Abstract

Increasing steel demand and growing competition from scrap-based mini-mills is forcing blast furnace (BF)-based plants to improve their performance in order to reduce operating costs and, at the same time, increase productivity. One way to achieve this is by injecting pulverised coal directly into the BF. Injection of coal causes a number of changes within the BF, some of which can be detrimental. This report begins by outlining some of the technical issues associated with high pulverised coal injection (PCI) rates. It then discusses the effect of coal quality on the performance of BFs, with the emphasis on the properties of coal that influence its selection. The requirements relating to coke quality have become more stringent at high PCI rates, and this is discussed, along with the quality of iron ore. The pulverisation and injection of coal is examined. With high PCI rates the reliability of the injection system and the equal distribution of coal through the tuyeres are important as any interruption can quickly lead to serious problems. Coal combustion is an important parameter as it affects the amount of coal that can be injected. It produces, along with coke combustion, both heat and reducing gases for the ironmaking process. Coal combustion within the raceway and the consumption of unburnt char outside the raceway are discussed. Finally, the transfer of silicon and sulphur from coal to the hot metal (pig iron), which adversely affects its quality, is described. The report concludes that blending offers advantages in improving the performance of coals. Its importance is likely to increase as injection rates approach the theoretical maximum and will provide furnace operators with the flexibility in coal selection to meet their particular needs. With better prediction and improved understanding of the effect of coal properties and how operating conditions can be optimised, there is the potential to identify suitable, as well as cheaper, coals. This could provide significant cost savings whilst maintaining a high productivity.
<table>
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<tr>
<th>Acronym</th>
<th>Definition</th>
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<td>ad</td>
<td>air dried</td>
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<tr>
<td>AFT</td>
<td>ash fusion temperature</td>
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<tr>
<td>AI</td>
<td>abrasion index</td>
</tr>
<tr>
<td>AS</td>
<td>Australian standard (Standards Australia)</td>
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<td>ASTM</td>
<td>American Society for Testing and Materials (ASTM International)</td>
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<tr>
<td>BF</td>
<td>blast furnace</td>
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<td>BS</td>
<td>British standard (British Standards Institution)</td>
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<td>CRI</td>
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<tr>
<td>CSR</td>
<td>coke strength after reaction</td>
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<td>CV</td>
<td>calorific value</td>
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<td>daf</td>
<td>dry and ash free</td>
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<td>db</td>
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<td>DTF</td>
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<td>FSI</td>
<td>free swelling index</td>
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<td>GCI</td>
<td>granular coal injection</td>
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<td>HGI</td>
<td>Hardgrove grindability index</td>
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<td>HT</td>
<td>hemispherical temperature</td>
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<td>HV</td>
<td>high volatile</td>
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<td>IDT</td>
<td>initial deformation temperature</td>
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<tr>
<td>IEA</td>
<td>International Energy Agency</td>
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<tr>
<td>ISO</td>
<td>International Organization for Standardization</td>
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<tr>
<td>JIS</td>
<td>Japanese Industrial Standard (Japanese Standards Association)</td>
</tr>
<tr>
<td>kg/thm</td>
<td>kilograms per tonne of hot metal</td>
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<tr>
<td>LTD</td>
<td>low temperature disintegration</td>
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<tr>
<td>LV</td>
<td>low volatile</td>
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<tr>
<td>Mt</td>
<td>million tonnes</td>
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<tr>
<td>PC</td>
<td>pulverised coal</td>
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<td>PCI</td>
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<td>RAFT</td>
<td>raceway adiabatic flame temperature</td>
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<tr>
<td>RDI</td>
<td>reduction disintegration index</td>
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<td>RI</td>
<td>reducibility index</td>
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<td>RR</td>
<td>replacement ratio</td>
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<td>theoretical flame temperature</td>
</tr>
<tr>
<td>TGA</td>
<td>thermal gravimetric analyser/analysis</td>
</tr>
<tr>
<td>thm</td>
<td>tonne of hot metal</td>
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<tr>
<td>TI</td>
<td>tumble index</td>
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<tr>
<td>VM</td>
<td>volatile matter</td>
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<tr>
<td>WMR</td>
<td>wire mesh reactor</td>
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<tr>
<td>XRD</td>
<td>X-ray diffraction</td>
</tr>
<tr>
<td>YGP</td>
<td>Yancey, Geer and Price</td>
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Use of PCI in blast furnaces
1 Introduction

The main route for production of iron for steelmaking is via the blast furnace (BF), accounting for about 60% of current world steel production. Increasing steel demand and growing competition from scrap-based mini-mills is forcing BF-based plants to improve their performance in order to reduce operating costs and, at the same time, increase productivity. One way to achieve this is through the injection of pulverised coal directly into the BF.

Pulverised coal injection (PCI) provides important economic and operational benefits. These include:

- lower consumption of expensive coking coals. Replacing coke with cheaper soft coking or thermal coals reduces reductant costs. It takes about 1.4 t of coking coal to make 1 t of coke, which can be replaced by 1 t of pulverised injected coal (Couch, 2001). Coke prices have risen in the last couple of years and are expected to remain high for the next two years or so, creating further demand for cheaper PCI coals;
- extended coke oven life since less coke is required to be produced. This is important as many coke ovens are reaching the end of their useful life and significant investment is required to replace or maintain them. This often involves additional costs to meet increasingly stringent environmental standards. PCI also reduces the need for new high cost coke ovens. However, coal cannot completely replace coke and so cokemaking facilities will always be needed in BF-based ironmaking;
- higher BF productivity, that is, the amount of hot metal produced per day (in conjunction with other operational changes);
- greater flexibility in BF operation. For instance, PCI allows the flame temperature to be adjusted, and the thermal condition in the furnace can be changed much faster than would be possible by adjusting the burden charge at the top of the furnace. The injection rate can be modified at short notice, while the coke plant output cannot easily be increased or decreased in a short period;
- improved consistency in the quality of the hot metal and its silicon content (Bennett and Fukushima, 2003);
- reduced overall emissions from steel plants, in particular, lower emissions from cokemaking due to decreased coke requirements.

PCI is not a new technology. It was patented in the nineteenth century, but it was not until the 1960s that it became an industrial reality. Following the oil price shocks in the 1970s, PCI became more widespread. Previously, oil was the preferred injectant due to its low price relative to coal and natural gas. Today, coal is the main injectant used in BFs. Coal typically costs less than oil and natural gas, and its supplies are more stable. Although the capital cost associated with natural gas injection is lower than that for PCI, the latter provides the means to ultimately replace higher amounts of expensive coke in the BF, simply by permitting higher injection rates (Thomson and others, 1996). Higher coal rates are possible because it does not reduce the flame temperature in the furnace as much as natural gas and oil. Initially coal injection rates were low, around 40 to 90 kg per tonne of hot metal (kg/thm). Increased understanding of PCI has led to higher coke replacements rates, with injection rates of over 200 kg/thm seen today. This represents about 40% of the total reductant rate.

The increase in consumption of PCI coals in various OECD countries, plus Colombia and India, from 1990 is shown in Table 1. The major consumers are Japan and Korea, followed by India, the USA, Germany and France. However, PCI coal consumption in China, omitted from Table 1, rose from 7.5 million tonne (Mt) in 1998 to over 14 Mt in 2002 (Pei, 2003), making it the largest consumer. Brazil is also a large consumer of PCI coal, about 2.3 Mt in 2004 (Espeschit, 2004). PCI consumption has decreased in some OECD countries as integrated steel production has declined. However, the total amount of PCI coals consumed worldwide has generally increased each year, with the largest increase since 1998 occurring in 2004, the last year for which figures are available.

Today in Asia, coal injection equipment is installed on all BFs in Japan, Korea and Taiwan and nearly all of the full sized furnaces in China. A goal was set for an injection rate of 150 kg/thm to be achieved in all of China’s large and medium BFs in 2005, and an average 100 kg/thm in the smaller ones (Pei, 2003). Coal injection is installed on most of the coke-based BFs in South America and the majority of Western European furnaces. In North America, just over half of the BFs inject coal. Co-injection is practised in North America whereby moderate levels of PCI are accompanied by the use of other injectants, with natural gas being the leading choice. Some additional PCI facilities could be installed here in the future (Poveromo, 2004). Despite the reduced output by some Asian steel producers mooted for 2006, the main area for increased PCI consumption is still thought to be in Asia, particularly China and India (Boyle, 2006). The construction of new BFs and Asian steel producers utilising PCI coal at higher consumption rates will drive the demand for PCI coal. New BFs will be preferred over scrap-based mini-mills wherever steel demand is large, scrap is unavailable, iron ore and coal are available, and electric power is expensive (Carpenter, 2004). PCI capability is nearly always fitted to new BFs.

The seaborne trade for PCI coal is currently around 30 Mt/y, which is small compared with the total world coal trade of around 550 Mt/y. The major countries supplying this market are Australia, South Africa, Indonesia, Venezuela and Canada. Low volatile coals from Queensland, Australia currently account for around half of this seaborne trade. This preference for low volatile coals for injection has led some market analysts to predict a significant growth in the export of semi-anthracites from Queensland (Stainlay, 2004). New mines are due to open in Australia in 2006, and later, to produce products for the PCI and other coal markets (Boyle, 2006).
PCI causes a number of changes in BF behaviour, some of which can be detrimental. This report begins by outlining some of the technical issues associated with high PCI rates. BF performance is predominantly governed by the quality and consistency of the raw materials. The quality of coal is the subject of Chapter 3, with the emphasis on the properties of coal that influence its selection. A wide range of coal types can be injected. This chapter also covers coal reserves. The requirements relating to coke quality have become more stringent at high PCI rates, and this is discussed in the following chapter, along with the quality of iron ore. The pulverisation and injection of coal is examined in Chapter 5. There is a significant amount of unburnt char introduced into the BF burden, particularly at high injection rates. For stable BF operation there is a need to attain as high a level as is practicable of char burnout in the raceway. Coal combustion is discussed in Chapter 6, whilst the following chapter covers the consumption of unburnt char outside the raceway. Finally, the transfer of silicon and sulphur from coal to the hot metal (pig iron), which adversely affects its quality, is described in Chapter 8.

The effect of PCI use on the technical and economic performance of a steelworks will be site specific. For example, the substitution of coking coal by PCI in an integrated steelworks not only reduces the production requirements of coke, but also the amounts of coke oven gas and by-products. This may be unfavourable for the economics of a plant which uses and/or sells these materials. This report therefore concentrates on the technical aspects of PCI, and only covers economic factors in general terms.

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<td>2343</td>
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<tr>
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<td>9021</td>
<td>17639</td>
<td>19108</td>
<td>20060</td>
<td>23326</td>
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Note: includes granular coal injection for some countries

\[ e \] estimated
The consensus among PCI users seems to be that at injection rates up to about 150 kg/thm, there is no need for significant alterations to blast furnace operating procedures. But higher PCI rates can result in a production loss and shorter furnace life if no operational changes are implemented. The concern is not so much to do with high injection rates as with low coke rates. This is because injected coal can substitute for coke as a source of heat and carbon, but cannot provide a permeable bed in the furnace through which the molten iron can descend and the gases ascend. This chapter outlines some of the technical issues associated with high PCI rates. To understand these issues it is first necessary to describe what happens within a BF.

2.1 Blast furnace process

The blast furnace (see Figure 1) is basically a countercurrent moving bed reactor with solids (iron ore, coke and flux), and later liquids, travelling down the shaft. Pulverised coal and oxygen-enriched air are injected near the base. The gases which are formed by the various reactions taking place pass up the shaft, reducing the iron ore as it descends.

The iron ore (lump, pellets, sinter), coke and flux (limestone or lime) are alternatively charged into the top of the furnace (see Figure 2). They are dried and preheated by the gases leaving the shaft. As the charge travels down the furnace, it is heated and, at a temperature around 500ºC, indirect reduction of the ore by the carbon monoxide (CO) and hydrogen (H₂) in the ascending gases commences. The transformation of higher oxides of iron to wüstite (FeO) starts in this zone. As the charge descends further and is heated to around 900–950ºC, reduction of the iron oxide by solid coke occurs. The ore is reduced by CO and H₂, and the CO₂ formed is immediately reduced by the coke back to CO. The net effect is the reduction of the ore by the coke. The reactivity of the coke to CO₂ (see Section 4.1.2) is an important parameter since this determines the temperature range where the transition from indirect to direct reduction takes place.

Figure 1 Blast furnace (photograph courtesy of Corus UK Ltd)

Figure 2 Blast furnace cross section

Lower down the furnace in a region termed the cohesive zone, the iron burden begins to soften and deform at around 1100ºC. As the temperature increases to 1400–1450ºC, it begins to melt and reduction continues. This is a critical region in terms of burden permeability.

In the next zone, termed the fluid or active coke zone, the temperature is about 1500ºC. There is considerable movement in this region and the coke in it feeds into the raceway. The raceway is the hottest part of the furnace, where temperatures can reach 2200ºC. It is created when hot air is injected through tuyeres into the furnace. Pulverised coal is injected with the hot air blast directly into the raceway. Combustion and gasification of the coal and coke occurs (see Chapter 6), generating both reducing gases (CO and H₂) and the heat needed to melt the iron ore and slag and to drive the endothermic reactions. The hot blast is enriched with oxygen in order to maintain the desired flame temperature and to improve combustion efficiency. Unburnt residues, such as coal char, exit the raceway and pass up the furnace into the
bosh and stack. The molten metal and slag pass through the
deadman (stagnant coke bed) to the base of the furnace where
they are removed through the taphole. The slag is then
skimmed off from the molten iron. Some furnaces have
separate tapholes for the slag and iron. It can take 6–8 hours
for the raw materials to descend to the bottom of the furnace,
although coke can remain for days, or even weeks, within the
deadman. The liquid metal, termed pig iron or hot metal, is
transported to a basic oxygen furnace for refining or to other
steelmaking facilities.

The hot gas leaving the top of the furnace (offgas) is cooled,
cleaned, and used to fire the stoves that heat the injected air,
with the excess used to generate steam and power for other
uses within the plant.

2.2 Chemistry

The chemistry occurring within the BF is complex. The
following discussion only illustrates the major reactions
taking place. The principal chemical reaction is the reduction
of the iron oxide charge (haematite, Fe₂O₃, or magnetite,
Fe₃O₄) to metallic iron. This simply means the removal of
oxygen from the iron oxides by a series of chemical reactions
(indirect reduction) as follows:

\[
\begin{align*}
3\text{Fe}_2\text{O}_3 + \text{CO} & = 2\text{Fe}_3\text{O}_4 + \text{CO}_2 \\
3\text{Fe}_2\text{O}_3 + \text{H}_2 & = 2\text{Fe}_3\text{O}_4 + \text{H}_2\text{O} \\
\text{Fe}_3\text{O}_4 + \text{CO} & = 3\text{FeO} + \text{CO}_2 \\
\text{Fe}_3\text{O}_4 + \text{H}_2 & = 3\text{FeO} + \text{H}_2\text{O} \\
\text{FeO} + \text{CO} & = \text{Fe} + \text{CO}_2 \\
\text{FeO} + \text{H}_2 & = \text{Fe} + \text{H}_2\text{O}
\end{align*}
\]

These reactions begin at temperatures below 900°C and
generate heat (exothermic). At the same time as the iron oxides
are going through these reactions, they are also beginning to
soften and melt. At the high temperatures near the fluid zone,
carbon (coke) directly reduces wüstite (FeO) to produce iron
and carbon monoxide. This reaction is highly endothermic:

\[
\text{FeO} + \text{C} = \text{Fe} + \text{CO}
\]

Coal and coke within the raceway are ignited by the hot air
blast and immediately react to produce carbon dioxide and heat:

\[
\text{C} + \text{O}_2 = \text{CO}_2
\]

Since the reaction takes place in the presence of excess carbon
at a high temperature, the carbon dioxide is reduced by the
Boudouard or solution loss reaction to carbon monoxide:

\[
\text{CO}_2 + \text{C} = 2\text{CO}
\]

In addition, water vapour produced during combustion is
reduced as follows:

\[
\text{H}_2\text{O} + \text{C} = \text{CO} + \text{H}_2
\]

Both of these last two reactions are endothermic. Their
products are necessary to reduce the iron oxide charge as
described above.

