders, humectants, and surfactants that can provide dust controls for coal storage as well as handling systems. Less equipment is needed compared to mechanical extraction of dust, thus requiring less power and maintenance.

6.3 Losses from rail transportation

Dust emissions cause a number of problems – not least health and respiratory ailments – but there is also the hazardous risk of combustion and the nuisance caused by settlement and clogging of moving or hinged parts. One source of dust is that from rail transportation during transit, loading and unloading. Studies have shown that the losses attributed to train transport that is not covered can, in windy conditions, reach 1–2 t per car per trip (Blazek, 1999). The deterioration of coal through combustion is similar to that experienced from barge transportation which is covered later in this report. Road transport is not discussed since the principles of losses from a rail wagon or mine dump trucks apply to that of a road haulage truck.

Some of the key locations where dust is acute are the unloading points for mine dump trucks or where bottom or side-dump rail cars unload. Rail cars can be loaded using dump trucks, but coal is commonly conveyed above the coal wagon, where the coal is discharged into a hopper, which funnels the coal into a coal wagon. Discharge can be via the base of the wagon through doors, or using wagon tippers (tippler), which lift and rotate either one or more wagons in a cradle and pours the coal out into a discharge pit. Often the wagon will have some compacted coal or ‘sticky’ coal that clumps together, thus requiring the wagon to be subject to external vibration or the manual loosening of the coal using jackhammers. For dust suppression, chemical sprays might be deployed as well as at conveyor transfer points and where stacking chutes deposit coal for stockpiling and also where reclaiming is carried out.

Calvin and others (1996) estimated the coal losses during rail transport along a 500-mile corridor of cargo for the *Norfolk Southern Rail Emission Study* (NSRES). Regarding weighing the rail cars, measurements taken used static, decoupled electronic scales with a reported accuracy of 0.01%. A number of measures were taken to ensure accuracy, so both weights and volumes were measured using a variety of techniques, to ensure coal settlement and moisture changes were accounted for. Once the coal losses were determined, several techniques were adopted to suppress the losses. These included:
- water spray (40–100 gallons per car);
- grooming (rounding of the load profile);
- water and compaction;
- surfactants only;
- surfactants and binding agents;
- binding agents only;
- covered tarpaulins.

An average loss of 0.5 t per car was measured, with losses in the range 0.2–0.4 t/car for metallurgical coals during sunny dry and windy conditions. More friable coals might experience higher losses. In order to suppress losses through dust, a combination of load top grooming, surfactants and chemical binding agents were effective. According to the detailed study based on field trials of 317 rail cars, untreated cars lost on average 0.4 t, ±0.1 t (sample size n = 52). Some rail cars showed a weight gain due to water uptake during transport, presumably net of the gain from the water or surfactant spray. Cars loaded at or below the sill lost less coal compared to normally loaded untreated coal. As a conclusion, material losses based on scale weight changes for ungroomed, untreated cars averaged about 0.4 s/car, compared with 0.22 t/car for groomed coal piles. Dust emissions increased in frequency and intensity when the speed of the train increased, and when it passed oncoming trains.

In Australia, other trials were carried out by *Queensland Rail* (QR) which prepared a study on fugitive coal dust emissions from trains travelling from mines to ports as part of an evaluation by the Queensland Environmental Protection Agency. The investigation included many aspects of rail transportation which have been discussed, but one relevant issue was the potential for coal spillage from so-called Kwik-drop doors located at the base of the wagons. Part of the report’s conclusions was that the average coal loss from Kwik-drop doors was estimated to be between 1900 t/y and 1750 t/y for Goonyella and Blackwater systems respectively, at an average 300 kg per train or 0.0027% of coal transported annually (Aurecon, 2009). The losses are therefore small with respect to the regions coal exports.

Coal dust losses of some 400 t/y were emitted from the ballast (originating from the doors), accounting for up to 6% of that emitted from the rail corridor. Coal losses via the doors are related to factors such as meteorological conditions, moisture content, washed/unwashed coal, the proportion of fines, and longitudinal travel forces (shunt and buff forces). The study suggested that coal loss was not necessarily related to door clearance if the clearance was 3–8 mm. Coal loss was mainly seen for particles less than the door clearance of 2–3 mm suggesting that expenditure to reduce door clearance to less than 3 mm was not necessary, but narrowing a clearance of 3–8 mm was an acceptable cost.

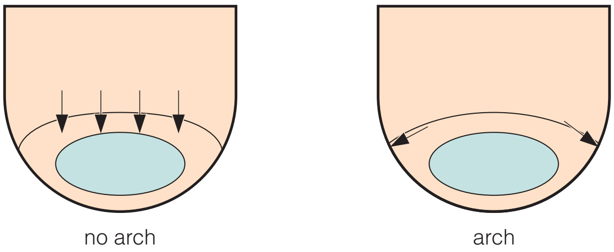

Figure 12 Potential force distribution in loaded wagons (Aurecon, 2009)

Figure 13 Example of coal spillage along a UK railroad (Network Rail, 2007)

Many processes can be deployed to reduce the presence of fines in the coal. This can start with effective fine recovery and drying at the coal preparation plant, to careful stockpiling and engineered conveyor transfers. Rail wagon practice can be improved to control the factors that contribute to losses from the doors. Loading directly onto the doors as opposed to the front slope sheet increases the forces placed on the doors causing door flexing and increased losses. Loading directly onto the doors also caused some coals to arch over the doors, creating greater forces outward towards the sides of the wagon, rather than evenly across the whole load (*see* Figure 12). When the coal is arched, the coal towards the sides had less compaction force, making the coal susceptible to vibration, settlement and sieving and more likely to escape through the door. Flexing of the wagon could also create distortions in the door clearance at different points leading to losses.

Similar research in the UK had different problems of losses by the rail track operator Network Rail (2007). Coal spillage occurred when wagons were over-filled above the top edge of the wagon or when they were poorly loaded, causing spillage onto couplings or other wagon surfaces that can then subsequently slide off in transit (*see* Figure 13). Thus, even those wagons with cowls/raves that are intended to reduce spillage from within the wagon, do cause problems if, when loading, coal is spilt onto the top of the raves which then slides off when the train gathers sufficient speed. Similar problems occur following the emptying of wagons when the discharged coal has been allowed to build up as the wagons pass over the discharge hoppers and the under-frames and running gear are not cleared before the train leaves the discharge point. Results showed that between 45% and 76% of trains were poorly loaded, and clearly the issue required attention. Typical problems caused by coal spillage include:

- points failures due to switch blades being obstructed;
- ballast blocked by coal dust leading to wet beds;
- track circuit failures due to wet coal slurry shorting out the rails;
- reduced life of track components (for example, rail corrosion due to sulphur content and moisture retention and shortened ballast life).

These problems lead to increased delay minutes and increased maintenance and renewal costs, such as employing additional maintenance gangs to clean sets of points, shortening asset life, and bringing forward renewals. Some 220 signal point failures in 2006-07 were related to coal spillage, although this would infer that there is a points failure every 1–2 days. The effect on cost through performance delays and sending out maintenance teams to clean and rectify each point failure was considerable. Many of the problems were associated with terminals using front loading shovels.

The effect of spillage also affected both the Hull river swing bridge and a steel bridge with waybeams which has been the subject of multiple track circuit failures. The Aire Valley suffers from coal contamination problems from trains into and out of the power stations in this area. Some spillage occurred from rail cars when coal came off the undersides of wagons where it had lodged following discharge, or where doors had gaps large enough to cause unintentional discharge.

The poor practice of loading has much wider implications than just the loss of coal. The impact on rail line disruption is considerable and is estimated to be as high as £5 million per year, although the figure was not verified at the time of publication. Coal spillage is always unintended, and recovery is often carried out if such spillage occurs at or around the mine, the coal preparation plant, port storage facility, and the transport in between.

6.4 Theft of coal in transit

Coal losses along the controlled supply chain in some countries can be a result of theft. Anecdotally, coal traders have experienced losses from Russian deliveries whereby coal has been replaced with waste rock or refuse, and after travelling thousand of miles it is not possible to trace the origin and location of the contamination.

In Vietnam, anthracite is smuggled via truck and river to customers in southern China, while in Indonesia illegal and unregulated mining has often been to blame for deforestation. Not only is the environment at risk of ‘theft’ but also, when done in large quantities, theft leads to a loss of revenue for legitimate business and taxation where it is applied.

According to the article published in The Hindu (2011), the national coal production company *Coal India Limited* (CIL) installed a GPS in its coal trucks to check pilferage of coal during transportation. CIL operates in 81 mining areas and produces more than 80% of India’s coal production. According to experts, the implementation of GPS will help in checking pilferage of coal during its movement from mine to the point of loading. At least a quarter of CIL’s 431 Mt production was lost in transit. In 2008, the Bharat Coking Coal Limited (BCCL, 2008) reported a loss of Rs.9.35 crore (approximately US$ 1.9 million) due to theft of raw coal in transit from collieries to Bhojudih washery during the period 2003-07. An audit check examining coal receipts for the Bhojudih washery revealed that 1.82 Mt of raw coal was despatched from the Burragarh and C K East collieries, but the washery received 1.71 Mt of coal resulting in shortage of 0.11 Mt coal, a shortfall of 6%. As a rough estimate, the coal was worth 17 $/t to BCCL.

Further analysis revealed major shortages in a significant proportion of the rail ‘rakes’, each rake being a series of 55–60 wagons. At least 33–40% of the rakes audited were subject to theft, with losses in the range 8–27%. Transportation of coal is at the owner’s risk, so no liability lies with the railways. This would infer that 2.7–10.8% of the all the coal transported within this section of rail could be lost to theft.

Interestingly, at the time of the report in 2008, shortages had no formal recognised standard to adhere to, with 3% being the loss accepted by the Ministry of Steel. Two years earlier, BCCL considered there were no (or little) transit shortages and the difference was on account of the varying methods of weighing at loading (static weighbridge) and unloading points (in motion weighbridge). This raises the issues discussed in previous chapters on verification and measuring of coal in transit. The weighbridges were calibrated and certified to within an acceptable ±1% error, so possibility of en route pilferage of coal could not be ruled out. BCCL decided to employ escorts for the rail rakes at vulnerable points towards receiving end and as a result considerable reduction in shortages was noticed during 2006-07.

One of the side effects of reducing coal theft is the impact on local markets. Given the local black markets that must exist in towns and villages across India, smaller consumers who would normally buy cheap coal from these markets have felt the effect. Primary schools in the Durgapur-Asansol coal area were forced to cut down on meal menus as their purchase of coal (unknowingly) from the black market was stopped (Chatterjee, 2011). The schools used to buy coal at Rs 100 per 5 kg sack, not knowing that the sellers were supplied by coal smugglers; the market price of a 5 kg sack of coal was Rs 200. When the supply of cheap coal stopped, the price of coal to some 1130 schools in the region doubled. The cost of cooking meals went up and the supply of protein rich meals were slashed by 75%. In Jharkand, uncovered rail bogies made theft easier and annual theft could total and estimated 5–6 Mt and could amount to a loss of 1800 crore a year, possibly accounting for 1–2% of national coal supplies per year (Singh, 2011).

6.5 Spillage from loading and unloading floating vessels

Quantifying the spillage from ship unloading and loading is rarely studied and this implies there is little concern for losses during ship loading and unloading. One of the most common methods of unloading a ship is the use of cranes, which pivot towards the vessel hold, and the use of line and grab then captures the coal which lifts the cargo for placement onto stockpiles. Either the unloading system is mounted on board the ship or the ship operator can make use of port side crane systems.

Another method of unloading coal is the continuous method, which differs for different dry bulk materials, but might include a mobile continuous bucket wheel (similar to that for opencast mining), which can access the barge or hold by means of a boom. Other methods include pneumatic suction or cork-screw designs which elevate the coal up to the boom where the coal is transferred to a conveyor which leads to the shore, supplied by companies such as Siwertell (USA). Some of these methods are designed more for barge unloading than ship, due to the ease of access to a barge cargo compared with the relative confinement of a ship's hold.

For ocean vessels, the most common type of loading and unloading is by grab, which can be suspended from a conventional pivoting crane which may be static or mobile (with lateral movement along rails parallel with the ship). Other include a non-pivoting boom, or a gantry, as the grab itself moves along a fixed boom, rather like a cable car (*see* Figure 14). The supporting boom can be moved parallel with the ship while in dock on rails, similar to the crane. Offshore unloading using floating transhipment barges is increasing in importance, and ship to transhipment barge is common in countries like Indonesia. The operation of these is naturally affected by sea and wind conditions and so losses. While some coal might be lost in offshore transhipment, operators tend to lose time during adverse weather conditions than coal. Transhipment equipment such as floating cranes are supplied by companies such as Coeclerici Logistics Spa (Italy).

Figure 14 Bulk unloader using gantry mounted grab system (gantry type) (Thyssenkrupp, 2012)

With regards to the means by which the coal is carried, the most common method is probably the grab method. The losses that can be experienced are much the same as those experienced for coal loading rail cars or indeed haulage trucks. The grab bucket unloader can allow spillage to dribble from the bucket lips, creating housekeeping problems at best requiring clean-up and gathering inside the ship hold using dozers, loaders, or even manual labour to sweep up the coal. Compacted coals that clump to the sides of the ship hull and ballast might require removal using a vibrating tool that can be mounted on a boom or performed manually. Airborne dust can also be generated as the grab bucket opens and drops its load into the hopper from a greater height.

Reports and journal articles reviewing various options for ship unloading, however, make little reference to spillage, and so presumably, problems chiefly arise from operator skills and training. The types of boom or grabs used tends not to lead to significant loss of coal, but spillage within the hold when the grab is ascending leads to longer unloading times.

6.6 Oxidation of lower rank coals during transit

Earlier in this report, there was discussion on the deterioration of coal while in storage and stockpile. The same principles apply when coal is temporarily stored in transit, ad on a ship or a barge. Ships are mobile stockpiles which have their own hazards during shipment, loading and unloading. However, the self combustion of coal in a confined space like a ship or barge can be an avoidable hazard.