Hydrogen (indirect reduction) is a more effective reducing gas
than carbon (direct reduction). The hydrogen regeneration
reaction \((\text{H}_2\text{O} + \text{C} = \text{CO} + \text{H}_2)\) is less endothermic and
proceeds faster than CO regeneration, the Boudouard reaction.
The use of coal increases the hydrogen concentration in the
furnace. Consequently, when the coal injection rate increases,
more hydrogen is available for indirect reduction of the iron
oxides (Hutny and others, 1991). In addition, higher hydrogen
contents promote higher rates of iron oxide reduction,
particularly in the high temperature region (Poveromo, 1996).

The limestone descends in the furnace and remains a solid
whilst it goes through the following reaction:

\[
\text{CaCO}_3 = \text{CaO} + \text{CO}_2
\]

This reaction is endothermic and begins at about 870°C. The
calcium oxide helps remove sulphur and acidic impurities
from the ore to form the liquid slag. It can also help remove
sulphur released from the coke and coal.

2.3 Process issues

PCI offers a substantial incentive for cost reduction in a steel
plant. However, good productivity with a high PCI rate
requires operational changes to be made. In general, though,
it is difficult to maximise both productivity and PCI rate at
the same time (Poveromo, 2004). The technical issues
associated with high PCI rates (>180 kg/thm) can be divided
into those associated with:

- coal performance in the raceway (see Chapter 6);
- unburnt coal char (see Chapter 7);
- behaviour of coke (see Section 4.1).

The stable operation of a BF depends on the even distribution
of the gas flow upwards and the unimpeded flow of hot metal
and slag to the hearth. Therefore maintaining permeability in
the furnace is vital to stable furnace operation, and therefore
productivity. The majority of the technical issues associated
with PCI are a response to permeability requirements.

Changes due to the injection of coal versus all-coke operation
include:

- alterations to the size and shape of the raceway. As PCI
  rates increase, both the amount of coal entering the
  raceway and blast momentum increase, leading to
  changes in the shape and size of the raceway;
- lower flame temperatures and changes in the temperature
distribution in the raceway (see Sections 6.2 and 6.5).
  The decrease in the flame temperature lowers the melting
  rate of the iron ore in the cohesive zone leading to
  unstable BF operation (Deno and Okuno, 2000);
- changes in the gas composition in the raceway, which
  can affect coke consumption in this region (see
  Chapter 6);
higher gas volumes in the tuyere and blowpipe from coal combustion (see Section 5.3). This can increase the pressure drop in the lower part of the furnace (Deno and Okuno, 2000);

- reduced permeability due to accumulation of unburnt coal char in the stack and hearth regions. For instance, char (and coke fines) can accumulate in the bird’s nest, a relatively compact zone between the raceway and deadman, and around the bottom of the cohesion zone. This can result in gas flow fluctuations and unstable operation. Peripheral gas flow can occur leading to increased heat load on the furnace walls, particularly in the lower part of the furnace. This can shorten the life of the furnace lining, accelerating the need for an expensive relining;

- higher heat loss from the furnace walls and from the furnace top due to a reduction in the heat flux ratio. The heat flux ratio is defined as the ratio of the heat capacity of the solid to the heat capacity of the gas (Deno and Okuno, 2000). As the burden velocity decreases with higher PCI rates, the heat flux is lowered, which raises the temperature of the ascending gases;

- slower dissolution rate of char in the metal and slag (see Sections 7.2 and 7.3, respectively);

- higher carbon contents in the emitted dust and offgas cleaning sludge (see Section 7.4). The dust and sludge rates also increase;

- greater amounts of molten material which can cause periphery liquid flow, contributing to erosion of the hearth lining and thus reducing furnace life (Choi and others, 2004). The higher slag volumes are due to added ash from the pulverised coal (see Section 3.7);

- more degradation of the coke between the stockline and deadman, but particularly in the lower part of the furnace (see Section 4.1.2). At higher PCI rates, the proportion of coke to ore in the furnace decreases resulting in thinner coke layers. Consequently, the coke is subjected to higher mechanical loads and longer residence time in the

Figure 3  Technical issues and their countermeasures at high PCI rates (Deno and Okuno, 2000)

Use of PCI in blast furnaces
furnace. In addition, the coke is subjected to further degradation in the raceway. The generation of coke fines can lead to poor blast penetration, impermeable deadman, peripheral gas flow and a high pressure drop.

Some of these issues and their countermeasures are summarised in Figure 3. Among the countermeasures are:

- increasing the hot blast temperature to raise the flame temperature in the raceway (see Section 6.5.2);
- increasing the oxygen content in the blast to improve coal combustion and reduce blast volume (see Section 6.5.1);
- changing the coal, coke and iron ore properties (see Chapters 3 and 4);
- changing the design and arrangement of the injection lances (see Sections 5.3 and 6.5.1);
- changing the burden distribution. Charging coke into the centre of the BF has resolved many of the problems relating to gas flow (such as heat losses) and improved bed permeability.

Most of the changes brought about by high PCI rates are interdependent. They are influenced by the properties of the injected coal and operating conditions. The influence of the quality of the coal is discussed in the following chapter, and coke and iron ore quality in Chapter 4.
BF performance is predominantly governed by the quality and consistency of the raw materials, especially at high PCI rates. This chapter discusses the principal properties of the injected coal that affect BF performance, whilst those for coke and iron ore are discussed in the following chapter.

A considerably wider range of coals can be used for PCI than for coking since the caking characteristics required for good coking coals are not required. Consequently, less expensive coals can be utilised. Coals ranging in rank from subbituminous through bituminous to anthracite have been successfully injected. Even lignite has been tested (Langner, 2005). Whilst the coal type seems to have little significant impact on BF operation at low injection rates (<100 kg/thm), coal properties become more important as injection rates increase. Pulverised coal quality is important not only in terms of its utilisation in the BF itself, but also in the preparation, handling and transport of the coal to the furnace. Within the BF, coal quality can influence the quality of the hot metal, furnace stability and productivity, and offgas composition.

The properties commonly used for evaluating PCI coals include:

- volatile matter;
- carbon content;
- hydrogen content;
- calorific value;
- moisture;
- ash content and composition;
- ash fusion temperature;
- sulphur;
- grindability.

Other important properties are the combustibility of the coal, and the assimilation characteristics of the char particles (discussed in Chapters 6 and 7, respectively). A consistent coal quality is additionally required for good performance.

An ideal PCI coal does not exist. A coal that is ideal for one BF will not necessarily meet the needs of another. Different site specific factors determine which coal properties are essential. It is also important to recognise that the true worth of a coal is not simply the delivered price. The effect of coal properties on BF performance and operating costs must be taken into account when assessing the true cost of the selected coal. Ultimately, the coals utilised will be those that provide the most benefits for the price. However, factors other than the coal cost can take priority in determining the PCI rate. Kobe Steel, for example, reduced the PCI rate to around 160 kg/thm at the Kakogawa 3BF because of the preference given to a higher productivity and more stable operation over reductant cost (Kentaro, 2006).

This chapter begins with a discussion of the coke replacement ratio, before examining the coal properties listed above. Coals are commonly blended to meet the required specification. Blends can reduce raw material costs since cheaper coals can be incorporated. The properties of a blend are calculated as the weighted average of the determined values for the individual coals in the blend. The ‘additivity’ of various coal properties is considered, but is covered in more detail in the report by Carpenter (1995).

### 3.1 Coke replacement ratio

The choice of coal significantly affects the cost benefit that can be obtained by its injection. The amount of coke that can be replaced by the injected coal and the coal price have the largest impacts on the economics of coal injection. One parameter for evaluating the economic benefits is the coke replacement ratio (RR). It is defined as the mass, in kilograms, of coke replaced per kilogram of coal, and can be reported as the ‘actual’ or ‘corrected’ value. The corrected RR is calculated by taking into account other changes in the energy and mass balance of the BF that influence coke rate, such as blast temperature (Bennett and Fukushima, 2003). The theoretical coke RR is between 0.8 and 1 kg coke/kg coal depending on the energy and carbon content of the coal. Actual RRs achieved in BF operation with low to moderate injection rates tend to be slightly higher due to reduced heat losses and some increase in reduction efficiency; at injection rates over 150 kg/thm heat losses can increase which may lead to RRs that are lower than theoretical (Bennett, 2000). A coke RR of 0.9 was achieved in China when injecting 100% anthracite at an injection rate of 150 kg/thm (Pei, 2003).

The RR depends on a complex interplay of chemical and physical processes (Hutny and others, 1996) and is affected by:

- coal quality;
- coal burnout;
- burden quality and gas flow distribution;
- raceway adiabatic flame temperature (RAFT).

In general, the RR increases with coal rank (Bennett, 2000; Kruse and others, 2003; Stainlay, 2004). As can be seen from Figure 4, the RR increases up to about a 91% coal carbon content.

![Figure 4 Variation of coke replacement ratio with coal carbon content (Kruse and others, 2003)](image-url)
content (semi-anthracite) when it levels out. Typically the RR decreases as coal VM increases (decreasing rank). However, Bennett and Fukushima (2003) report considerable variation when coal VM is plotted against the calculated RR. They found the partial heat of combustion gave a better parameter for estimating the RR since there was a near linear fit between the two parameters. The partial heat of combustion is the heat released when the coal is gasified to CO and H₂.

### 3.2 Volatile matter

Volatile matter (VM) released during coal pyrolysis consists of combustible gases (such as H₂, CH₄ and CO), incombustible gases (such as CO₂ and steam) and condensible volatiles, mainly tar. VM yield generally increases with decreasing rank, and the proportion of incombustible gases increases as coal rank decreases (Hutny and others, 1996). Maceral composition also affects VM yield and composition (Carpenter, 1995). Liptinite produces more VM than vitrinite, which, in turn, produces more than inertinite. In addition, liptinite has the highest hydrogen yield which lowers the RAFT (see Section 6.2), and the highest tar yield. Tar formation, which occurs at low temperatures, is detrimental since it generates soot, which has poor combustibility, contributing to raceway blockage, decreased bed permeability and other operational difficulties in the BF (Chatterjee, 1999). Liptinite forms a minor component of bituminous coals, but forms a higher proportion in lower rank coals.

The coal volatile content can affect char formation, blast momentum and generate coke fines in the raceway (see Figure 5). This is due to coal devolatilisation in the hot.

Figure 5  Effects of coal volatile content on raceway characteristics (Williams and Fellows, 1988)
blast and the action of the volatiles liberated in the tuyeres (Lüngen and Poos, 1996). A higher volume of gases injected into the raceway creates a greater blast momentum, and increases the raceway depth. These, and other factors, need to be considered before deciding whether a low or high volatile coal is suitable for injection:

- low volatile (LV) coals give higher coke RRs, and hence lower coke rates, coupled with minimum cooling (VM production is endothermic) (Hutny and others, 1996). They produce a lower volume of top gas with a lower calorific value, give a lower gas reduction of the iron ore, and have a higher RAFT and lower combustion efficiency than high volatile coals (although there are exceptions – see Section 6.3);
- high volatile (HV) coals generally have superior combustion performance due to higher volatile release. They generally produce more reactive chars, and hence better burnout. However, inertinite-rich LV coals, such as the Australian Permian coals, can produce reactive chars (see Section 6.4). Unburnt char can reduce bed permeability and lead to carbon losses through the top gas. Good combustibility is particularly desirable at high injection rates because of the short residence time available for combustion in the raceway; burnout typically decreases as injection rate increases. HV coals also contribute more hydrogen for reducing the iron ore. The higher gas volume, though, may lead to back pressure problems in the tuyere.

The blast temperature and/or the oxygen enrichment rate can be adjusted to suit the injected coal (see Sections 6.5.2 and 6.5.1, respectively). The amount of VM in coal, though, will be an issue at plants that have limited oxygen enrichment facilities.

Mid volatile coals are often perceived as the optimal solution. A blend of low and high volatile coals though could optimise the respective strengths of the two types of coal. However, the individual coals in these blends (Carpenter, 1995; Shaw, 2004) could:

- grind at variable rates to varying degrees (see Section 5.1.4);
- handle differently to each other during injection;
- combust at different temperatures and at different rates (see Section 6.5.4);
- burnout at varying rates (see Section 6.5.4).

HV coals have traditionally been injected due to concerns about coal combustibility and consequent effect on BF permeability. China was an exception starting with LV coals due to an explosion when testing HV thermal coals (Pei, 2003). Over the last five years or so, the proportion of LV coals included in the blend has been increasing with the realisation that char can be consumed outside the raceway. Posco in Korea, for instance, has increased the proportion of low (7–14% VM ad) and mid (30–38% VM ad) coals in the HV (30–38% VM ad) blend to 88% in 2003 (Kwon, 2005). Indicative specifications for PCI coals are given in Table 2. Kobe Steel in Japan no longer use VM as the main constraint in their coal selection. Their PCI technology allows coals with a wide range of VM contents to be used (Kentaro, 2006).

Highest injection rates have been achieved with either HV

### Table 2 Indicative PCI coal specifications (Garcia, 1999; Kentaro, 2006; Klaudat, 2006; Nightingale and others, 2003; Shaw, 2004; StaRosa and others, 1998)

<table>
<thead>
<tr>
<th>Coal</th>
<th>Kumba Coal (South Africa)</th>
<th>Gijón Works (Spain)</th>
<th>Port Kembla (Australia)</th>
<th>Great Lakes Works (MI, USA)</th>
<th>ThyssenKrupp Stahl (Germany)</th>
<th>Kobe Steel (Japan)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coal</td>
<td>High and low volatile coal blend</td>
<td>High and mid volatile coal blend</td>
<td>Coal blend</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total moisture, %</td>
<td>6–8</td>
<td>8.2</td>
<td>1.85 (ad)</td>
<td>&lt;10</td>
<td>0.9 (db)</td>
<td>&lt;13</td>
</tr>
<tr>
<td>Volatile matter, %</td>
<td>20-38</td>
<td>25</td>
<td>26.9 (db)</td>
<td>32–38</td>
<td>19-23 (db)</td>
<td>10–45</td>
</tr>
<tr>
<td>Ash, %</td>
<td>8 max</td>
<td>8.3</td>
<td>10 (db)</td>
<td>&lt;10</td>
<td>8.55 (db)</td>
<td>&lt;10 (db)</td>
</tr>
<tr>
<td>Sulphur, %</td>
<td>0.8 max</td>
<td>0.64</td>
<td>0.47 (db)</td>
<td>&lt;1</td>
<td>0.38 (db)</td>
<td></td>
</tr>
<tr>
<td>Phosphorus, %</td>
<td>0.05 max</td>
<td>0.01</td>
<td>&lt;0.025</td>
<td>0.03 (db)</td>
<td>depends on total alkali input from all sources</td>
<td></td>
</tr>
<tr>
<td>Alkalis, % (Na₂O, K₂O)</td>
<td>0.2 max</td>
<td></td>
<td>&lt;0.35</td>
<td>0.14 (db)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HGI</td>
<td>45–70</td>
<td>63</td>
<td>57</td>
<td>40–60</td>
<td>50–60</td>
<td>&gt;30 (single) &gt;40 (blend)</td>
</tr>
<tr>
<td>Ash fusion temperature, °C</td>
<td>1311 (ST)</td>
<td>&gt;1550 (IDT)</td>
<td>1315-1482</td>
<td>1350-1650 (IDT)</td>
<td>&gt;1375 (HT)</td>
<td></td>
</tr>
<tr>
<td>Calorific value, MJ/kg</td>
<td>33.9 (gross)</td>
<td>30.9 (gross, ad)</td>
<td>33 (gross, ad)</td>
<td>31 (net, db)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
coals or a blend of high and low volatile coals (Kruse and others, 2003). Coal injection rates of over 200 kg/thm were achieved during trials at the Corus IJmuiden 6BF using 42% VM Indonesian subbituminous coal (Sert and Godijn, 2002). However, the coke rate could not be reduced below 290 kg/thm, even at a PCI rate of 265 kg/thm. Switching to a blend of this HV coal with mid or low volatile coals showed improvements, allowing a coke rate well below 300 kg/thm (den Exeter and others, 2003). The standard methods for determining the VM content form part of the proximate analysis of coal (along with fixed carbon, ash and moisture contents). However, the actual VM yield in the tuyeres will be higher than that determined in the standard test (see Section 3.12). Some care in the use of the additivity rule for VM may be needed. It was found in the power generating industry that the proximate VM of a coal blend was not a reliable guide to its combustion behaviour if the blend contained coals of widely differing volatile yields (Carpenter, 1995).