During the 1980s, there were reports of US coals being transported across the USA by barge which suffered from spontaneous combustion during transit. Barges were loaded with coal but the stacks were not trimmed, and instead appeared as peaks through the length of the barge. Much of the coal travelling down the Mississippi suffered from warm air passing through the conical heaps. Some coals destined for export were loaded onto ships at an elevated temperature, and they had to return to port to discharge the burning cargo. Sometimes the temperature exceeded 70°C. If the discharged material was then stockpiled, and subject to rainfall, the drainage liquid exiting the stockpile indicated an acidic pH of 1 due to the sulphuric and sulphurous acids. The potential effects of this could lead to a twofold problem for a ship, firstly the cargo would be burning and secondly the effects of the acid leaching onto the sides and floor of the vessel hold could lead to expensive repairs.

Williams (2010) described how low rank coal, such as that loaded off Kalimantan, is particularly susceptible to self-heating and may spontaneously combust if loaded at a temperature in excess of 55°C. Shippers and local suppliers have sometimes delivered coal to vessels off Kalimantan at a temperature close to this figure. Coal awaiting shipment is often stored in barges close to the anchorage areas where it may be exposed to strong winds and rain. Such conditions may promote self-heating, and barges containing coal with a temperature exceeding 55°C have sometimes been encountered. However, not all operators appear to be aware of the risks and some vessels have only identified the problems after the cargo has been loaded. Once on board it is not easy to remove the coal due to the lack of discharging facilities in the region.

An interesting paper on the oxidation losses occurred within shipments of export coal was written by a US based scientific consultancy firm *Minton, Treharne & Davies Ltd* (MTD) a specialist survey and testing consultancy (MTD, 2009). MTD carried out sample and analysis of Southern Hemisphere coal supplies for imports into the UK. The finding suggested that coal discharged in the UK was generally 0.5% less than the calorific value of coal that was loaded. There was a possibility that sampling and analysis was creating problems, and if so presumably it would be the responsibility of MTD to rectify the surveying. However, during a sampling at the ship (prior to coal discharge), water vapour escaped from the hatch covers when they were opened for cargo inspection. The coal in the vessel was measured at an elevated temperature of 50°C. It was assumed that the ship's ventilation permitted air to enter the cargo hold which led to partial oxidation of the coal. To try and investigate and alleviate this loss, a representative sample was placed in a steel bomb and the space above the coal was filled with nitrogen to replace air. The coal heating value during shipment again had still lost 0.5%. The resulting loss was therefore deemed acceptable for future shipments.

Enclosed vessels require extra sealing of cargo compartments to exclude the entry of air, and an additional requirement to monitor the atmosphere in the hold area to measure CH_4, CO, and O_2 levels. CO levels rise during the first few days of a voyage following the oxidation of coal, while O_2 levels drop. The experience gained by subbituminous coal transportation and storage does have some parallels with biomass. Therefore creating an inert atmosphere as possible is preferred. Retention periods can reach up to 10–12 weeks and low oxygen content can mean storage can be longer, as experienced by a vessel that was in captivity holding Indonesian coals, whilst under the control of Somali pirates.

In Indonesia, guidelines help improve the handling and storage of high volatile coals that are prone to self combustion. In the past, some shippers failed to provide adequate cargo declarations in accordance to the *International Maritime Solid Bulk Cargoes Code* (IMSBC). Shippers should provide appropriate information in advance on the properties of the cargo along with recommendations regarding its safe handling, stowage and carriage so that the necessary precautions can be taken.

Shippers should provide, in writing, the moisture content, sulphur content and particle size of the cargo, and information on whether it is liable to self-heat or emit methane, or both. In order to avoid problems of self-heating during the voyage and loading, an infra-red thermometer can be used to ‘scan’ the surface of the cargo prior to and during loading to be alerted if the temperature readings are found to be high. Vessels should also reject cargo exhibiting clear signs of self-heating such as barges containing smouldering coal.

Under certain circumstances, during loading, the holds should be sealed if the vessel faces a delay of more than an hour. After loading is complete, the cargo should be trimmed level to the boundaries of the cargo hold to prevent the development of fissures. Fissures increase the surface area of the cargo exposed to the air and increase the risk of self-heating. Each hold should be closed immediately on completion, and hatch sealing tape may be applied to the hatch covers as an additional precaution. Only natural surface ventilation is permitted, limited to the absolute minimum time necessary to remove any methane which may have accumulated. Any vents that lead below the level of the cargo should be sealed as the introduction of air into the body of the cargo may promote self-heating.

7 Problems with estimating global losses using statistics

Table 5 shows the trend in world coal production and supply between the years 1980 and 2009 (IEA, 2012). The time series also shows coal industry related consumption, where some is transformed into liquefaction plants and used by the coal industry. In these data series, losses refer to deductions after production but before the coal is consumed by the end-user. It probably does not include losses in the mine or coal preparation plant, or losses during energy conversion during power, steam or heat generation.

The IEA statistics, att first glance, appear to show negligible losses, the percentage is a fraction of one per cent every year. What the statistics show is that recorded losses are minimal, perhaps 0.05–0.10% of production, and so perhaps little concern should be paid to supply chain loss. However, in some of the most crucial coal producing countries, there are no data for losses. One example of this is India. This is probably due to the fact that losses are not reported or properly verified, or in either case lost in statistical differences.

Figure 15 shows the percentage losses and shows a disparity between those countries that are able to record losses, and those that cannot due to the immense task of keeping track of such losses. To assume that the global average for losses in the coal supply chain at just 0.4% must logically be a gross under estimate. Interestingly, the UK and Kazakhstan record some of the highest losses, 1% of production, but these markets could not be more different. Kazakhstan is a large lignite based industry operating opencast mines while the UK comprises of smaller producers of bituminous coals coming from both opencast and underground mines.

It seems highly unlikely that operations in the three largest producers in the world – India, China, and the USA – would be able to accurately record losses due to the scale of the coal markets in these countries However, it is unlikely losses would be zero which is seen for the data in India, for example. A greater understanding of such losses would be valuable for those large coal producing countries.