### 3.3 Carbon content

Generally, as the carbon content of the coal increases:

- the coke RR increases (see Section 3.1);
- blast momentum decreases but only when carbon content (daf) is more than 85%. The blast momentum directly influences the raceway depth and coke degradation within the raceway. At high injection rates and injecting a coal with a carbon content (daf) less than 85%, any fluctuations in the coal rate delivered to a tuyere will result in fluctuations in the raceway depth and the generation of coke fines. This will reduce BF stability and therefore productivity (Australian Coal Review, 1998; Bennett, 2000);
- blast oxygen enrichment requirements to maintain raceway gas temperatures decreases (Australian Coal Review, 1998). This is discussed in Section 6.5.1.

The standard methods for determining the carbon content of coal form part of the ultimate analysis. Carbon content is additive for blends.

### 3.4 Hydrogen content

Hydrogen from the coal contributes to the bosh gas hydrogen content. The beneficial effects of hydrogen on BF operation (Poveromo, 1996; Stainlay and Bennett, 2001) are:

- physical. An increase in the percentage of hydrogen in the bosh gas decreases bosh gas density, and therefore reduces the pressure drop or allows a greater gas flow for the same pressure;
- thermochemical. At high injection rates, a significant amount of the coal is consumed in the reduction of FeO. The extent of solution loss reaction decreases as bosh gas hydrogen content increases, as was observed at the Fukuyama 4BF when the PCI rate was raised to over 200 kg/thm (Kimura and others, 1996). Since reduction by hydrogen is less endothermic than the C-FeO solution loss reaction, there is a decrease in the energy requirements in the reduction zone. Additionally, reactions with hydrogen are substantially faster allowing reactions to potentially occur at lower temperatures. Thus the optimum RAFT in furnaces operating with higher hydrogen contents can be lower than those operating with lower hydrogen contents (Juniper, 2000; Poveromo, 1996);
- kinetic. The ability of H₂ and H₂O to diffuse into and out of individual pellets and sinter is significantly higher than CO and CO₂. Higher diffusibility promotes higher reduction rates, particularly at lower temperatures.

However, a higher hydrogen concentration can lead to higher amounts of coke fines in the furnace shaft. In general, coal hydrogen content increases with decreasing rank. Although the use of HV coal may translate into less carbon input, the higher hydrogen content can help to compensate for this. The standard methods for determining the hydrogen content of coal form part of the ultimate analysis. Hydrogen content is additive for blends.

### 3.5 Calorific value

The calorific value (CV) of a coal affects:

- the coke RR. Generally, the RR increases as coal CV increases (Hutny and others, 1997; Kruse and others, 2003). The CV of coal normally increases with increasing rank;
- furnace stability. Higher CV coals should increase the heat flux in the raceway and consequently, the RAFT (Kruse and others, 2003; Thomson and others, 1996).

There are standard methods for determining the calorific value for coal. It is additive for coal blending.

### 3.6 Moisture

Moisture increases transportation costs and affects the handleability of coals. Coals with poor handling properties can cause blockages during transport to the BF. The total moisture content of coal consists of surface (free) moisture and inherent (residual) moisture. Usually, as the surface moisture increases, so does the difficulty in handling the coals, especially when combined with a high coal fines content. Heavy rainfall and other climatic processes can increase the coal moisture content in open air stockpiles to such an extent that handling problems occur, such as plugging of belt conveyors and chutes.

Moisture additionally affects both the energy consumption and output of the pulveriser by increasing the volume and temperature of the air needed for adequate coal drying. The maximum PCI rate can be limited by pulverising plant capacity (see Section 5.1.3). Blockages during transport to the injection lances have been linked to the moisture content of the pulverised coal (see Section 5.2.3). A higher moisture content tends to lower the RAFT and will require more energy for evaporation of the moisture. Thus lower moisture coals allow higher rates of injection at a given flame temperature. Although HV coals may have better combustibility than LV ones, they typically have higher
moisture contents. They may therefore require drying before being pulverised, adding to the operating costs, or they could be blended with lower moisture coals. In general, a total moisture content of less than 10% is preferred for PCI coals (see Table 2 on page 13).

There are standards for determining the total and inherent moisture contents of coal. The surface moisture can be calculated by subtracting the inherent moisture from the total moisture content. The standard methods for determining moisture and their shortcomings are discussed in Carpenter (2002). Moisture content is considered to be additive.

3.7 Ash content

With high PCI rates, the injected coal becomes a major source of ash and other impurities. A low coal ash content, typically less than 10%, is normally favoured (Chatterjee, 1999; Innes and Davis, 1998; Juniper, 2000) because:
- high levels of mineral matter can reduce pulveriser performance and throughput, and increase wear in the pulveriser and conveying pipelines (see Section 5.1);
- lower slag volumes, and therefore a better thermal efficiency, are attained. Less energy is needed to melt the ash in lower ash coals;
- high levels of mineral matter can cause lance blockage;
- it reduces flux requirements;
- a higher coke RR is achieved, although this is relatively small. The reduction in the RR is about 0.01–0.05 for each 1% increase in ash content. This arises from the requirement to add additional carbon to compensate for the extra ash. Ash can act as an inhibitor in the oxidising process if, for example, there are reduced species present in the ash. For furnaces with a total reductant (coal plus coke) rate of 500 kg/thm, every 1% reduction in coal ash reduces the coke rate by 6 kg/thm (Poveromo, 2004);
- to limit undesirable constituents present in the ash, such as silica, alumina and chlorine (see Section 3.8).

Thus better productivity and lower operating costs may be obtained with lower ash coals. Bennett and Fukushima (2003) utilised the BF process model developed by Rist and Meysson in 1967 to investigate the impact of the coal ash content (10%, 9% and 8% ad) on operating costs. Three PCI rates (100, 150 and 200 kg/thm) were modelled with constant blast temperature and moisture allowing the coke rate and blast volume to change. It was found that only at high injection rates (150 and 200 kg/thm) with high energy costs (natural gas) for the energy consumed within the steelworks that a lower ash significantly lowers operating costs. The second approach kept the coke rate and raceway flame temperature at similar values but changed the PCI rate and oxygen enrichment for three cases:
- Case 1: blast temperature and moisture held constant;
- Case 2: blast temperature held constant;
- Case 3: blast moisture held constant.

These three cases correspond to normal control strategies to maintain constant raceway flame temperature. The impact of ash on costs is calculated as a bonus (US$/t PCI coal) from the base case of 430 US$/t for the 10% ash coal. Figure 6

Figure 6 Bonus in PCI price versus ash content (Bennett and Fukushima, 2003)
shows how the ash content influences this bonus; also shown is the bonus calculated to a dry, ash free basis (daf). At low energy costs (thermal coal) the cases evaluated do not depart significantly from the daf adjustment. However, the three different operating strategies differ significantly from the daf adjustment at high energy costs (natural gas price). Case 3 shows a negative bonus for a 1% decrease in ash, that is, ash seems to be beneficial. In all the cases at high energy costs, the control strategies to maintain constant coke rate at different PCI coal ash content are having a greater influence than the ash of the injected coal. The calculations did not take into account the possible impact of ash on furnace operation which could affect productivity, and therefore costs.

There are standard methods for determining the ash content (technically, the ash yield), discussed in Carpenter (2002). Some care in the application of the additivity rule for ash content is required when blending coals of widely different rank (Carpenter, 1995).

### 3.8 Ash composition

The constituents in the coal ash (and similarly, in the coke ash) can influence furnace operation and the quality of the hot metal product. These include:

- alumina (Al₂O₃) which is considered to be responsible for the largest increases in flux requirements (Innes and Davis, 1998);
- silica (SiO₂). Coals with low silica (SiO₂) in the ash are favoured to help ensure that the slag formed can be easily tapped from the furnace (Juniper, 2000). A low silica load at the tuyeres also results in lower amounts gaseous silicon monoxide (SiO), and hence a lower hot metal silicon content (see Section 8.1). Coal char consumption is also influenced by its silica content (see Section 7.3.2);
- alkalis. Sodium- and potassium-containing compounds derived from coal minerals can contribute to coke degradation and to deterioration of the refractory lining (Hutny and others, 1996; Juniper, 2000). They can also contribute to sinter disintegration (Lectard and others, 2003). Removal of alkalies by slag requires lowering both slag basicity and flame temperature, conditions opposite to those needed for a low sulphur metal product (Hutny and others, 1996). The combined upper limit for sodium and potassium oxides is usually 0.1% ad (Innes and Davis, 1998);
- chlorine. Chlorine (mostly in the form of alkali chlorides) can cycle in the shaft. It is associated with refractory deterioration. Chlorine, as HCl, exits in the top gas. This humid top gas is acidic and very corrosive, resulting in the chemical attack of unprotected metal components (Lectard and others, 2003). The rest of the chlorine is removed in the molten slag (Myoung and others, 2003). The partitioning of chlorine between the top gas and molten slag depends on process conditions. The limit for chlorine is typically 0.05% ad (Innes and Davis, 1998). However, chlorine inputs have reached 1 kg/thm in the Dillinger BF in Germany where chlorine-rich coals are injected (Lectard and others, 2003);
- phosphorus, as it affects product quality (Juniper, 2000). A low coal phosphorus content, usually below 0.08%, is preferred;
- sulphur (see Section 3.10).

The standard methods for determining ash composition are reviewed in Carpenter (2002). The elements are reported as their oxides. There are separate standards for determining the chlorine content of coal. Chlorine content and ash composition values are probably additive for blends.

### 3.9 Ash fusion temperature

An important characteristic is the initial deformation temperature (IDT) of the coal ash. If the IDT of the coal is too low, then ash deposition in the injection lance and tuyeres may occur (see Section 5.2.3). This problem is analogous to the slagging problem frequently encountered in coal-fired power plant boilers, where it is also mitigated by using coals with higher ash fusion temperatures. Positioning the injection lance closer to the tuyere can reduce the extent of ash impingement in the blow pipe. This may allow a lower IDT coal specification. Some operators prefer a low IDT to help ensure that the slag formed in the furnace is easily tapped.

Ichida and others (2001) found that the formation of <1 mm fines from highly viscous slag originating from the coal ash can reduce permeability in the deadman zone. Experiments have indicated that in the raceway molten coal ash may enhance coke degradation by chemical interactions with the coke (Khairil and others, 2001a; Naruse and others, 2000). IDTs of more than 1375°C are typically specified (see Table 2 on page 13). The softening temperature (ST) or hemispherical temperature (HT), both higher than the IDT, are sometimes specified instead.

The IDT is a reflection of the ash composition. The presence of alkaline oxides (CaO, MgO, Fe₂O₃, FeO) act as fluxes, lowering the melting temperatures, especially in the presence of excess SiO₂. High sulphur (from pyrite) can result in a lower IDT. Lower rank coal ash, like lignite ash, are often highly alkaline, and thus their melting temperatures are usually lower than bituminous coal ash. Consequently, these coals are more likely to give ash deposition problems than higher rank coals.

There are standard methods for determining the IDT, namely the ash fusion temperature (AFT) test (see Section 3.12). IDTs are non-additive for coal blends. Drawbacks of the AFT test are reviewed in Carpenter (2002), albeit from the viewpoint of the power generating industry. Alternative thermomechanical techniques for determining ash fusion temperatures have been proposed. These measure the shrinkage, electrical conductance or electrical resistance of ash samples. But there are disadvantages with these tests (see Carpenter, 2002) and, like the AFT test, they are still based on a coal ash chemistry that is different from that found in blast furnaces.

### 3.10 Sulphur

Sulphur in coal can be either organic or inorganic (sulphide
Use of PCI in blast furnaces

3.12 Coal evaluation

Most of the coal properties described in the previous sections are determined by laboratory methods specified in national and international standards and these are discussed in Carpenter (1988, 2002). Common causes of confusion in the comparison of coals and the interpretation of analytical data that were identified included:

- the different domestic and international classification schemes used. A coal classified as subbituminous coal in one classification scheme may be classified as a bituminous coal in another;
- the wide range of analytical bases on which the analytical data are reported (for example, as received, air dried, dry and ash free, moist and ash free, mineral matter free) and the failure of workers to identify the basis of their results clearly.

The majority of the standard tests are empirical and hence the values obtained depend on the specified conditions. The tests were developed for the coking and power generating industries and therefore the relevance of some of the tests under the conditions pertaining in the BF tuyeres and raceway may be questionable. For example, the conditions of the standard VM test (notably final temperature 900/950ºC, slow heating rate and a residence time of minutes) differ significantly from those occurring within the BF raceway (with temperatures around 2200ºC, heating rates about 10⁵–10⁶ ºC/s, residence time about 10–40 ms). In addition, devolatilisation in the BF occurs under pressure (around 450 kPa) and in an oxygen enriched hot air blast. Thus the total VM yield in a BF will be different from the proximate VM. The standard AFT test for determining IDT is based on the properties of laboratory-prepared ash samples which are produced under conditions that are different from those occurring in the injection lances and tuyeres. The conditions specified for determining a particular property can vary between standards. For instance, the ASTM VM yield will be different from the ISO value. Therefore, the standard followed should be stated.

It should be emphasised that the coal, or blend, to be evaluated must truly represent the mass of material from which it is taken. Various national and international standards specify the procedures for collecting samples for analysis; following these should minimise any bias. However, there is the question of whether the milligrams or gram samples used in standard and non-standard bench-scale tests can provide a truly representative sample of the tonnes of coal consumed in a BF.

There is also the question of how far data obtained from bench-scale tests can be extrapolated to pilot- and full-scale industrial plants. The practical applications of many of the laboratory studies may well be limited since the results are obtained at controlled experimental conditions that are different from those occurring in BFs. Mathematical models are proving useful in understanding the laboratory experiments and in extrapolating these to the pilot and industrial plant scale. However, the validity of computer models of the BF is questionable because the mechanisms they are portraying are complex and not fully understood. Their accuracy will depend on the validity of the relationships and the assumptions made, and on the validity of any coal quality-based index built into the model.
3.13 Coal reserves

PCI coal production is the fastest growing sector in the coal market. The seaborne PCI coal trade has generally risen each year to over 30 Mt at the end of 2003 (Stainlay, 2004). The major countries and regions that supply this market are shown in Figure 7, which also indicates how the growth is expected to increase in future years. New mines are currently being opened in, for example, Australia and Canada to supply the PCI market, particularly for Asia where demand for PCI is strong. Japan, Korea and Taiwan are all strong users of PCI (see Chapter 1) with little domestic coal. China is the largest consumer of PCI coals and is also an exporter of these coals. One Asian country where PCI consumption is expected to grow rapidly is India, where economic growth is forecast to rise dramatically, raising the demand for steel. Other major PCI coal importers include Brazil and some Western European countries. PCI anthracite consumption in Brazil is predicted to increase from around 230,000 t in 2004 (about 10% of its total PCI coal consumption) to over 1.8 Mt, as the percentage of anthracite in the PCI coal blends is increased (Espeschit, 2004). Brazil imports anthracite from China, its main source, and from South Africa, Vietnam and Russia. The demand for LV coals has risen in the last five years due to greater understanding of the impact of coal quality on BF performance. As indicted in Figure 7, Australia (Queensland) is expected to be the biggest exporter of LV coals. HV coals from China, Canada, Indonesia and Venezuela are in demand today (Cochrane, 2004).

Coal is widely dispersed throughout the world. The major coalfields of the world are described in the IEA Clean Coal Centre report by Walker (2000). Table 3 gives the proved recoverable coal reserves, in Mt, for countries at the end of 2002, listed in order of the total amount of anthracite, bituminous and subbituminous reserves. Proved recoverable reserves are the amount of coal which would be economically recoverable using current technology. Lignite reserves are included but will not be discussed any further since little lignite, if any, is currently utilised in BFs. Lignite has been tested, for example, at the Hamborn 4BF in Germany (Langner, 2005); Germany has 6,556 Mt of lignite. The data are taken from the ‘Survey of Energy Resources’ produced by the World Energy Council every three years (Trinnaman and Clarke, 2004). They are open to some uncertainty since coal reserves can change significantly and rapidly, as policies change and resources lose or gain viability. In addition, there is no universally accepted system of demarcation between coals of different rank. What is regarded as subbituminous coals, for example, tends to vary from one country to another. Moreover, if subbituminous coal is not isolated as such, it is sometimes included with bituminous coals and sometimes with lignite. Overall, it has been estimated that world coal reserves (including lignite) will last for about 165 years at current levels of production (IEA, 2005).

The largest amounts of proved recoverable reserves of subbituminous, bituminous and anthracitic coals are in the Asia Pacific region (228,487 Mt), principally in China, India and Australia (Trinnaman and Clarke, 2004). Of these three, China has the largest reserves (see Table 3). Total Chinese geological coal resources, though, are over 770,000 Mt (Walker, 2000). There are 474,000 Mt of anthracite, forming

Figure 7 Major PCI coal exporting countries (Stainlay, 2004)
about 10–12% of the coal resources (Pei, 2003; Suen, 2004). The majority are in the provinces of Shanxi (42.6%), Guizhou (24.2%) and Henan (9.3%). A typical specification for Chinese PCI anthracite is 11% ash, 0.5% sulphur and 7–10% VM, all on a dry basis, CV 31.43 MJ/kg, HGI 60–80, and a size of 0–15 mm. In 2003 2.24 Mt of anthracite were exported for PCI (Suen, 2004). Resources of semi-anthracite (about 10–16% VM daf) are 146,800 Mt, with the largest amount again in Shanxi province (40%). The quality of semi-anthracite from Guizhou, Ningxia and Yunnan provinces is comparatively poorer. Anthracite is expected to be the dominant PCI coal used in Chinese BFs in the short term, whilst the use of HV coal will gradually take a larger share in the future (Pei, 2003).

Australia has proved recoverable coal reserves of 40,800 Mt (excluding lignite), mainly in Queensland and New South Wales. It is the largest exporter of PCI coals, with Queensland’s LV coals, mostly semi-anthracites, currently accounting for around half of the seaborne traded PCI coals. In addition, semi-soft coking coal, and low and medium volatile thermal coals from Central Queensland can be utilised for PCI. The exported LV coals from Queensland come from the Bowen Basin which has reserves of 26,000 Mt with 6000 Mt accessible by surface mining. Due to their properties, these PCI coals are not generally suited to the thermal or coking coal markets (Stainlay, 2004). Typical coal qualities are 7.7–10.5% ash (ad), 10–16% VM (ad), <0.65% sulphur (ad), 31.2–32.9 MJ/kg CV and about 75–85 HGI.

### Table 3 Recoverable coal reserves (Mt) at end of 2002 (Trinnaman and Clarke, 2004)

<table>
<thead>
<tr>
<th>Country</th>
<th>Anthracite and bituminous coal</th>
<th>Subbituminous coal</th>
<th>Lignite</th>
<th>Total reserves, excluding lignite</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>111,338</td>
<td>101,978</td>
<td>33,327</td>
<td>213,316</td>
</tr>
<tr>
<td>Russian Federation</td>
<td>49,088</td>
<td>97,472</td>
<td>10,450</td>
<td>146,560</td>
</tr>
<tr>
<td>China</td>
<td>62,200</td>
<td>33,700</td>
<td>18,600</td>
<td>95,900</td>
</tr>
<tr>
<td>India</td>
<td>90,085</td>
<td>2,360</td>
<td></td>
<td>90,085</td>
</tr>
<tr>
<td>South Africa</td>
<td>48,750</td>
<td></td>
<td></td>
<td>48,750</td>
</tr>
<tr>
<td>Australia</td>
<td>38,600</td>
<td>2,200</td>
<td>37,700</td>
<td>40,800</td>
</tr>
<tr>
<td>Ukraine</td>
<td>16,274</td>
<td>15,946</td>
<td>1,933</td>
<td>32,220</td>
</tr>
<tr>
<td>Kazakhstan</td>
<td>28,151</td>
<td></td>
<td>3,128</td>
<td>28,151</td>
</tr>
<tr>
<td>Poland</td>
<td>14,000</td>
<td></td>
<td></td>
<td>14,000</td>
</tr>
<tr>
<td>Brazil</td>
<td></td>
<td>10,113</td>
<td></td>
<td>10,113</td>
</tr>
<tr>
<td>Colombia</td>
<td>6,230</td>
<td>381</td>
<td></td>
<td>6,611</td>
</tr>
<tr>
<td>Czech Republic</td>
<td>2,094</td>
<td>3,242</td>
<td>216</td>
<td>5,336</td>
</tr>
<tr>
<td>Canada</td>
<td>3,471</td>
<td>871</td>
<td>2,236</td>
<td>4,342</td>
</tr>
<tr>
<td>Indonesia</td>
<td>740</td>
<td>1,322</td>
<td>2,906</td>
<td>2,062</td>
</tr>
<tr>
<td>Chile</td>
<td>31</td>
<td>1,150</td>
<td></td>
<td>1,181</td>
</tr>
<tr>
<td>Mexico</td>
<td>860</td>
<td>300</td>
<td>51</td>
<td>1,160</td>
</tr>
<tr>
<td>Turkey</td>
<td>278</td>
<td>761</td>
<td>3,147</td>
<td>1,039</td>
</tr>
<tr>
<td>Uzbekistan</td>
<td>1,000</td>
<td></td>
<td>3,000</td>
<td>1,000</td>
</tr>
<tr>
<td>Peru</td>
<td>960</td>
<td></td>
<td>100</td>
<td>960</td>
</tr>
<tr>
<td>Serbia &amp; Montenegro</td>
<td>9</td>
<td>656</td>
<td>15,926</td>
<td>665</td>
</tr>
<tr>
<td>Korea (DPR)</td>
<td>300</td>
<td></td>
<td>300</td>
<td>600</td>
</tr>
<tr>
<td>Zimbabwe</td>
<td>502</td>
<td></td>
<td></td>
<td>502</td>
</tr>
<tr>
<td>Spain</td>
<td>200</td>
<td>300</td>
<td>30</td>
<td>500</td>
</tr>
<tr>
<td>Netherlands</td>
<td>497</td>
<td></td>
<td></td>
<td>497</td>
</tr>
<tr>
<td>Venezuela</td>
<td>479</td>
<td></td>
<td></td>
<td>479</td>
</tr>
<tr>
<td>Argentina</td>
<td>424</td>
<td></td>
<td></td>
<td>424</td>
</tr>
<tr>
<td>Iran</td>
<td>419</td>
<td></td>
<td></td>
<td>419</td>
</tr>
<tr>
<td>Hungary</td>
<td>198</td>
<td>199</td>
<td>2,960</td>
<td>397</td>
</tr>
<tr>
<td>Japan</td>
<td>359</td>
<td></td>
<td></td>
<td>359</td>
</tr>
<tr>
<td>Others</td>
<td>1658</td>
<td>1011</td>
<td>19,897</td>
<td>2669</td>
</tr>
<tr>
<td>Total</td>
<td>478,771</td>
<td>272,326</td>
<td>157,967</td>
<td>751,097</td>
</tr>
</tbody>
</table>

Note: data for Mongolia are not available
Several new coking mines are planned within the Rangal Coal Measures. In washing to meet the coking coal specification, a secondary product may be produced; this can be either a thermal or PCI product. Typically the PCI product will be 9–10% ash and 18–22% VM. This will generate additional high energy PCI coal (Stainlay, 2004).

India has a hard coal resource base of about 206,000 Mt (Walker, 2000), of which some 90,100 Mt are proved recoverable reserves of anthracite, bituminous and subbituminous coals. Most of the coal deposits are in the east of the country. However, the coal is generally of poor quality (high ash of 30–35%) and difficult to wash (Chatterjee, 2002). Thus India is likely to become a significant importer of PCI coals when its steel industry expands.

Indonesia is a major supplier of PCI (see Figure 7), principally HV coals. It has proven recoverable reserves of 2100 Mt (excluding lignite), the majority of which are subbituminous (see Table 3). Most of the export mines are situated in Kalimantan.

North America (USA, Canada and Mexico) has the next largest amount (218,818 Mt) of proved recoverable coal reserves after the Asia Pacific region, although there are more coals of lower rank (subbituminous). The USA has the largest proven recoverable coal reserves in the world. There are ample quantities of good quality coal available for PCI. Walker (2000) gives the quality parameters of the coals in the major geologic formations.

Canada is the largest PCI coal exporter in this region. Canadian coal reserves are concentrated in the western provinces of British Columbia and Alberta, which are well positioned for exporting coals to the Asian market and elsewhere. The current strong market for coking and PCI coals has led to a number of new coal mine projects, particularly in north east British Columbia, resulting in Canada emerging as a new supply source of LV PCI coals. For instance, the Willow Creek and Dillon mines, with current mineable reserves of 15.2 Mt and 1.56 Mt, respectively (Lane, 2005), started exporting LV PCI coals in 2004. The Dillon coal has <14% VM. The Mount Klappan project, with measured and indicated resources of 230.9 Mt, will produce anthracite suitable for PCI and other uses (Fortune Minerals, nd). The Fording River mine in south east British Columbia produces mid-volatile (22–24% VM) PCI and coking coals, and has measured and indicated reserves of over 200 Mt. The Grande Cache mine (formerly Smoky River) in Alberta restarted in 2004 and produces both PCI and coking coals. It has reserves of around 50 Mt.

Proven recoverable coal reserves in Europe are 200,809 Mt, principally in the Russian Federation, Ukraine and Poland (see Table 3). The majority, though, is subbituminous (117,982 Mt). Bituminous and anthracitic coal reserves are becoming depleted in Western Europe and so these countries are now mostly PCI coal importers. Russia is exporting PCI coals, mostly low volatile, to Japan, Turkey, Brazil and elsewhere. It has huge coal resources, of which those in eastern Siberia and the Russian Far East remain largely unexploited because of their remoteness and lack of infrastructure. This is changing with the planned Elga project in the Russian Far East. Elga, with recoverable reserves of 2173 Mt, will produce both coking and thermal coals. Some of the coal will be exported to the Pacific Rim countries through the Port of Vostochny via a new railway (Elgaugol, 2001). Walker (2000) discusses the coal qualities and resources in the major Russian, Ukrainian and Polish coal basins.

The Eurasia region has 32,279 Mt of proven reserves, principally in Kazakhstan. This country exports coking and thermal coals, mainly to Russia and the Ukraine. Quality parameters of some Kazakh coals are given in Walker (2000). Some of these coals would be suitable for PCI.

The coal reserves in Africa (50,332 Mt), South America (19,769 Mt) and the Middle East (419 Mt) together represent about 10% of the total proved recoverable reserves. The only significant coal resources in Africa lie within South Africa, Botswana, Swaziland, Zimbabwe, Mozambique and Zambia. While both Zimbabwe and Zambia have limited production, and Botswana and Mozambique have the geological potential for substantial future coal mining, only the South African deposits currently support large-scale production (Walker, 2000). South Africa is the largest PCI coal user in Africa. It has proven recoverable bituminous and anthracitic coal reserves of 48,000 Mt. Low to medium volatile (13–25% VM) bituminous PCI coals, with 0.01–0.04% phosphorus, 0.65–0.8% sulphur, 10–15% ash and 55–67 HGI are produced from the Leeuwpan and Grootegeluk mines, along with a HV (37.4% VM) PCI coal (Shaw, 2004). Anthracite is also mined, with ‘reserves’ estimated at 1340 Mt (Pinheiro, 2004), although not all of these coals may be suitable for PCI.

The expansion of and planned new BF plants in Brazil will increase its import needs for PCI coal. Brazil only has reserves of subbituminous coal (see Table 3). Both Colombia and Venezuela host substantial resources of high quality thermal coal, some of which is exported as HV PCI coal. Their geographical location provides easy access to markets in Brazil, North America, Europe and, via the Panama Canal, to the Far East. Colombia has proven recoverable bituminous coal reserves of 6230 Mt, with a further 15,400 Mt in inferred resources (Walker, 2000). Venezuela has less coal, with proven reserves of 479 Mt. Exports from Venezuela are expected to increase with the opening up of new mines. The planned Las Carmelitas mine (Cosila project), with proven reserves of 29 Mt, will produce thermal coal, and a HV (39.5% VM), low ash (5%) PCI coal, with a sulphur content of 0.5% and HGI of 41 (Madrigal, 2005).
4 Coke and iron ore quality

This chapter discusses the properties of coke and iron ore that have a significant impact on BF performance under high PCI rates.

4.1 Coke quality

The quality of coke is becoming more stringent with higher rates of coal injection and larger BF hearth diameters. Coke performs three main roles in a BF:
- chemically, it is a reducing agent. Its combustion provides reducing gases to reduce the iron ore, and alloying elements such as silicon. It also supplies carbon for carburisation of the hot metal;
- thermally, its combustion in the raceway provides a source of heat to melt the iron and slag, and to drive the endothermic processes;
- physically, by providing support for the iron burden on a permeable matrix, through which the gases and liquid iron and slag can flow.

Coal can contribute to the first two roles but not to the third physical role. Here, the coke has to guarantee permeability for the furnace gas in the region above the cohesive zone, within the cohesive zone, and for gas and molten products in the bosh and hearth regions. Coke plays a particularly important role in the cohesive zone where the softening and melting of the iron ore can form impermeable layers, separated by permeable coke layers or windows. Additionally, in this zone coke forms a strong grid which supports part of the weight of the overlying burden (Großpietsch and others, 2000). This is why BF operation with just coal is impossible.