Perhaps for the purpose of preserving global reserves, there might be some value in taking care in minimising losses and maximising efficient production and usage of all fossil fuels. While the losses in the coal supply might be considered unacceptable, it is worth noting that, based on similar IEA data, losses in the natural gas transport chain average 0.8% worldwide. This ignores the gas that could

Table 5 World coal balance 1980-2009, Gtce (IEA, 2012)

Gtce	1980	1990	2000	2004	2005	2006	2007	2008	2009
Production	2.57	3.19	3.18	3.95	4.2	4.43	4.59	4.85	4.92
Total primary energy supply	2.55	3.18	3.27	3.96	4.14	4.37	4.55	4.73	4.71
Statistical differences	0.0	–0.02	0.03	-0.04	-0.02	0.0	0.03	-0.01	–0.04
Liquifaction plants	0.0	–0.02	–0.02	–0.03	–0.03	–0.03	–0.03	–0.03	–0.03
Energy industry own use	–0.05	–0.05	–0.07	–0.09	–0.09	–0.09	–0.11	–0.12	–0.12
Losses	–0.01	–0.02	0.0	0.0	0.0	0.0	0.0	0.0	0.0
% Losses	0.381	0.554	0.118	0.073	0.085	0.081	0.081	0.062	0.049
% Losses and statistical differences	0.39	1.33	-0.88	1.03	0.45	0.05	-0.60	0.25	0.77

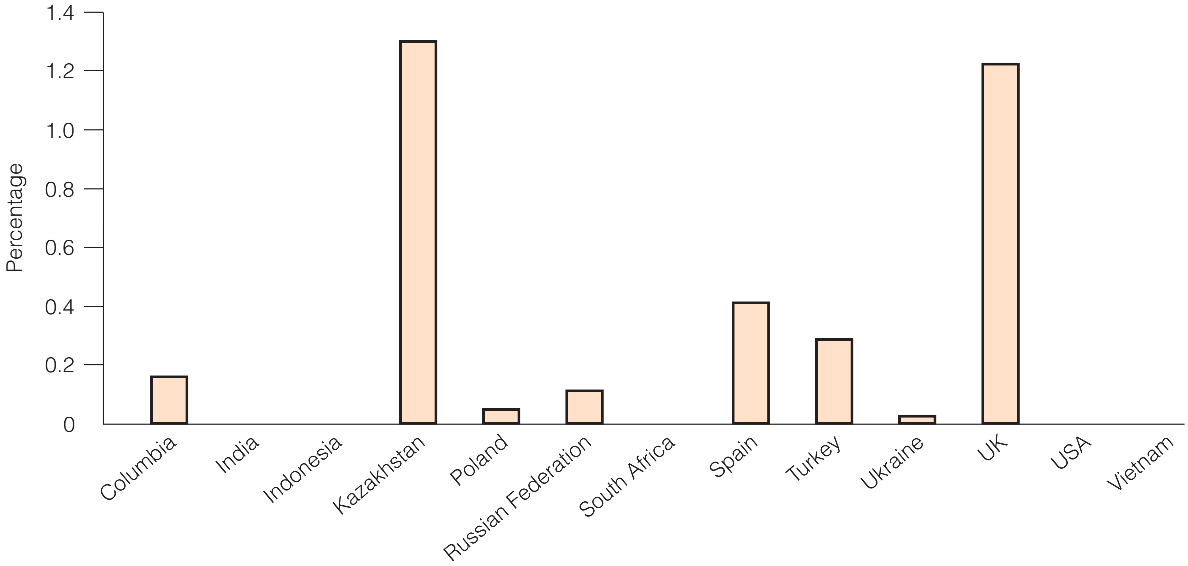

Figure 15 Average losses 2000-09 as a % of production (IEA, 2012)

be flared off or leaked at production facilities. While coal may be a fairly benign product in its raw form, natural gas methane has a high global warming potential and so from a greenhouse gas emission point of view, coal losses are less of an immediate concern.

On a global scale, coal losses between production and the end-user are therefore not fully understood. Local losses may be well documented, and often written off, but when aggregated worldwide the losses could be meaningful, especially for global mining companies. Global coal producing companies wish to maximise value from each tonne of coal, and so care is taken wherever necessary. Vast quantities of coal produced in developing countries are sold at below market prices, how much is not precisely known, and so the true value would be considerably less. Given that losses are more likely to occur in industrialising countries, it remains difficult to assess how much losses are worth in monetary terms on a global scale. Conservatively, if both low cost coal and historically low market prices were considered, financial losses due losses in coal supply might be around $10 billion.

Assuming market coal prices are at 2009 levels (steam: 100 $/t; coking coal: 200 $/t; brown coal: 30 $/t), the global coal industry was worth $687 billion (probably closer to $400 billion if 2012 prices are considered). With percentage losses of 0.049%, potential financial losses would be $336 million to the global industry. Assuming losses of 1% then losses would be 20 times ($6.7 billion).

If 2011 production figures of 7695 Mt (BP, 2012) are taken, losses could be as little as 3.75 Mt. This would suggest that the world supply of coal is an extremely efficient process, but unless a better understanding of losses in India and China is improved, no such conclusion can be made.

Naturally, these losses might be partly due to *force majeure* occurrences such as storm and flood damage, the capsizing of vessels, the derailment of train wagons, and so on, it is further difficult to partition the losses due to normal operating practice.

8 Biomass preparation, storage, and handling

While much of this discussion has been on coal, biomass production and transport is growing in importance. Biomass is a dry bulk commodity facing the same losses and handling issues as coal, but unlike coal biomass in storage and transit has risks associated with agricultural commodities. Handling biomass has the potential for considerable error when estimating stock mass and volume due to the fibrous nature of the fuel.

Moisture and compaction in biomass can be even more variable, and the increasing volumes of biomass required in future will no doubt require a greater degree of understanding and care. Biomass fuel is not a homogenous commodity, in much the same way as coal. It is too easy to assume all fuels are the same. Traditional methods of determining inventory have been to measure the volume of a pile and from that back-calculate the tonnage. Accurately determining the mass of fibre in a pile of biomass remains problematic, and fibre measurement does not have an easy solution (Janze, 2011a).

8.1 Contaminants in biomass – need for preparation

Biomass storage, transportation and handling can lead to biomass gaining material that may be undesirable. The following section draws heavily from observations and experience gained by Janze (2011a) who discusses the contamination (dilution) of biomass which can consist of varying amounts of sand, dirt, grit, and small and large stones. Contamination occurs generally as a result of bad handling practices, including:

- sand and rock build-up on trucks;
- dragging felled wood along the ground where dirt and rocks can become embedded in the bark;
- dirt, grit and stones can build up on transport trucks and, if not properly cleaned-off, find their way into the biomass stream;
- storing woody biomass on unpaved ground. Even providing for a sacrificial layer of biomass, rocks will work their way up from the underlying soil;
- picking up grit and stones when reclaiming *roadside logging debris* (RLD) or pre-processed ‘hog fuel’;
- not taking the requisite care with primary plant residuals – for example, allowing clean sawdust or chips to be mixed with `dirty’ bark.

8.2 Unpaved ground surface for biomass storage

The best method of minimising rock contamination is to prevent the non-organics from entering the biomass flow in the first place. One pulp mill found that rocks were migrating from the unpaved chip storage yard into the chip supply, and once the area was paved the problem was alleviated. Another mill found that removing the sand, snow and small stones that fell off trucks onto the truck dumper before they could get into the chip stream solved their contamination problem. As it is not always possible to prevent rocks from entering the biomass flow, some form of rock removal is sometimes necessary. Trying to remove 100% of the non-organics from 100% of the material stream would be prohibitively costly. Rather like the coal preparation plant, the typical size range of rock particles must be determined before designing an appropriate and cost-effective system to remove them.

8.3 Mineral matter removal methods

Effectively removing mineral matter from biomass requires a lot of equipment that is costly to operate and similar to coal separation using a variety of media to perform density-based separation, such as a water bath. Since most woody biomass is lighter than water and floats, most sand and rocks are heavier and sink, which makes the water bath effective for rock removal. However, the water bath has serious disadvantages, including:

- the addition of moisture to a fuel susceptible to high moisture contents already.
- wet biomass can freeze in very cold climates.
- the separation water quickly becomes contaminated and must be continually refreshed. Treating the wastewater can be costly, unless the facility already has a plant with a large wastewater treatment system.

8.3.1 Air density separation

Air density separation works on the principle of heavier particles fall out of a moving air stream whilst lighter particles are suspended in the air stream, hence permitting separation. *Air density separation* (ADS) systems are effective at rock removal, but also have disadvantages, for example where a large piece of wood can weigh more than a small pebble. ADS systems tend to work effectively over a small range of densities where the particles are similar in size. Generally, they are capacity limited with low throughputs, requiring multiple machines. Large volumes of air are required, resulting in large fans and motors. Effective air clean-up systems that will meet emission standards are required.

8.3.2 Screening for size

If only one particular size of mineral matter is causing problems, screening rock particles and discarding them is necessary. However, with screening alone, similar sized particles of biomass might also pass through (or are retained) in the screening process, which may or may not be acceptable. As in coal preparation, a combination of screening for size and air density separation is the best method of removing rock particles from biomass. In most cases it is fairly easy and not too costly to retrofit a rock removal system into industrial processes that already utilise multi-levels of size screening, as many of the required components are already in place.

8.3.3 Removal of mineral matter from biomass fuel

The simplest and lowest cost rock removal system for biomass being utilised as fuel would include two possible dry solutions – the scalping screen and a trommel screen. The scalping screen is similar to a rotary crusher for coal. It removes large rocks, lumps of frozen biomass, and large chunks of wood while passing through appropriately sized biomass. The next stage is robust trommel screen with up to two different screen sizes depending upon the rock size to be removed. Trommel is the German word for ‘drum’ and is a cylindrical rotating steel tube with at least a 2 m diameter for screening biomass or waste streams into different fractions. While a trommel screen is ideal, a number of other screen methods are used, but vibration screens, such as those used for coal screening, are generally unsuitable for biomass.

The mineral fines would fall out of the first screen section. An intermediate particle size would fall out the second screen section, while very large pieces of material would pass out the end of the trommel screen. One or both of the larger sized streams could be passed over a vibrating de-stoner conveyor equipped with one or two air knives. Heavy particles would fall out the opening at the lip of the air knife and lighter particles would be blown over the gap. This is easily done as the biomass has a much lighter density, but wet biomass may cause some problems. If required, the grit-laden fines could be cleaned on a dedicated ADS system. If there was an excessive amount of gross oversized material, it could be further processed on or off-site.

8.4 Biomass stockpiling

According to Janze (2011b), pulp and paper mills everywhere have struggled with the problems of pile estimation for many years. From year to year, stock disappears, while other years see an unintended surplus inventory. Years ago variances in stock were written off.

Pile surveying is similar to that for coal, with similar problems. Problems arise where the level of compaction of biomass is not determined, and so pile density is not known. Without this knowledge, calculation tonnage from volume measurement is quite ‘hit and miss’. Inventories based on volume or green biomass can lead to inaccuracies. For biomass, more so than any other fuel, density variations occur due to moisture and compaction, and moisture will change according to climate and the period of storage. Loosely compacted chips can dry out faster. Rubber tyred vehicles compact chips more than tracked vehicles because of the smaller tyre footprint. Biomass handling is typically smaller volume and so dozer and truck is a more common method of stockpiling and moving.

As with coal, large biomass chip sizes will be compacted differently to smaller particles, and compaction around the middle and base of the pile will be higher than that on the periphery of the pile or near the top. Particle size segregation naturally occurs, as the pile is being built. Larger particles tend to roll down the surface to the outer edges of pile. Size segregation is greatly affected by wind and can concentrate fine particles in one part of the pile.

Some studies have shown that the density deep inside a large pile can increase by 25–30% compared to the surface density while the overall density can increase by 14–15%. This type of variation is not known in coal. Nuclear depth density is a more successful method. For biomass piles, the lower density means plastic tubes need to be inserted into bore holes, and the nuclear and moisture gauge is lowered, and measurements taken every metre to make a 3D density and moisture map of the pile. This is costly and time consuming for large piles, and probably not economic for smaller piles.

Biological action resulting in a loss of mass is a natural feature of biomass. Up to 1% of useful fibre can be lost per month of storage due to this. Losses in highly compacted piles is lower due to the lower availability of oxygen. Biomass is not always handled on a first-in, first-out basis, and so is almost always subject to some biodegradeability. Biomass left for too long can be subject to spontaneous combustion. A way of avoiding biomass degradation is to ensure none of the older biomass is left in storage. This way the inventory can be rationalised more frequently and fewer errors in inventory estimation will occur. It also minimises loss due to biological action and spontaneous combustion. Multiple pile management (if there is enough space onsite) leads to fewer problems.

8.5 Biomass handling

So far the discussion of biomass stockpiling has considered the stockpiling and reclaiming of biomass and coal. This is often done using dozers, but larger-scale handling with the increased market for biomass is giving rise to grab cranes, often used for other dry bulk commodities. The company Demag has installed automatic handling systems for small combined heat and power (CHP) plants in Germany. The system is controlled by computer and the biomass is stored in a covered warehouse. In one plant site, the throughput is only 32,000 t/y. Raw biomass is delivered by truck. The biomass is loaded into a tipping pit where moisture content and fuel grade is monitored. The crane then transfers the woodchip to three fixed zones. When volume sensors indicate that the warehouse minimum has been reached, the crane automatically tops up the warehouse with biomass from the pit into the silo. If the material is too moist or of insufficient grade, the material is blended with appropriate material. Drax has a fuel processing plant which also uses Demag grab and handling systems, which also include a 400 t/d straw bale handling warehouse with a fully automated system that grabs bales prior to transport. The system can handle up to 12 t of straw at a time, for 24 hours a day, for delivery to the straw pelleting plant.

8.6. Biomass logistics and shipments

The low energy density of biomass makes the fuel expensive to transport. However, transportation costs for biomass pellets are half that of wood chips given they are generally twice the density.

Wood pellets are reported to have resulted in catastrophic fire loss in storage, although rather than treating the fuel like a fossil fuel, it is possible to treat the fuel like a cereal, using flat stores to reduce such risks (DCI, 2012). Some of the largest biomass exporters are USA, Canada, Australia, South Africa Chile and Vietnam which together can ship 5 Mt/y of biomass to China, Korea and Japan. Vietnam is the largest exporter of loose chips. Woodchip facilities have to date generally been geared towards the paper and pulp industry. To transport wood pellets, some adaptation is required. Pellets cannot be stored outside (pellets with moisture expand and degrade to a useless mush). Woodpellets are also extremely dusty to handle so dust control is essential but water spray is best avoided for the reasons given earlier.