At higher PCI rates, the proportion of coke to ore in the furnace decreases considerably resulting in thinner coke layers. Hence the permeability of the burden materials to gas flow decreases and the coke is subjected to higher mechanical load. The lower coke to ore ratio also leads to a lower burden descent velocity for a given iron production rate. The average residence time of the coke inside the furnace thereby increases. It has been estimated that, at high PCI rates, the residence time of coke in the high temperature zone is 3 to 5 times that of an all-cok e operation (Lüngen and Poos, 1996). Consequently, coke suffers longer periods of mechanical, thermal and chemical stresses, leading to increased degradation and hence more fines generation. A higher coke quality is therefore needed to reduce fines generation that could lead to poor permeability, unstable BF operation, and lower productivity. The production of higher quality coke, though, can result in higher coking costs due to the use of more expensive higher quality coal and longer coking times with lower coke plant productivity. For steel works with in-house coking plants, this means a reduction in coke supply and consequently, a higher amount of imported coke. The production of coke is covered in the Clean Coal Centre report by Couch (2001).

The rate at which the coke degrades and generates fines as it descends through the furnace is mainly controlled by solution loss reaction, thermal stress, mechanical stress and alkali accumulation, depending on its position within the furnace (and operational conditions). Thus the principal coke properties of interest are its:
- cold strength, and resistance to breakage and abrasion during handling;
- hot strength, and the retention of structural integrity in the coke lumps when reacted with CO\textsubscript{2} at high temperatures;
- chemical composition, particularly its ash, sulphur and alkali contents;
- mean size and size distribution. Undersize material has to be screened out before charging. The size distribution impacts directly on furnace permeability, both in the stack area and the lower parts of the furnace.

The consistency of the coke quality is also important because furnace operation is adapted to suit it. Once a poor quality coke is charged into a BF, it can take days to pass from the furnace top through the deadman. Therefore, even the immediate charging of higher quality coke will not improve BF operation in the short term. Operational measures to reduce coke degradation include charging the coke into the centre of the furnace (Matsui and others, 2005). Coke fines are consumed within the furnace by the same mechanisms discussed for unburnt coal char in Chapter 7 (solution loss reaction, hot metal carburisation and reaction with the slag).

4.1.1 Cold strength

The mean size of coke reduces by 25 to 75% from the top of the furnace to the tuyere level, depending on factors such as its strength and reactivity (see Section 4.1.2). Shattering and abrasion mechanisms dominate fines generation in the upper part (stack) of the furnace. These mechanisms are often related to coke cold strength, which is influenced by the physical properties of coke, such as porosity (Gupta and others, 2005a,b).

There are various standard tests for assessing the mechanical degradation (cold strength) of coke. The Micum test is a measure of the coke’s resistance to abrasion at ambient temperatures. A sized sample of coke is tumbled in a rotating drum for 100 revolutions in a set time. The percentage retained on a 40 mm mesh sieve is the $M_{40}$ index (mechanical strength) while that passing through a 10 mm mesh sieve provides the $M_{10}$ index (abrasion index). The equivalent Irsid test uses more severe conditions as the coke is tumbled for 500 revolutions in the drum. In a similar way, the proportion retained on a 40 mm sieve provides the $L_{40}$ index and that passing through a 10 mm sieve, the $L_{10}$. These indices (Micum and Irsid) are used principally in Europe (AS 1038.13, BS 1016-108.2, ISO 556). A variation on these tests is the JIS K 2151 Drum Index (DF\textsubscript{30,15} (mechanical strength))
and DI15015 (hardness), used mainly in Japan and Australia (AS 1038.13), and the ASTM D3402 tumbler test (stability factor (percentage of +25 mm) and hardness factor (percentage of +6.3 mm)) utilised in the USA and Canada.

Permeability problems in the upper part of the furnace can be avoided by using cokes with high cold strength (I40, M40, and DI3015) values. Coke raking at tuyeres showed that higher I40 indices result in coarser bosh coke, which is beneficial for gas permeability. It decreases preferential flow of liquid hot metal along the walls, and therefore prevents hearth wear (Großpietsch and others, 2000; Janhsen and others, 2002).

Typical values for coke quality used at various BFs with high PCI rates are given in Table 4. In terms of mechanical strength, coke should generally have an I40 index of over 49% or DI3015 index over 92%.

Between the stockline and the tuyeres, abrasion resistance, I10, plays an important role (Großpietsch and others, 2000). Experiments have shown that abrasion of coke (indicated by I10) increases as it is heated, especially between 1500 and 1700°C. This is due to graphitisation which weakens the coke (Janhsen and others, 2002; van der Velden and others, 2003). Typical values for coke quality used at various BFs with high PCI rates are given in Table 4. In terms of mechanical strength, coke should generally have an I40 index of over 49% or DI3015 index over 92%.

Relationships established by Janhsen and others (2002) between feed coke properties and BF permeability showed that the best correlation was with the I10 coke cold strength, rather than the Micum indices. This is probably because the I40 test is determined under more severe conditions than the Micum test. They also found that the cold and hot strengths of coke are insufficient for describing the required coke properties. The use of coke with high I40 and high CSR (see Section 4.1.2) values can lead to a disaster in the BF. This occurred at ThyssenKrupp Stahl with a Chinese coke that had been produced in a beehive oven at long coking times. Tests showed that this coke was strongly unreactive.

### 4.1.2 Hot strength and reactivity

Coal injection brings about changes in the mechanism of coke degradation, especially in the lower regions of the furnace. Larger quantities of coke fines can accumulate at the tuyere level with increasing PCI rates. As PCI rate increases and the residence time of the coke is prolonged, the reaction of coke carbon with CO2 (the Boudouard or solution loss reaction) increases. This reaction promotes coke degradation and the production of coke fines (Chen and others, 2003; Gupta and others, 2005a,b; Janhsen and others, 2002; Kasai and others, 2000). In addition, coke circulates for longer within the raceway where it can react with the molten coal ash (Khairil and others, 2001a; Naruse and others, 2000) and with the hydrogen/steam originating from pulverised coal combustion (Kasai and others, 2000). Moreover, the blast energy is generally increased to raise productivity when the PCI rate goes up. This can lead to further degradation of the coke within the raceway by mechanical impact and abrasion (Choi and others, 2004; Pandey and others, 1999). Inferior coke can result in distorted raceway and cohesive zones, and accumulation of coke fines in the deadman giving permeability problems. Consequently, the strength and
stability of the coke structure after its reaction with CO$_2$ at high temperature is an important parameter.

Two indices are used to provide an indication of the potential behaviour of a coke at high temperatures, namely the Coke Reactivity Index (CRI) and Coke Strength after Reaction (CSR). The CRI and CSR tests are described in the standard ASTM D5341, which is derived from the test developed in Japan by Nippon Steel. The CRI is the percentage loss in weight of a coke sample after two hours of reaction with CO$_2$ gas at a temperature of 1100°C. The CSR is determined using the cooled sample from the test and tumbling it in a rotating drum. The product is then sieved, and the amount of material retained on a 9.5 mm mesh sieve is used as a basis for the assessment. Both CRI and CSR are expressed as percentages. A similar test for determining CRI and CSR is specified in the AS 1038.13, JIS K 2151 and ISO 18894 standards.

A higher CRI value means a more reactive coke, and a higher CSR value a stronger coke. Thus the CRI index needs to be as low as possible to shift the solution loss reaction to higher temperatures. Higher CSR indices are preferred for the coke to withstand the thermal, chemical and mechanical attacks during its descent. In this way, the required permeability in the deadman can be ensured (Beppler and others, 2000; Fukada and others, 1998). Experience in America, for example, found that increased coke stability led to a lower hot metal silicon content and variability, fewer burnt tuyeres and an increased casting time. Higher coke CSR values resulted in longer slagging times, increased bosh permeability and a reduction in the hearth sidewall temperatures (O’Donnell and Poveromo, 2000). CSR and CRI have a reasonably strong correlation in that a high CSR is usually associated with a low CRI (Arendt and others, 2000).

BF operation at BaoSteel, with a PCI rate of over 200 kg/thm, showed that the hot properties of coke have a larger effect than its cold strength on furnace permeability (Chen and others, 2003). More emphasis should therefore be put on maintaining high coke CSR and controlling the blast energy. With better coke CSR indices, coal injection rates can be increased whilst lowering the total reductant (coal plus coke) rate (see Figure 8). Bosh gas permeability also improves. A higher CSR index increases the raceway length, an important prerequisite for good BF performance at high PCI rates (Janhsen and others, 2002). It was found at ThyssenKrupp Stahl’s Schwelgern 1BF that the higher the CSR index, the higher the amount of nut coke that could be used instead of lump coke (Großpietsch and others, 2000). However, the amount of coke fines in the dust emitted in the top gas increases with increasing CSR. The coke with the least degree of graphitisation at temperatures over 1400°C produced the lowest amount of fines in the top gas (Gupta and others, 2005a,b).

In general, CRI values below 29% and CSR above about 60% are preferred for high PCI rates (see Table 4). The optimal values are strongly dependent on individual BF operating practice. However, the CSR/CRI test does not simulate the actual stress on coke within the BF. Measurements of the CSR of coke before it is fed into the furnace and when sampled at the tuyere showed that the hot strength of the tuyere coke (CSR 5–20%) was much lower than that of the feed coke (CSR 52–68%). Impregnating the coke with alkalis and longer CO$_2$ treatment at 1100°C than is specified in the standard procedure decreased the coke CSR to the same range as that measured on the tuyere coke (Janhsen and others, 2002). The CSR test does not reflect the influence of coke graphitisation or the impact of mineral transformations at high temperatures, which can affect coke degradation (Gupta and others, 2006; Sahajwalla and Gupta, 2005). Therefore a coke test at temperatures higher than 1100°C is required to cover coke properties in the high temperature region of the furnace. A number of high temperature coke tests have been developed, but none have yet been standardised. In addition, the reproducibility of CRI and CSR values among different laboratories have been found to vary widely (Arendt and others, 2001).

4.1.3 Chemical composition

The requirements for the chemical composition of coke for
some European BFs are given in Table 5. A high coke ash content means additional flux and higher slag volumes to be removed, and hence increased energy consumption and lower furnace productivity. A 1% increase in coke ash raises the slag rate by 10–12 kg/thm, and the energy demand for every 10 kg/thm of slag is about 63 MJ/thm (Kumar and Mukherjee, 2004). Ash contents are normally restricted to below 11%.

The ash composition of coke influences its behaviour. Alkalis (and other basic oxides such as iron oxides) increase the coke’s reactivity towards CO2 due to their catalytic effect, and lowers its abrasion resistance. Thus the coke is more susceptible to degradation. In addition, higher alkali contents hamper coke dissolution in the iron melts. Alkali metal vapour (originating from coke and coal combustion, and from the sinter) circulates in the furnace and can be picked up by the coke with detrimental effects. The coke alkali content increases as it descends towards the lower parts of the furnace (Gupta and others, 2005a,b; Hilding and others, 2005; Sahajwalla and others, 2004a). Contact of coke with alkali containing slags also increases its alkali content (Janhsen and others, 2002). High PCI rates prolong the residence time of coke in the furnace, resulting in a longer alkali attack on the coke and iron burden. For these reasons, coke alkali metal content is typically limited to less than 0.3%.

Sulphur content is restricted to below 0.75% in European BFs since, like the injected coal (see Section 8.2), it contributes to the hot metal sulphur content. Unfortunately, it is difficult to remove both sulphur and alkalis from the furnace at the same time. Sulphur is picked up in a basic slag, whilst the alkalis can only be removed by an acid slag.

Phosphorus tends to stay in the hot metal and so tight limits are set on its content. Chlorine, if present, leaves the furnace in the offgases, and is collected in the scrubber water. Like PCI coal, the chlorine content should be as low as possible to minimise corrosion. Evaporation of moisture consumes energy and so the coke moisture content is typically kept below 6%. Variation in moisture content, though, is a larger impediment to BF operation. The chemical composition of coke can be determined using standard methods.

### 4.1.4 Grain size

Coke size is another important issue for maintaining furnace permeability. USSteel, for example, found that permeability improved when charging larger sized coke (15% +50 mm) into the centre of the furnace (O’Donnell and Poveromo, 2000). However, too large a coke size can be detrimental. In Germany, the +80 mm coke sized fraction is limited to a maximum of 10% and the fraction over 100 mm to zero (Großpietsch and others, 2000).

Degradation of the coke occurs during its transport to the BF. Therefore undersize material has to be screened out before charging. In European BFs the amount of -40 mm is normally limited to 15 to 25% and the amount of -10 mm to 3% (Großpietsch and others, 2000). Sidmar currently limit the 25–40 mm fraction to 10% (Bonte and others, 2005). Thus the preferred coke sized fraction is 40 to 80 mm. This fraction should contain coke that is resistant to abrasion as evidenced at the Corus IJmuiden plant showed that changes in the I40 index (see Section 4.1.1) are directly proportional to the percentage of +40 mm of coke transported to the furnace (Großpietsch and others, 2000; Janhsen and others, 2002).

Nut coke with a grain size of about 10 to 35 mm commonly forms part of the coke feed. The more reactive nut coke is mixed with the iron burden and charged to the furnace periphery. The less reactive larger coke is usually charged to the centre of the furnace for stable operation. By appropriate distribution, gas can be directed more to the centre or to the walls. This will also help in controlling the heat losses and gas efficiency (which go down with PCI).

### 4.2 Iron ore quality

The iron ore feed consists mainly of iron oxides, either as haematite (Fe2O3) or magnetite (Fe3O4), in the form of lumps, pellets and/or sinter. Sintering or pelletising of the ore is necessary as the BF requires a lump feed so that the charge is permeable to the gases formed in the furnace. The majority of BFs operating at high PCI rates and with high productivity use a large proportion of prepared iron ore, over 80% pellets...
and/or sinter (Lacroix and others, 2000). Pellets are produced from iron-poor ores. Sinter is produced by heating iron ore fines, mixed with limestone and small coke, without melting to form bonded and coherent agglomerates. On-site sinter plants can incorporate recovered iron ore fines and iron-bearing steel plant wastes. Where there are no sinter plants the ore fines are briquetted for addition in limited amounts to the furnace.

BF operation and productivity can be improved by controlling the quality of the raw materials and the resultant iron burden mixture (ore/pellets/sinter). However, interactions between the iron burden components complicates selection of an optimum mixture. The principal iron burden properties of interest are:

- particle size distribution. For permeability reasons, a limit is placed on the amount of fines and coarse fraction allowed. The preferred size is typically in the range 5–50 mm for sinter and 8–16 mm for pellets. Reducing the lump ore size range from 6–60 mm to 8–45 mm helped Companhia Siderúrgica Nacional in Brazil to increase the PCI rate from around 150 kg/thm to 180 kg/thm (Bentes and others, 2000);
- degradation behaviour;
- reducibility;
- chemical composition, which influences both degradation and reducibility.

It is important that the quality of the burden material is consistent to ensure stable BF operation, and it is distributed into the BF in such a way as to achieve smooth operation with high productivity. For example, the pellets are radially distributed at Kobe 3BF to control the shape of the cohesive zone (Matsui and others, 2003b, 2005).

### 4.2.1 Degradation behaviour

Degradation of the iron burden materials strongly affects BF performance since it determines the efficiency of gas utilisation, and hence reductant rate and productivity. Fines generation can lead to permeability problems. The resistance (cold strength) of sinter, pellets and sized ore to degradation by impact and abrasion is determined by the tumble index (TI) and abrasion index, respectively, as specified in ISO 3271. Typical requirements from European experience are given in Table 6 and sinter properties used in Japanese BFs in Table 7. This latter table shows that the higher PCI rates at the plants were achieved using a higher sinter quality.