Wood pellets are generally located close to the place where the raw material is harvested. Fire precautions are essential using a ‘first in, first out’ regime, making allowances for material flow characteristics, and CO exhaust. CO poisoning has already claimed nine lives in Europe since 2002 (HSE, 2012). Flat storage of flexible skin buildings can be used. With flat storage, ventilation is simple and tubes may be incorporated into the stockpile combined with exhaust fans to ensure there is no CO gas build-up. The company B&W Stormajor has operated cereal and oil seed storage for some years at Port of Fredericia in Denmark, and the same designs could be applied to storing biomass pellets. The silo receives biomass via tipping truck from local farms. Shiploading occurs with a conveyor system either directly linked to the tipping pit, requiring a reasonable constant supply of truck supplies.

According to Sublett (2010), manual reclaim is probably the simplest step of the process because it involves just a loader and an operator to pick up and move the material.

However, since the fuel is stockpiled on the ground, dirt and metal contaminants will contaminate the fuel easily. Usually a concrete pad is used, but these foreign materials often become part of the biomass, which could add maintenance cost and labour to keep the plant operational. An alternative storage and reclaim operation can be used to minimise the problems of contamination. A hopper receives a truck load and then to reclaim the material, uses an automated multi-strand chain, stoker or screw reclaim system that extracts the material out of the hopper. This automated process keeps the material moving through the process in steady and measurable rate and also reduces the opportunity for additional contaminants to enter the system.

Covered storage is costly and is only necessary in certain urban environments that mandate it, or where the biomass must be kept quite dry (<25%) and the climate is very wet; or conversely where the material is wet and there is a real possibility of the material freezing into lumps. In most climates and locations, open storage piles are suitable. Dusting issues can be minimised by the use of wind fences. Stockpiling is similar to that of coal stockpiling using a conveyor boom to stack conical or ridged stockpiles.

9 Losses at the end of the supply chain

The final stage of the supply chain is the end-user, whether it is a power station, a coking plant or an industrial boiler. For all end users, the coal is transferred from the receiving mode of transportation. For large power stations this will typically be by rail, or for power stations located on the coast or by a river, dedicated jettys may be located close to the stockpile. Smaller end-users might receive coal by truck. All the coal is transferred, stacked in the storage yard, and later reclaimed. The elements of moving coal from the bulk transport to the end-user is common to the earlier stages of the supply chain. These include stackers, reclaimers, conveyor belts, hoppers, and so on.

In power stations however there is an extra stage of processing which completes the supply chain prior to firing in the boiler, and this involves fuel pulverisation to a fine powder. The grinding of the lump coal increases the surface area to volume ratio. While coal in this form is close to dust (a nuisance elsewhere in the supply chain), at this stage the pulverised fuel (PF) is perfect for 'suspension' through air blown pipes and then fired into a boiler. PF is so fine its entry into the boiler can be controlled, while having a high surface area to volume ratio enabling excellent combustion.

The combustion of coal is a full transformation of coal to release heat energy, which results in the production of new compounds and effectively ends the supply chain. Coal effectively stops being a fuel in its black solid form and so ends the supply chain. The same situation occurs when coal enters a coking plant or an industrial boiler for heat/steam generation.

9.1 Pulverised fuel preparation

Firstly the coal is obtained from the power station stockpile, usually located next to the rail terminus. Reclaimers or mechanised shovels then transfer the fuel to a conveyor which is then transported a short distance to the station mills. In the mills, the coal is ground to its finest for blowing through burners with air for final combustion. As a finely ground fuel, the surface area to volume of the fuel is high and therefore at greatest risk of explosion, but also the surface area of the pulverised fuel makes it at risk of acquiring moisture. At this stage the term 'raw coal' can adopt a different meaning to that at the coal mine. Raw coal at the power station is the delivered product in the stock yard, but is the also the coal that is fed to the milling system.

The pulverised coal is obtained by grinding the raw coal in pulverising mills such as vertical spindle mills. The grinding action takes place between two surfaces, one rolling over the other. The rolling element may be a ball or a roller while the surface over which it rolls may be a race, a ring or a bowl. Essential functions of pulverising mills are drying of the coal, grinding, and separation of the particles to a desired size.

Fuel feed is often determined using gravimetric analysis, which is superior to volumetric analysis, and mass measurement systems such as belt weighers. Gravimetric analysis is more accurate as it can carefully determine the fuel feed required for the boiler, and so the heating value of the fuel feed suffers from less variation than volumetric measurements.

Coal received at modern power plants is typically more reliable and consistent given the modern demands for validation and surveying in the fuel supply chain. Contractual obligations will ensure that the coal supplier and trader delivers the desired coal quality and quantity required by the station operator. Even so, the power station fuel operator can also operate a reject system. In some power plants the rejection of shale, stone and iron pyrites (or other non-coal materials) need to be separated. Even at the milling stage, the materials which have no useful heating value are discarded into hoppers and conveyed elsewhere on the site.

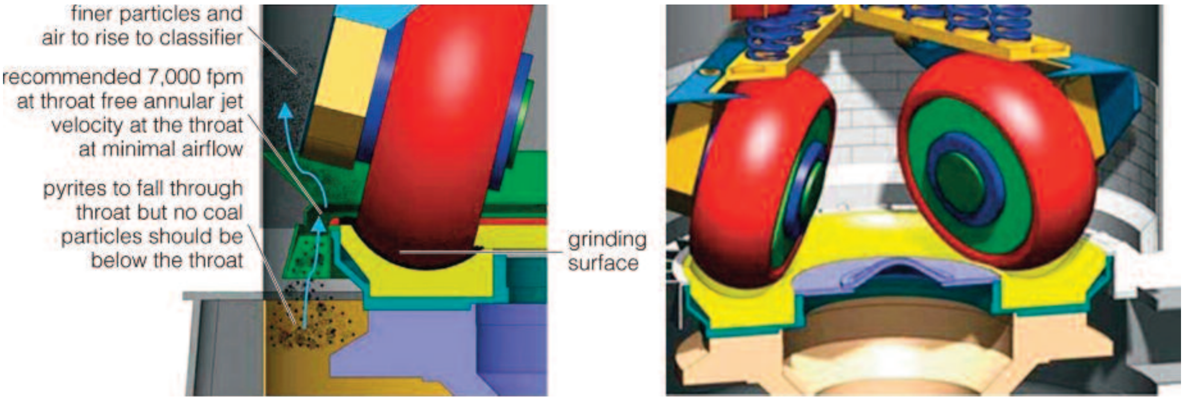

Figure 16 Coal mill rollers and dust and particle loss (Storm, 2011)

Figure 16 illustrates a typical coal pulveriser roller belonging to a commonly used MPS-89 type design which uses rollers as the pulverising crushing surface. Another typical design uses conical rollers.

The discharge area adjacent to the roller contact surface located around the perimeter of the circular vessel is a potential area where losses might occur. Heavier particles such as iron pyrites are undesirable, as they increase wear on the pulverisers. Upward airflow occurs around the pulverising vessel to avoid coal dust from falling in the void below the main vessel, where there is a risk of explosion. The airflow has to be sufficient to maintain upward pressure to keep the coal in the vessel for either recirculation (for coarser particles), or for extraction to the boiler feed. Too low an air flow results in coal particles escaping with the discarded iron pyrites. Elsewhere around the coal handling areas of the power station, there are various transfer points, such as chutes, hoppers and conveyors, where coal particle loss will occur as it does at the coal, mine hence the risk of explosion.

9.2 The ultimate loss of coal – combustion

Determining the amount of loss of coal mass during combustion is quite a different matter to assessing the loss of coal during its travel from mine to the end-user. Coal combustion in a power station or industrial steam raising boiler is an immensely complex subject and within the last ten years, the area was re-examined by the IEA CCC by Wu (2005) in a report titled *Fundamentals of pulverised coal combustion* and Barnes (2009) in *Slagging and fouling in coal-fired boilers*. The process of coal combustion occurs in several stages within seconds and is not easy to simplify due to the nature of the different coal components, but as a general rule coal particles undergo the reaction illustrated in Figure 17.

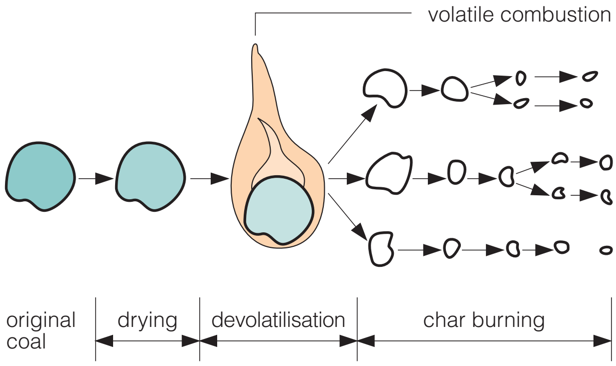

Figure 18 Coal combustion processes (Wu, 2003)

Coal particles and the components undergo a process of drying, liberating both surface and inherent moisture, causing particle shrinkage, and if the moisture is trapped within a particle, the liquid to gas phase can cause cracking and splitting of the particle. As soon as the particle is dry, the particle is heated to the pyrolysis reaction temperature, to the next stage of devolatilisation, where according to Wu

(2005), the volatile components migrate instantly towards oxygen, at a gas phase temperature that is much higher than the particle temperature. The combustion time has a negligible effect on the total combustion time. Gas phase reactions are however important in determining the formation of airborne pollutants such as NOx and SOx.

After volatilisation, the chemical and physical changes in the coal undergo further changes, a bulk of which is converted to char (98% carbon) and tar (organic liquid or vapour which can also result in soot). Char oxidation is the latter stage of combustion, it is slower than the volatile stage, yet is most important in terms of the heat release. Char reactions contribute to a majority of the heat released and is therefore critical. While volatiles combust readily, diffusing towards O_2 rich atmosphere in the boiler, and so spreads quickly in a larger reaction area, O_2 for char oxidation must be transported to the relatively small particle surface (Sami and others 2001). Char oxidation being slower therefore determines the burn time of a coal particle. The main oxidation reactions are simplified as follows:

$$C + O_2 \rightarrow CO_2$$
$$C + \tfrac{1}{2}O_2 \rightarrow CO$$

However, these transformation losses do not necessarily provide the mass loss of coal in the power station boiler. The addition of O_2 and N_2 as combustion air, along with the air that the PF coal feed is 'additional' mass, as well as the additional mass of limestone required for FGD. The O_2 reacts with the C to create CO_2. The carbon (in CO_2 and CO), sulphur (SO_2) and trace elements are emitted into

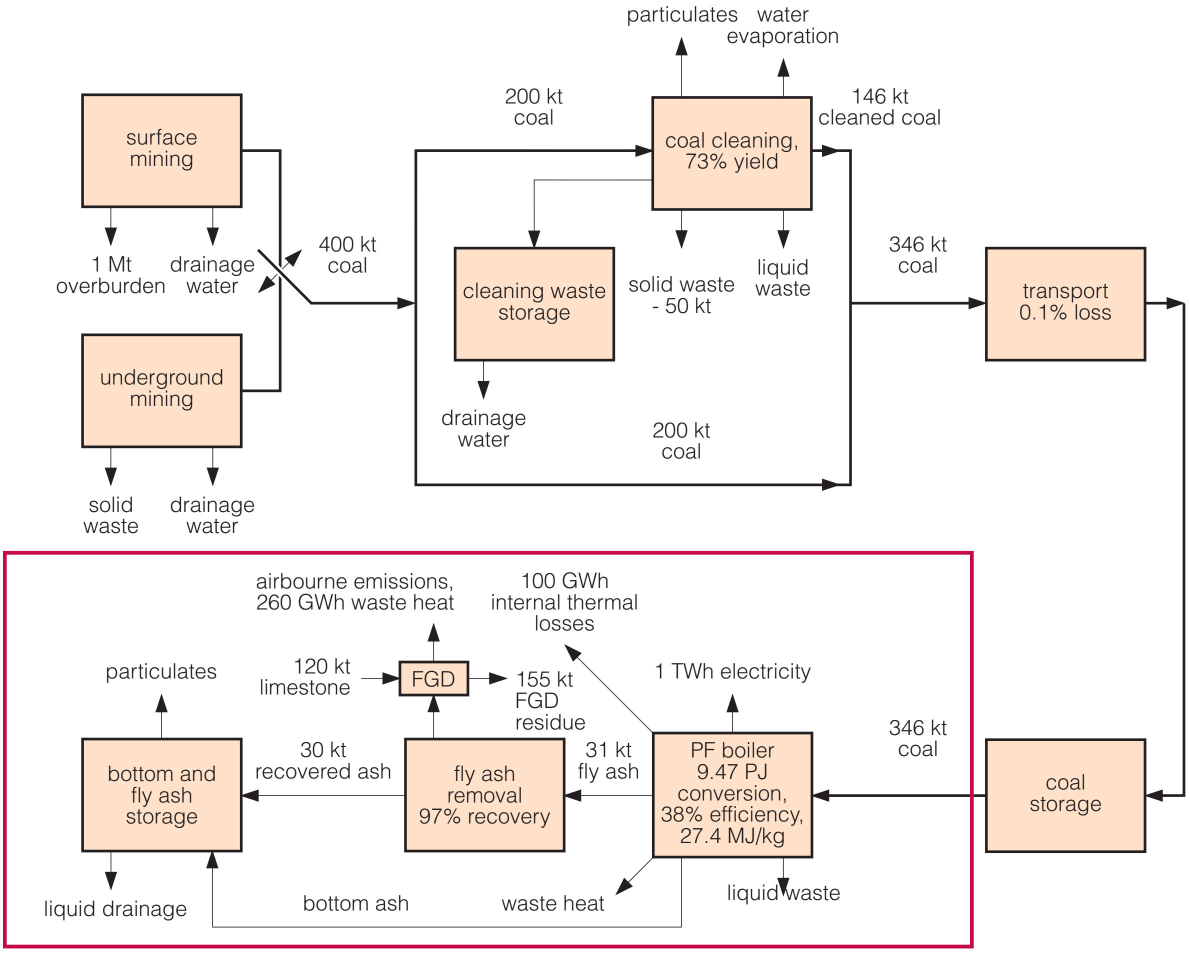

Figure 18 Coal cycle emphasising power generation, emissions, residues and effluents (Couch, 1995)

the atmosphere or in some cases captured, while solid bulk mass in the form of ash and slag reused for landfill and FGD residues can be used in the construction industry as a source of gypsum. While there has been some attempt here at determining the mass loss of coal in the power station, the complexity of combustion and reactions means that it becomes an extremely difficult process.