Pellets are also tested for their cold compression strength (ISO 4700). At Corus IJmuiden where a 47% sinter and 50% pellet feed was charged, the limit was a maximum of 5% with a cold compression strength under 60 kg/pellet (Lacroix and others, 2000).

Various laboratory tests have been developed to measure the degradation behaviour of the burden during reduction at low temperature. The reduction disintegration index (RDI) test for sinter (ISO 4696) is a static test, whereas the low temperature disintegration (LTD) test for pellets (ISO 13930) is a dynamic test, reducing the pellets at 500ºC while tumbling in a drum. There is also a static test for determining the physical properties of pellets and sinter.

### Table 6 Requirements for the physical and metallurgical properties of sinter and pellets (Mülheims and others, 2003)

<table>
<thead>
<tr>
<th>Material</th>
<th>Property</th>
<th>Standard</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sinter</td>
<td>Tumble index, TI</td>
<td>ISO 3271</td>
<td>&gt;6.3 mm</td>
</tr>
<tr>
<td></td>
<td>Grain size</td>
<td></td>
<td>&lt;5 or 6 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&lt;10 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&gt;50 mm</td>
</tr>
<tr>
<td></td>
<td>RDI</td>
<td>ISO 4696-1</td>
<td>&lt;3.15 mm</td>
</tr>
<tr>
<td></td>
<td>Reducibility, R40</td>
<td>ISO 4695</td>
<td>1.4–1.6%/minute</td>
</tr>
<tr>
<td>Pellets</td>
<td>Grain size</td>
<td></td>
<td>&gt;16 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>8–16 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&lt;6.3 mm</td>
</tr>
<tr>
<td></td>
<td>Tumble index, TI</td>
<td>ISO 3271</td>
<td>&gt;6.3 mm</td>
</tr>
<tr>
<td></td>
<td>Abrasion index</td>
<td>ISO 3271</td>
<td>&lt;0.5 mm</td>
</tr>
<tr>
<td></td>
<td>LTD</td>
<td>ISO 13930 (dynamic)</td>
<td>&gt;6.3 mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&lt;0.5 mm</td>
</tr>
<tr>
<td></td>
<td>Reducibility, R40</td>
<td>ISO 4695</td>
<td>1.4–1.6%/minute</td>
</tr>
<tr>
<td></td>
<td>Swelling</td>
<td>ISO 4698</td>
<td>maximum 15%</td>
</tr>
</tbody>
</table>
stability of pellets and sized ores reduced at high temperatures (1050°C) under load (ISO 7992).

The residence time of the burden materials increases with high levels of PCI (see Section 4.1). Consequently, a higher degree of degradation is to be expected due to longer exposure to high temperatures and an increase in alkali attack. Consequently, sinter and pellets (and sized ore) with a high cold strength and low RDI or LTD are preferred (see Tables 6 and 7).

Sinter disintegration is influenced by its chemical composition. Generally, disintegration improves with increasing SiO2 content and basicity (CaO/SiO2), and decreasing Al2O3 (Kawakami and Yamaguchi, 2000; Ritz and others, 2004). A 10% drop in sinter alumina (from 3.1 to 2.1%) can improve its RDI by 12 points (Chatterjee, 1999). PCI rates of over 200 kg/thm were achieved by Baosteel when processing a low silica sinter with a RDI of less than 2.1%). can improve its RDI by 12 points (Chatterjee, 1999).

Developments in the sintering process have allowed a decrease in the silica content whilst maintaining the sinter’s mechanical strength. For example, SiO2 was reduced from 4.38 to 3.8%, whilst keeping the TI at 63.5%, by proportioning 3% burnt lime and 1.3% serpentine (a SiO2-Al2O3-MgO flux) in the sinter mix (Zhu and others, 2003). A PCI rate of 266 kg/thm was achieved at the Fukuyma 3BF when processing a low SiO2 sinter with a RDI of less than 36% (Zhu and Guo, 2000). Posco improved the sinter RDI at the Gwangyang BF’s by spraying a calcium chloride solution onto the sinter on the conveyer belt. By covering the sinter surface, the reduction of Fe2O3 to Fe3O4 in the temperature range 550–600°C was prevented. The calcium chloride also decreased the temperature gap between softening and melting by 10–15°C (Choi and others, 2004). Unfortunately, improving sinter disintegration behaviour may adversely affect its reducibility.

### 4.2.2 Reducibility

Iron ore with a high reducibility is preferred. There are various standard methods for determining iron ore reducibility. In ISO 4695, the test sample (iron ore, sinter or pellets) in the size range 10 to 12.5 mm is reduced at 950°C under CO and N2, and the degree of reduction after time t, in minutes, is determined. The reducibility index is then calculated from the derived reduction curve and is expressed as a reduction rate (dR/dt) in per cent per minute. ISO 7215 determines the relative reducibility (Rr, expressed as a %) of iron ore, sinter or pellets reduced at 900°C under CO for 3 h. Tables 6 and 7 list typical reducibility values for sinter and pellets. According to Kawakami and Yamaguchi (2000), sinter with JIS-RI ≥70% and JIS-RDI ≥38% is required for PCI rates over 200 kg/thm (high sinter operation); these values are determined by the equivalent Japanese standard (JIS) methods. Ritz and others (2004) provide a critical review of the ISO standards for determining the reducibility and degradation properties of the burden materials at high PCI rates.

The initial softening and melting of burden materials (lump, sinter and pellets) should occur at high temperatures for more favourable reduction conditions and within a small temperature range in order to maintain a narrow cohesive zone. The gangue composition of sinter and pellets is important in determining its melting and dripping qualities (Matsui and others, 2003b; Mülheims and others, 2002, 2003). Many BF operators have developed their own in-hose test for assessing iron ore materials in more depth. These include, for example, Corus’s Advanced Softening and Melting test and the IJmuiden Swell and Softening test. It is unfortunate that improving reducibility can increase the degradation and disintegration of the iron ore materials. Lower SiO2 and CaO contents, and higher alkali contents increase reducibility but also increase disintegration (Ritz and others, 2004).

Developments in the sintering process have allowed a decrease in the silica content whilst maintaining the sinter’s mechanical strength. For example, SiO2 was reduced from 4.38 to 3.8%, whilst keeping the TI at 63.5%, by proportioning 3% burnt lime and 1.3% serpentine (a SiO2-Al2O3-MgO flux) in the sinter mix (Zhu and others, 2003). A PCI rate of 266 kg/thm was achieved at the Fukuyma 3BF when processing a low SiO2 sinter with a high RI. The sinter was produced in the Hybrid Pelletised Sinter process (Okochi and others, 2000). Lowering the amount of gangue (SiO2 and Al2O3) decreases the slag volume which helps improve permeability in the lower part of the furnace (Kawakami and Yamaguchi, 2000). A lower Al2O3 content also leads to a higher RI.

The use of high quality sinter and coke has enabled Posco and Baosteel to maximise the amount of coal injected, whilst maintaining high furnace productivity. The sinter RI at

### Table 7 Sinter properties at high PCI rates (Kawakami and Yamaguchi, 2000)

<table>
<thead>
<tr>
<th>Blast furnace</th>
<th>Month</th>
<th>PCI rate, kg/thm</th>
<th>Slag volume, kg/thm</th>
<th>JIS-RDI, %</th>
<th>JIS-RI, %</th>
<th>SiO2, %</th>
<th>Al2O3, %</th>
<th>TiO2, %</th>
<th>Tumble index, %</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kimitsu 3BF</td>
<td>Sep 1993</td>
<td>118</td>
<td>295</td>
<td>32.6</td>
<td>66.2</td>
<td>5.14</td>
<td>1.89</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>Nov 1993</td>
<td>203</td>
<td>278</td>
<td>31.2</td>
<td>69.1</td>
<td>5.17</td>
<td>1.61</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Koke 3BF</td>
<td>Jan 1990</td>
<td>104</td>
<td>283</td>
<td>43.8</td>
<td>70.4</td>
<td>4.69</td>
<td>1.74</td>
<td>69.6</td>
<td>70.4</td>
<td>Pellet ratio=36%</td>
</tr>
<tr>
<td></td>
<td>Jan 1996</td>
<td>204</td>
<td>279</td>
<td>38.3</td>
<td>69.6</td>
<td>4.91</td>
<td>1.71</td>
<td>68.9</td>
<td>69.8</td>
<td>Pellet ratio=33%</td>
</tr>
<tr>
<td>Kakogawa 1BF</td>
<td>Jun 1993</td>
<td>134</td>
<td>276</td>
<td>22.5</td>
<td>65.9</td>
<td>5.60</td>
<td>1.88</td>
<td>68.9</td>
<td>66.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Jun 1994</td>
<td>204</td>
<td>283</td>
<td>27.1</td>
<td>67.2</td>
<td>5.60</td>
<td>1.86</td>
<td>67.8</td>
<td>65.1</td>
<td></td>
</tr>
<tr>
<td>Fukuyma 4BF</td>
<td>Aug 1994</td>
<td>112</td>
<td>322</td>
<td>44.3</td>
<td>69.4</td>
<td>5.10</td>
<td>1.80</td>
<td>67.8</td>
<td>65.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Oct 1994</td>
<td>218</td>
<td>274</td>
<td>40.0</td>
<td>70.7</td>
<td>4.70</td>
<td>1.71</td>
<td>66.5</td>
<td>65.8</td>
<td></td>
</tr>
<tr>
<td>Kokura 2BF</td>
<td>Mar 1995</td>
<td>132</td>
<td>312</td>
<td>37.2</td>
<td>67.3</td>
<td>4.77</td>
<td>1.99</td>
<td>77.8</td>
<td>79.1</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mar 1996</td>
<td>171</td>
<td>320</td>
<td>38.1</td>
<td>70.1</td>
<td>4.69</td>
<td>1.94</td>
<td>77.8</td>
<td>79.1</td>
<td></td>
</tr>
</tbody>
</table>
Posco’s Gwangyang BF s was improved by increasing the limonite (hydrous ferric oxide) content (it has a porous microstructure), and reducing the slag volume (lowering SiO₂, Al₂O₃ and MgO in sinter) and FeO content. Increasing limonite by 10% increased RI by about 3.5%. Additionally, decreasing slag volume and FeO content by 1% increased RI by 1.8% and 2.1%, respectively. With the iron ore used, the alumina content in the slag could not be decreased below 15% for operational reasons. Therefore to obtain a better slag fluidity, the slag MgO content was reduced to below 5% (Choi and others, 2004).

High PCI rates, with high productivity, are characterised by the use of good quality sinter, pellets and coke. The challenge now is to achieve this whilst using cheaper, lower quality raw materials.
5 Coal preparation and injection

The main elements of a PCI system are:
- a mill to pulverise and transport the coal to storage bins;
- a distribution system which meters and transports the coal from the storage bins to the injection lances;
- injection of the coal through lances into the tuyeres and raceway.

This chapter will discuss each of these three elements in turn.

5.1 Pulverisers

Pulverised coal (PC) is produced in single or multiple grinding plants depending on the requirements of the steelworks and the capacity of the mills. The majority of PCI facilities serve more than one blast furnace. The coal preparation system represents about two thirds of the capital costs of a coal injection system. Coal reclaimed from stock is screened to remove foreign materials such as wood and rocks, and any large lumps of coal are crushed. The coal is then fed into the mill where it is pulverised and dried. Coal of the required size is transported out of the mill by the hot gas stream, collected in a bag filter and conveyed to the storage bins. Grinding and transport are carried out under an inert atmosphere to minimise the risk of ignition of the dry coal particles. The performance and safety of pulverisers are discussed in the Clean Coal Centre report by Scott (1995).

5.1.1 Drying

Drying of coal in the pulveriser is necessary as moisture contributes to problems of free flow through the pneumatic handling systems and in the storage bins (see Section 5.2.4). Furthermore, moisture should be minimised as additional energy will be needed for its removal in the BF. Evaporation of the coal surface moisture avoids agglomeration problems within the pulveriser; coals with high moisture and clay contents are particularly prone to sticking. Coal moisture also affects both the energy consumption and output of the pulveriser. High moisture coals require a higher inlet gas temperature and/or a higher gas flow. These requirements can reduce the mill capacity or cause mill fires, especially as these coals are more prone to spontaneous combustion. Typically, coals with a total moisture content of less than 10% (as sampled) are specified, contingent on the mill design.

The drying and transport gas is heated in a hot gas generator to around 300–400°C before entering the pulveriser. BF offgas, coke oven gas and/or hot stove waste gas can be used to lower fuel costs. A portion of the exhaust gases from the pulveriser is recycled back to ensure that the oxygen content is kept below 10–12% to minimise the risk of fire and explosion. The maximum mill inlet temperature is around 300–350°C, and the outlet temperature is around 100°C, depending on the coal and mill design. A margin of at least 30°C between the dew point and mill outlet temperature is required to avoid condensation and ensure trouble-free filtering of the PC/gas mixture (Salewski, 1996).

Waste gas from the BF hot stoves is utilised at Stelco Inc’s Hilton Works in Hamilton, Canada. A single pulveriser feeds the two blast furnaces (4BF and 5BF). The pulveriser has a (dry) capacity of 64.4 t/h with a design particle size output of 80% <74 µm. A flowsheet of the PCI system is shown in Figure 9. A large blower located after the baghouse draws the hot stove gas from 5BF’s stove gas waste stack. Gas enters the pulveriser at a maximum temperature of 300°C. The dried and pulverised coal is separated from the moisture laden waste gas in a double compartment baghouse. The coal leaves the bottom of the baghouse via screw conveyors and passes through a vibrating screen before entering the storage bin. The spent waste gas is carried through the main blower and discharged through the waste gas stack. A recirculation line returns a portion of the gas to the pulveriser inlet for temperature control. The recirculation line contains gas coolers and a recirculation fan. The oxygen content of the drying and transport gas is measured at the inlet to the pulveriser and the outlet of the baghouse. If the oxygen content at the baghouse outlet reaches 12%, then nitrogen is automatically injected prior to the pulveriser. The CO content, which indicates coal combustion, is monitored in the PC bin (Hutchinson, 2001; Hyde and others, 1996).

The natural gas-fired hot gas generator supplements the hot stove gas. It can be used as the sole provider to pulverise up to 13.2 dry t/h when hot stove gas is unavailable. This allows injection to continue at 4BF when 5BF is shut down and on both furnaces at a reduced rate when 5BF is operating with only 2 of the 3 stoves.

5.1.2 Wear

It is important to ensure that the coal product is ground to the desired fineness with minimum wear on the pulveriser components and with minimum power consumption (see Section 5.1.3) in order to lower operating costs. The two major sources of wear in PCI facilities are:
- abrasion, where the hard particles in the coal cause wear of the mill grinding elements;
- erosion of the pipes and ducts caused by the particles carried in the gas streams impinging on the surface.

Wear of mill components during the grinding of coal is influenced by the coal properties, the design and operation of the pulveriser, and the metallurgical composition of the grinding elements. Pulveriser shutdowns and maintenance costs are affected by wear and so it is important to evaluate whether the chosen coal/blend will cause excessive mill wear. The most commonly used test is the Abrasion Index (AI), derived from the Yancey, Geer and Price (YGP) test. This gives a relative comparison of the abrasion properties of coals. Generally, coals with a high AI can be expected to result in high wear rates.
Mill manufacturers can usually provide correlations between the AI and the life of the grinding elements. However, the AI does not always correlate well with the actual wear rate in the pulveriser (Conroy and Trenaman, 1990; Spero, 1990). Coals with similar AI values can produce different wear rates, suggesting that pulveriser wear is influenced by factors not adequately explained by the AI. There are significant differences between the conditions of the YGP test and those in commercial mills. Limitations of the YGP test are covered in Carpenter (2002).