Figure 18 illustrates the entire coal supply and demand chain, and highlighted is the power generation stage. According to this representative supply chain, 400 kt of coal produced eventually ends up as 346 kt of coal feed to the power station. This suggests that a substantial 13.5% of the coal that was mined was lost. Most was lost as part of the coal preparation process, where ROM coal was ‘refined’ to a saleable product coal. However, the physical changes to coal during combustion that has been discussed so far is less straightforward to quantify. The waste and by-products of combustion are a function of the heat reaction with air, which contains mainly 78% nitrogen and 20% O_2.

Almost all of the useful components of coal are combusted, but mineral matter forms ash.

Most of the coal supply chain up to the point of combustion might see a 20–35% reduction in coal mass from mine to power stations while coal is still in its raw commodity form. The transformation of coal during combustion sees a complete loss of coal as a fuel, no longer resembling the material found in the ground, but produces a new set of gaseous and solid compounds. Losses are therefore less relevant in the case of pf in the boiler

10 Conclusions

Global coal production has increased from less than 4000 Mt in the 1980s to 7200 Mt in 2010. The growth has overwhelmingly come from the rise in bituminous steam coal, although coking coal and subbituminous coals have seen significant growth also. International trade has maintained a similar growth, accounting for some 15–20% of global supplies. As a result, more coal is being mined and transported across the world than ever before.

This report raises some of the issues along the coal supply chain that may affect a tonne of steam coal as it moves along the chain from the mine to the customer. The report also discusses some of the potential confusion that can arise when looking at this subject. It is impossible to produce a complete list of locations and reasons for coal losses (or additions through exposure or contamination) as each mine operation is unique with varying supply chain lengths.

If a customer wants a tonne of coal, the reporting procedure must ensure that a tonne of coal passes all the way down the supply chain. If it doesn't, then coal will need to be found further down the chain, but quantifying this is not straightforward. This report examines the losses experienced along the coal supply chain, which may result in a reduction in the quality or value of a consignment of coal.

Few papers are published and relatively little importance is paid to the losses that might occur throughout the coal chain in terms of reports and published materials. However, as coal production keeps rising, so too must losses, but industry analysts admit there are few attempts to quantify them on a global or even regional scale.

Losses start at the mine, with either incomplete extraction of the seam, leaving coal in the ground, or over-mining at the peripheries, or incorrect blasting of overburden rock therefore diluting the coal with excess waste rock, causing a loss in heating value of each tonne of extracted material. Different areas of the coal seam can lead to varying losses.

Intentional losses such as the coal left in the supports for room-and-pillar mining can be substantial, in extreme cases up to 90% of a coal reserve, but typically more like 40%. Possibly the largest source of mass loss in the coal supply chain has to be the preparation plant, removing mineral matter and inert inorganic substances that cannot otherwise be burnt.

These waste extractions lead to a cleaner more mineral free coal product, so called washery yield. These yields vary widely across the world, with yields in the range 40–90% depending on the coal and the need for processing.

Coal washeries can account for 20–30% mass loss through the separation processes of mineral matter from the coal, but for some coals these losses might be as high as 50% or more, especially for particularly friable coal. Depending on the coal, the separation of fine coal can be a large part of this loss. Fine coal can be utilised separately or stored in settlement ponds, but are usually not a desirable material to transport with the coarse and intermediate coal fractions. It is possible that some 430–1090 Mt of waste could be rejected from the world's coal washeries, some of which is coal. Coking coal undergoes a more rigorous process of separation of mineral matter since the quality parameters are tighter than for steam coals.

The actual mass of material that would yield a heating value from the world's washeries is unclear, but studies done on fine coal (<0.5 mm) suggest fine discards alone could be 70–90 Mt/y in the USA, equivalent to roughly 10% of the country's saleable coal production. The amount that has a useful heating value is uncertain since a great deal of this could be less suitable as a combustible fuel.

Maintaining a check on the mass of coal passing through the supply chain from mine to end-user is naturally fraught with error, but efforts to track coal tonnage are easily done using stockpile surveys, weighing mass on conveyor belts during transit, or draft surveys of ships for seaborne traded coal. The accuracy of such measurement systems is high but still gives a small error of ±0.5–5%.

Losses in mass and heating value of coal due to spontaneous/self combustion are small perhaps 0.5% in some examples, but this is dependent on the conditions of storage, the access to air flow, and the residence time of the coal stock in its static state.

Losses from spillage and dust can be sizeable if not properly controlled. Fully covered conveyor systems and enclosed storage depots can minimise dust loss during windy conditions. Similarly, dust loss from coal wagons from rail haulage can also be considerable. Dust can either be windblown, or washed away with rainfall. At best it is a nuisance, at worst it is a hazard for both respirable health or leaching into the environment.

Dust loss and spillage occurs anywhere along the chain where there is exposure to weather, and especially during transit and transfers between two modes of transit, whether it is conveyor to conveyor, conveyor to ship, hopper or dumper truck to rail wagon, and so on. Simple and cost-effective methods of minimising dust include water spray, but surface moisture can increase by up to 4%, something best avoided for lower rank coals.

In some countries, theft of coal is a problem. This makes production data difficult to reconcile with the actual supply of coal to end-users. As such considerable amounts of coal can be lost in the statistics as losses or merely ‘statistical differences’.

Biomass incurs many of the problems associated with coal, for instance the removal of mineral matter that is often acquired during the loading and moving of biomass. Dilution of the biomass matter can a problem. Biological degradation can lose 1% of useful fibre per month.

Finally, it is at the power station where perhaps the greatest losses occur. In the first instance minor losses might happen at the milling stage, with stockpile reclaiming and conveyor transportation experiencing the same losses seen in the coal mine, and where the milling equipment can generate some losses in pulverised fuel. At this stage, the power station fuel preparation stage can lead to further rejects of shale and iron pyrites.

The largest loss is during the conversion of fuel through the process of combustion and conversion to electricity. The efficiency of the power station can lead to losses of coal of 55–70% (in energy terms). In terms of mass, the waste ash and by-products of flue gas cleaning equipment can be reused, so in effect, the residues of coal and the emissions are all that are tangibly left of the coal at the end of its journey along the coal chain.

Understanding mass loss of coal at the power station is as varied and complex as attempting to understand it further upstream. Quantifying these losses is a difficult task, and possibly too small to be of concern. However, identifying the locations and events that occur to a tonne of coal from the seam to the power station is more straightforward. Ensuring best practice in coal mining, preparation transportation, and finally in combustion should ensure efficient use of a depleting resource and longevity of the world’s reserves.

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