Coal properties influencing wear, and hence the AI, include the mineral matter content and composition, particle size distribution, moisture, and bulk density. The abrasive (hard) minerals in coal include quartz (SiO$_2$) and pyrite (FeS$_2$). Finer particles, less than 100 µm, cause less wear than coarser particles. If a coal has a high moisture content then wear may be accelerated by the combined effects of wear and corrosion.

Erosion of the pipes and ducts is mainly dependent on the size and shape distribution of the hard minerals in coal, the transport gas velocity and the impingement angle. The YGP test is even less representative of the impact wear that occurs in pipework. Other abrasion and erosion indices have been proposed, but are not yet widely accepted by the coal industry (Carpenter, 2002).

5.1.3 Power consumption and capacity

Mill power consumption and capacity depends on the mill design, mill settings, the required fineness, and the properties of the coal. The principal coal properties influencing mill power consumption and capacity are:

- hardness, determined by the HGI (see Section 3.11). Generally, the higher the HGI, the easier the coal is to grind, with consequent lower power consumption and higher throughput of the coal. A low HGI coal reduces mill capacity since the coal will be recirculated in the mill until it is pulverised to the required size. A pulveriser operating at 20 t/h on a typical bituminous coal (HGI 50) has a theoretical capacity of almost 30 t/h when grinding a softer (HGI 80–85) coal (Stainlay and Bennett, 2001). If the design capacity of the pulveriser is limiting the PCI rate, then it may be possible to increase injection rates by switching to a softer coal. Increasing the percentage of low volatile, high CV soft coal in the high volatile, hard coal blend allowed the Gijón steelworks to increase the pulveriser capacity, as well as lowering the blast pressure in the furnace and improving coal consumption (better coke RR) in the furnace (Garcia, 1999);
- moisture. Generally, a higher coal moisture leads to higher power consumption although, exceptionally, the...
grinding energy requirement may actually decrease with increasing moisture (Scott, 1995);

- maceral composition. The effect of maceral composition on grindability is difficult to interpret, partly because the relative grindabilities of vitrinite and inertinite reverse as the coal rank increases (Unsworth and others, 1991). In general, higher vitrinite coals tend to have lower grinding energy requirements than lower vitrinite coals (Carpenter, 1995). Vitrinite is more easily ground than inertinite and liptinite. The energy requirement when grinding some high vitrinite coals has been found to be significantly lower than that predicted from the HGI value (Carpenter, 2002). Bennett (2004) found that size distribution based on the petrographic analysis gave a better estimate than that obtained based on HGI alone.

In addition, the greater the coal size reduction required, the greater the power consumption. Reducing the coal fineness can increase mill capacity, and may be necessary when grinding difficult coals.

Mill manufacturers provide curves relating the pulveriser capacity with coal properties such as HGI and moisture content, and power consumption with HGI. However, HGI is not always a reliable indicator of mill capacity and power consumption since, as noted above, other coal properties may have a stronger influence than HGI alone. In addition, the HGI test does not simulate the actual grinding process taking place in a pulveriser (Carpenter, 2002).

### 5.1.4 Particle size

Most injection systems use coals ground to approximately 70–80 wt% below 75 µm. The grinding plant can be located away from the BF because of the relatively low pneumatic conveying costs. For grinding plants located near the BF, a granular coal injection (GCI) system may be preferred, where the coal is ground to a 2–3 mm top size, with a limit of 2% >2 mm and 20–30% <75 µm. The coarser grind has the advantage of lower grinding and drying costs, and in some cases enables greater output from smaller mills to be achieved. It was estimated that granular coal required 60% less energy to grind than pulverised coal production at the Burns Harbor works in Indiana, USA (Hill and others, 2004). A HV (37%) bituminous coal was used. The granular product may also be easier to handle. The finer grind, though, has a higher burnout in the raceway. PCI is favoured in Japan and Germany, for example, and GCI in British and some American steelworks. These days, though, many PCI operators have relaxed their grind size in order to maximise coal throughput (Poveromo, 2004).

Coal fineness can be varied in the pulveriser by a number of measures, including varying the coal feed rate, the classifier settings, the air flow rate or the roller pressure (vertical spindle mills) (Scott, 1995). Although mills can be tuned to suit a particular coal, this may be impracticable where a large number of coals are being used and so some of these may not achieve the required fineness.

Coals are commonly blended to optimise the relative strengths of the constituent coals and produce a lower cost product. However, blending different types of coal, such as low and high volatile coals, can lead to problems. Factors that need to be considered include:

- the grinding behaviour of the blend;
- combustion behaviour. The individual coals can combust at different temperatures and at different times, and burn out at varying rates (see Section 6.5.4).

Preferential grinding of the softer coal occurs when blends of two coals whose HGI differs by more than 20 are pulverised. Pulverisation of blends of ‘hard’ and ‘soft’ coals have shown that the poor characteristics of the constituent coals tend to dominate the blend, with the pulveriser performance more closely resembling that of the harder coal (Carpenter, 1995). The Port Kembla steelworks in Australia inject a blend of medium and high volatile coals, which are widely divergent in hardness. The blend did present some initial problems in the pulveriser, but these have been overcome, although the authors do not say how (Nightingale and others, 2003).

The combustion (and handling) behaviour of the blend should be considered when determining the appropriate fineness; blends containing coals that produce less reactive chars may require a finer particle size.

### 5.2 Injection systems

With high PCI rates the reliability of the injection system and the equal distribution of the coal through the tuyeres is important as any interruption can quickly lead to serious problems. The higher the rate of coal injection the more serious the consequences of an unplanned interruption to the injectant supply. The injection system pneumatically transports the PC from the storage bin through the injectant vessel, where it is pressurised up to or above the BF pressure, to the tuyere injection lances. The various injection systems available primarily differ in:

- arrangement of the injection vessels;
- conveying line (individual pipes or a common pipeline with a distributor).

A number of steel plants have reported blockages in the injection systems, and this is discussed at the end of this section. The required handling characteristics of the coal will vary because of differences in the design of the coal preparation and injection systems.

#### 5.2.1 Injection vessels arrangement

At least two injection vessels are required to provide a continuous coal flow to the BF. Basically, there are two different arrangements of these vessels:

- serial arrangement where two vessels are installed in series. The upper vessel periodically replenishes the lower one which is always kept under pressure and injects the coal continuously into the BF. Weighing systems on the two vessels allow the injection rate to be calculated (Nolde and Wagner, 1996). This arrangement is employed, for example, at the Hilton Works.

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IEA CLEAN COAL CENTRE
In the common pipeline system, the injection vessels feed Materials Handling, 2001). Use of PCI in blast furnaces the total coal flow remains almost constant. The fluidising closing while the other is simultaneously opening, ensuring fluidising and inerting the PC storage bins; or repressurised with nitrogen. This procedure is repeated alternately. An overlapping operation is required to maintain coal injection during the change over period. A weighing system indicates the vessel content and the actual injection rate. The Gijón Works in Spain uses this arrangement (Garcia, 1999).

All injection systems operate with nitrogen for safety reasons, and its consumption forms a major part of the injection system’s operating costs. Nitrogen is used:

- for fluidising and inerting the PC storage bins;
- for depressurising (venting) the injection vessels prior to refilling;
- as a carrier gas for transporting the coal to the tuyeres.

The resulting consumption of nitrogen depends primarily on the injection rate and on the working pressure of the injection vessel (Nolde and Wagner, 1996).

5.2.2 Conveying line

Coal from the injection vessels can be transported by:

- individual pipes to each tuyere;
- a common pipeline to a distributor.

The individual pipe system is usually used in the serial arrangement of injection vessels, for instance, at the Hilton Works in Canada. Individual pipes convey the coal into the tuyeres, typically with closed loop control of the flow rate in each individual pipe. The coal flow amount can be independently controlled and changed in each pipe. The RotoFeed® system for PCI or GCI, developed by Clyde Materials Handling Ltd, employs a rotating volumetric feeder at the outlet of the injection vessel, and valves to control the air supply, coal flow and vessel pressures. Coal can be injected volumetrically with an accuracy of ±2% or gravimetrically to ±0.5%. The length of each pipe is limited to 500 m, with back pressure of up to 3 MPa(g). Injection rates of over 200 kg/thm have been achieved (Clyde Materials Handling, 2001).

In the common pipeline system, the injection vessels feed into a single pipeline that conveys the coal to a distributor adjacent to the BF. The distributor then equally divides the coal into the individual pipes leading to each tuyere. The coal flow is typically closed loop controlled in the common pipeline. A metering and control valve is located between the injection vessel and conveying line. In the parallel vessel arrangement, the metering valve of the empty vessel is closing while the other is simultaneously opening, ensuring the total coal flow remains almost constant. The fluidising gas is also kept constant. A second control valve regulates the conveying gas allowing the coal to gas ratio to be optimised. The pressure in the injection vessels is kept higher than the resulting pressure in the injection line. The inherent self-regulating feature of this system helps prevent clogging of the conveying lines. The Gijón Works, for example, uses this system (Garcia, 1999). An advantage with the distributor system is that the distance between the coal preparation plant and BF can be longer than with the individual pipe system. One centrally located grinding, drying and injection system can serve several BFs in an integrated steel plant.

Two main pipes are employed at most of the German Küttner plants. They are fed by two independent parallel twin vessel injection systems. Each of the two distributors feeds alternating tuyeres in the BF (Schulte van Bentheim, 2004). By using a distributor-based system, fewer RotoFeed® units are required, giving a simpler system than the individual pipe system described above. However, this provides less accurate flow control to each tuyere (VAI, 2002). The distance between the injection vessels and the BF can be up to around 900 m.

Differences in the routing of the pipes to the tuyeres and the inevitable uneven splitting of the coal at the splitting points can result in an uneven feed to the tuyeres. Imbalances can also cause uneven wear on the pipes and distributor.

Heat exchangers can be installed on the conveying pipes to preheat the coal before it is injected. Combined with the use of oxy-coal lances, faster oxidation of the coal in the tuyere results, allowing PCI rates to be increased (see Section 6.5.3). In the test carried out on the Schwelgern 1BF in Germany, the pipe heat exchangers were installed on the conveying pipes just behind the individual flow control system (Langner, 2003).

5.2.3 Blockages

Depending on the ratio of coal to conveying gas, the PC is pneumatically transported from the injection vessel to the tuyeres in either:

- dilute phase; or
- dense phase.

In dilute phase systems, the transport gas loading is typically around 10 kg coal per kg conveying gas, and the transport gas speed is around 15–20 m/s. The transport gas is normally a mixture of nitrogen and air; compressed air is added to the pipeline below the injection vessel. In dense phase systems, the loading is around 40–80 kg coal/kg gas, and the transport gas speed is about 1–5 m/s. The carrier gas is usually nitrogen or a mixture of air and nitrogen (Nolde and Wagner, 1996; Schulte van Bentheim, 2004). The transport gas velocity must always be higher than the minimum transport velocity in order to prevent blockages. This minimum velocity depends on a number of parameters including the system pressure and pipe diameter.

The high transport speed and low transport gas loading of dilute phase systems can lead to wear in the pipes.
High moisture coals/blends can be problematic. At IJmuiden in the Netherlands, the HV coals are dried to below their and/or the presence of ultrafine particles. This has been attributed to the coal moisture content, clay minerals, and as the coal properties. Blockages of the transfer lines can also minimise the amount of cool, inert gas injected into the furnace along with the coal (Juniper, 2000). Higher injection rates can be achieved with dense phase systems.

A number of steel works have experienced coal handling problems with blockages occurring in the:  
- PC storage bins;  
- conveying pipelines;  
- injection lances where the coal enters the blowpipe.

These handling problems have been related, in some cases, to the properties of the coal, particularly, its moisture content and particle size distribution. Concern over potential blockages may limit the selection of coals in some PCI systems.

**Storage bins**

Operators have imposed strict moisture limits in the milled coals to avoid blockages in the storage bins and transfer lines. Condensers have been fitted to remove any excess moisture in the return gas (Stainlay and Bennett, 2001). External heaters and/or insulation may be required to reduce the likelihood of bin blockages in colder climates where there may be condensation on the inside of the bin walls. This is especially important when the hot gas from the pulveriser enters the bin (Bennett, 2000). At the Hilton Works in Canada, nitrogen is blown through aeration pads in the bottom of the intermediate injection tank (see Figure 9 on page 29) to ensure free flowing when the PC is transferred to the lower injection tank (Hyde and others, 1996).

A finer particle size distribution can also lead to handling problems. Adjustments to the pulveriser settings can alleviate this problem. In bulk storage bins, the Hausner Ratio, the ratio between the compacted and uncompacted bulk density, is used to indicate possible onset of bridging in bins. This ratio increases when the amount of <5.8 µm material increases above around 12% (Bennett, 2000).

**Conveying pipelines**

Good flowability without clogging in the conveying pipeline is determined by a number of factors including operating system pressure, pipe diameter, and coal/gas loading, as well as the coal properties. Blockages of the transfer lines have been attributed to the coal moisture content, clay minerals and/or the presence of ultrafine particles.

High moisture coals/blends can be problematic. At IJmuiden in the Netherlands, the HV coals are dried to below their equilibrium moisture content to avoid dangerous deposits in the pipelines. Scaling has occurred in the injection lines, causing pressure build-up and tiny holes in the pipes. The remedy was cleaning the lines with steel grit (Toxopeus and others, 2000). The presence of clays, which swell in the presence of water, may cause problems if there is a pressure drop in the transport system (Marlière and others, 2005).

As the fines content (<5.8 µm) of the PC increases, the pressure drop in the conveying system increases. If the pressure drop goes above a certain value, which is related to the design of the plant, then blockages may occur (Juniper, 2000). Plugging of the pipelines have been reported with LV coals (Hill and others, 2004; Stainlay and Bennett, 2001). The build-up of these deposits at bends in the pipes have been related to the soft nature of the coal (finer particle size distribution). Investigations at the Hilton Works, injecting HV coals, showed that ultrafine coal (<10 µm) initiated the process by sticking to the elbow wall, and that once a rough surface formed, larger particles began to adhere. The gradual build-up caused line restrictions resulting in unusually high injection vessel pressure requirements to maintain injection rates, and uneven distribution of the coal. Perforations of elbows resulted due to increased velocities at the restrictions (Hutchinson, 2001; Hyde and others, 1996). Blockages can be alleviated by using a coarser particle size, and by improvements in pipe layout and distribution systems (Stainlay and Bennett, 2001). At the Hilton Works, the pulveriser was adjusted to produce a coal grain size of about 65% <74 µm instead of 80% <74 µm, resulting in a reduction in the amount of <10 µm particles generated.

Injection systems have purge ports on the transfer lines for clearing blockages, typically with high pressure air. Systems for detecting blockages are included. The differential pressure between the injection tank and each respective transport line is monitored to detect line plugging at the Hilton Works (Hutchinson, 2001).

A simple and practical test is needed to assess the flowability and handleability of pulverised coals and their blends. This would enable problematic coals to be identified before they are utilised. The flowability characteristics of a PC can be determined (Juniper, 2000; Kruse and others, 2003) by measuring the:

- cohesive strength of the PC at different consolidating pressures;
- permeability of the powder in, for example, a Jenike permeability;
- fluidising pressure gradient when fluidising the PC in a vertical column.

If the cohesive strength is low and the permeability high, then the coal should be free flowing. Permeability results are used to calculate the critical steady state discharge rates from bins.

Marlière and others (2005) used a range of flow testing equipment, including the Johanson indicizer system, Edinburgh cohesion tester and Freeman powder rheometer, to evaluate the handleability and flowability of various pulverised coals and their blends. They found that the Flow Rate Index (determined in the Johanson indicizer) and drying curves together indicated which coal would give flowability and caking problems. A pilot plant was also used to evaluate the pulverised coals. The conveying status diagram created could be utilised to identify the overall coal properties or behaviour which are likely to cause flow and handleability problems.
Injection lances and tuyeres

At the Gijón Works in Spain, a high moisture (9.08%) coal clogged the injection lances. Switching to a lower moisture (7.26%) coal with a similar HGI (45), solved the problem (Garcia, 1999). Ash from coal can form deposits inside the tuyere, retarding coal injection and eventually blocking the tuyere. A tuyere blockage can cause the unburned coal to flow backwards, causing serious damage in the tuyere stocks and hot blast bustle main (Toxopeus and others, 2000).

Optical systems that detect a blocked tuyere and automatically cuts the coal off to it have been installed at IJmuiden plants (Toxopeus and others, 2000) and Hilton Works (Hutchinson, 2001), among others. Cooling air still flows to protect the injection lance while the coal is shut off. At Inland Steel, USA, coal backups in the tuyere are detected by measuring the differential pressure between each tuyere and the hot blast main pressure (Chaubal and others, 1996).

The design and position of the injection lance affects the pattern of and propensity for ash deposition in the tuyere and blowpipe. Positioning the injection lance closer to the tuyere, for example, can reduce the extent of ash impingement in the blowpipe (Bennett, 2000). Ash deposition can also be minimised by utilising coals with a high AFT (see Section 3.9). If the temperature of the hot blast is lower than the AFT, the ash will probably leave the blowpipe and tuyere as dust (Kruse and others, 2003). For all practical purposes, the AFT should be 50ºC higher than the hot blast temperature (Chatterjee, 1999).

Injection lances can plug if coals with a high fluidity cake near the tuyere tip. This problem can be overcome by avoiding coals with high caking indices. Caking properties are determined by the free swelling index (crucible swelling number). Inland Steel uses the coal’s caking properties and petrographic composition, in conjunction with its AFT and ash composition, to evaluate lance plugging propensity (Chaubal and others, 1996). Lance plugging can also be avoided by increasing the flow rate (Kruse and others, 2003), and by ensuring the temperature of the coal in the injection lance does not exceed 300°C by cooling the lance or shortening the length of the lance that protrudes into the blowpipe (Bennett, 2000).

5.3 Injection lances

The injection lance injects coal into the blowpipe which leads up to the tuyere (see Figure 10). The coal particles are immediately heated by the hot blast, ignite and burn. Factors that need to be considered in an injection lance system include:

- PC combustion efficiency which is influenced by lance design and placement;
- durability of the injection lance, as lances burn up over time. Ignition on the lance tip may lead to degradation and loss of the lance body. The life of a lance is an important operational consideration;
- deposition of ash from the PC in the tuyere (see Section 5.2.3). Ash deposition at the outlet of the lance may perturb cooling gas flows (coaxial lances), and possibly conveyed flows, resulting in inappropriate development of the combustion plume. Ash deposition on the inner surface of the tuyere is likely to have catastrophic consequences;
- abrasion and erosion of the tuyere which can also have catastrophic consequences.

Experience has shown that lance designs that improve PC combustion efficiency contribute significantly to the ability to achieve stable furnace operation at high PCI rates. As well as lance design, the combustion of the PC is strongly influenced by the high speed hot blast. For high PCI rates, gasification of the coal should start at the earliest moment (injection lance tip) and be completed within the tuyere (Langner, 2003; Schulte van Bentheim, 2004). The time available to achieve this short, about 10 ms for a coal particle. Increasing the intensity of combustion by increasing oxygen, raising the temperature or enhancing mixing within the tuyere/raceway can improve combustion (see Section 6.5). This not only increases the reaction rates but also enhances the volatile matter yield (Stainlay and Bennett, 2001). This section will look at two types of injection lances where high PCI rates have been achieved.

The employment of eccentric double lances (see Figure 11) was one of the factors contributing to the high PCI rate attained at the Fukuyama nos. 3 and 4BFs in Japan (3BF achieved 266 kg/thm in June 1998). Numerical modelling showed that combustion efficiency was more than 15% higher than with a single lance arrangement. This efficiency
increase was attributed to better mixing of the coal with oxygen in the hot blast, thereby reducing the amount of unburned char that is required to be consumed by the solution loss reaction (Ariyama, 2000b). The eccentric arrangement of the two lances achieved a more uniform distribution of PC over the blowpipe cross-section by preventing the two PC streams from colliding.

Oxy-coal lances inject cold oxygen directly into the flow of the PC particles, providing a zone rich in oxygen and thereby promoting contact between the coal particles and oxygen. This is achieved by using coaxial lances where coal is injected through the inner pipe and oxygen through the surrounding annulus. The oxygen can be swirled which provides local turbulent mixing of the coal and oxygen, further improving combustion. This has been employed by Posco in Korea (Nozdrachev and others, 1998). Other design variants have also been tested. Toxopeus and others (2002), for example, introduced a mixing chamber within the coaxial lance (see Figure 12). This reduced the amount of oxygen injection required to obtain coal ignition at the lance tip. A large mixing chamber and a high oxygen flow can cause part of the lance tip to melt. Therefore the size of the mixing chamber is restricted to the oxygen supply level applied. The addition of cooling air to the oxy-coal lance has been investigated in Japan (Ariyama, 2000b). Two coaxial lances per tuyere (double coaxial lances) are also employed to improve burnout and gasification at high PCI rates (Du and others, 2001; Schulte van Bentheim, 2004). The addition of cold oxygen at the blowpipe, however, does degrade the coke replacement ratio (Sert and Godijn, 2002).

Yeh and others (2002) discuss the results from an evaluation of the combustion efficiency of single lance, double lance and a single oxy-coal (coaxial) lance in a combustion test rig. The coal used had a VM content of 37.8% (db), 81% (daf) carbon and 6.2% (db) ash. The highest PC combustion efficiency was achieved with the double lance and the lowest with the single lance. The single coaxial lance, with and without swirl flow, had an intermediate combustion efficiency. It is suggested that although the higher oxygen content at the coaxial lance exit was helpful for volatile and char combustion, the lower temperature oxygen retarded devolatilisation.

Problems that occurred when PCI was first introduced, such as lance and tuyere blockages and melting of the lance tip, have largely been mitigated. For instance, using air-cooled coaxial lances has helped prevent clogging and erosion (Yeh and others, 2002), and can prolong the life of the tip (Ariyama, 2000b). The flow rate of the cooling air should be

![Figure 12 Coaxial lance with mixing chamber (Toxopeus and others, 2002)](image-url)
6 Coal combustion

Coal combustion within the raceway is an important parameter as it affects the amount of coal that can be injected. It produces, along with coke combustion, both heat and reducing gases for the ironmaking process. Poor coal combustion can result in operational problems, such as reduced permeability from unburnt char, and undesirable gas and temperature distributions. In general, the amount of unburnt char exiting the raceway increases with PCI rate. This chapter examines the combustion behaviour of coal within the tuyere and raceway. Factors influencing combustion, both coal properties and operational factors, and hence how combustion efficiency can be improved, are discussed. It has become apparent that furnaces can consume more injected coal than that combusted within the raceway – the coal char is consumed elsewhere in the furnace. The subsequent reactions of unburnt char outside the raceway, and the emission of soot will be covered in the following chapter.

6.1 Combustion process

Combustion of coal between the exit of the injection lance and the rear wall of the raceway (a physical distance of around 0.7–2 m) occurs at high temperatures (1400–2200ºC), elevated pressures (about 450 kPa) and very short residence times (10–40 ms). It is under these severe conditions that a high level of pulverised coal (PC) combustion needs to be achieved. The combustion process can be divided into the following steps, some of which are overlapping:

- heating. The injected coal particles are rapidly heated as they enter the oxygen-enriched hot air blast. The heating rate is determined by the operational conditions but is around 10^5–10^7 °C/s. The hot blast temperature is typically 1000–1200°C and the gas velocity is about 180–250 m/s;
- pyrolysis of the coal particles to produce non-condensable volatiles (gases), condensable volatiles (tars) and a carbonaceous char. It takes about 2–20 ms to complete coal devolatilisation (Hutny and others, 1991; Yeh and others, 2002);
- ignition and combustion of the volatiles to produce principally CO2 and H2O. This takes a few milliseconds (Wu, 2005);
- partial combustion of the residual char by oxygen. Char combustion contributes the majority of the heat released during combustion. It is a slower process than volatile combustion;
- gasification of the residual char by CO2 and H2O to produce CO and H2. This is the slowest reaction of all these processes, and will mainly take place outside the raceway.

The extent of combustion (combustion efficiency), and hence the amount of unburned material transported out of the raceway, depends on several factors, including:

- coal properties, such as particle size and volatile matter content;
- blast gas composition and temperature;
- lance position and design.

Before discussing these factors, the Raceway Adiabatic Flame Temperature (RAFT) is described.

6.2 RAFT

The flame temperature affects the slag and metal chemistry, evaporation and recirculation of the alkali elements present, and the flow of metal in the hearth. It is difficult to measure the flame temperature and so it is usually calculated from an energy balance of the raceway zone. The calculated value is known as the Raceway Adiabatic Flame Temperature (RAFT), or the Theoretical Flame Temperature (TFT) in China, Korea and Japan. RAFT/TFT calculations can vary from one company to another depending on the assumptions made, and so values may not be directly comparable. Some RAFT/TFT equations are unsuitable for calculating RAFTs/TFTs at high PCI rates, as greater heat compensations are required (Gustavsson and others, 2002; Zhang and Bi, 2003). The latter authors have proposed a new method for calculating the TFT that takes into account coal combustion efficiency in the raceway.

A minimum RAFT is required to supply heat for melting and heating the metal and slag, and for other reactions such as the reduction of silica to silicon. High RAFTs tend to increase the rate of reactions in the BF and hence the productivity. But too high a temperature can cause premature formation of CaO-FeO-SiO2 slag. Subsequently, the reduction of FeO increases the slag’s melting point and causes its solidification. The gas permeability of the burden is reduced resulting in improper gas flow and temperature distribution, as well as slow and irregular descent of materials. A high rate of (unwanted) alkali vaporisation also occurs (Hutny and others, 1991). Thus there is an optimum RAFT for each furnace depending on factors such as the burden composition and permeability, coke quality, and blowing rate; a typical value is around 2200°C. Injecting coal lowers the RAFT as it promotes endothermic reactions. Low and high volatile coals lower the flame temperature by 80–120°C and 150–220°C per 100 kg/thm, respectively (Babich and others, 2002). The RAFT also decreases with increasing PCI rate. Therefore changing the type of coal and/or amount of coal injected can alter the RAFT. Otherwise increasing the blast temperature and/or oxygen enrichment of the blast (see Sections 6.5.2 and 6.5.1, respectively) can compensate for the cooling effect of coal.

6.3 Pyrolysis and volatiles combustion

Coal devolatilisation begins within the tuyere. A rapid initial release of about 80–90% of the volatiles is followed by a slower release of the remaining 10–20%. The early release consists primarily of tar, aliphatics, CO2 and H2O, while the
Coal combustion

latter release includes predominantly CO and H$_2$. Methane is an intermediate species which overlaps both regimes (Wu, 2005). An experiment in a plasma arc heater found that the generated gas mainly consists of CH$_4$, CO and H$_2$ in the lower temperature zone, whilst the emission of H$_2$ increases in the higher temperature zone (Ariyama, 2000a). Tests under nitrogen in a wire mesh reactor showed that at a heating rate of 10$^3$ °C/s, volatile release was virtually complete by the time the temperature reached 1500°C (about 300 ms). The total VM yield only slightly increased when the heating rate was increased to 5x10$^3$ °C/s. This suggests that under raceway conditions, devolatilisation will be complete, provided this can be achieved within the limited residence time (Pipatmanomai and others, 2003). However, measurements at the Schwelgern 1BF, Germany, indicated that devolatilisation was still occurring in the shaft area (Bachhofen and others, 1998).

The generated gas rapidly burns with oxygen in the hot blast, raising the temperature of the gas and particles. This probably accelerates ignition and pyrolysis, and consequently increases combustion efficiency (Ariyama, 2000a). It is the combustion characteristics of coal that govern the gas composition and temperature distribution in the raceway rather than coke combustion since coal is preferentially combusted. Figure 13 shows how the gas composition varied within the raceway at the Kakogawa 1BF (Japan) with a PCI rate of 190 kg/thm. Most of the oxygen is consumed near the tuyere nose, whilst a CO$_2$-rich atmosphere is produced in the middle, and a CO-rich atmosphere at the end of the raceway. This indicates that PC combustion (oxidation) takes place within a short distance in the raceway (Kamijou and Shimizu, 2000). The Figure also indicates some of the reaction steps of the combustion process.

Combustion experiments under conditions simulating the BF environment have indicated that combustion efficiency generally increases with increasing coal VM (Ariyama, 2000a; Hutny and others, 1996; Kamijou and Shimizu, 2000; Mathieson and others, 2005; Zhang and Bi, 2003). Injecting PC into a coke bed in a test rig showed that a higher VM coal resulted in the combustion peak (that is, the point with the highest CO$_2$ concentration) moving towards the tip of the tuyere. Raising the PCI rate also increased oxygen consumption, and the combustion peak moved closer to the tuyere (Ariyama, 2000a; Kamijou and Shimizu, 2000). HV coals typically produce more reactive chars than LV coals, and hence a better burnout (see Section 6.4). However, this is not always the case. For example, a 36.5% VM coal had a much lower burnout than the other coals (VM 16–37%, db) when combusted in a pilot-scale test rig. This coal did not burn very intensively near the point of injection, but the burnout improved significantly by the end of the reactor (around 26% at an injection rate of 8.5 kg/h). Hutny and others (1996) suggest that this is because this subbituminous coal produces more CO$_2$ during the initial stages of devolatilisation, which delays combustion. Khairil and others (2001b) found that the evolution rate of VM was only dependent on the type of coal if the particle temperature was below 2000 K (1727°C).

The calorific value of the evolved volatiles generally decreases with increasing coal VM (decreasing rank). Compared to HV coals, low and mid volatile coals generate more char and a relatively smaller quantity of gas which has a relatively high calorific value. Consequently, gas combustion is more important for HV coals than char combustion (Toxopeus and others, 2002). Kamijou and Shimizu (2000) found there was little difference in the ultimate combustion efficiency of two coals with different VM contents (46 and 35%) but similar fixed carbon contents (49 and 55%, respectively). Since ignition and combustion of the VM is rapid, the ultimate combustion efficiency is governed by reactions of the fixed carbon (char) as the coal VM content decreases. The reaction efficiency of char, though, varies with its structure and ash (mineral) content and composition (see Section 6.4).

Measurements at operating furnaces have generally confirmed the above findings. Tests carried out in one tuyere of the Wakayama 5BF in Japan (PCI rate 200 kg/thm) showed that coals with high VM contents did have a better combustibility, at least in the vicinity of the tuyere nose (see Figure 14); about 70% ultimate combustibility was achieved. As the coal moved towards the rear wall of the raceway, the difference in combustibility between the coals

Figure 13 PC reactions in raceway (Kamijou and Shimizu, 2000)
Coal combustion

Figure 14 Effect of volatile matter on combustibility (Kamijou and Shimizu, 2000)

(VM 6 to 44%) tended to disappear (Kamijou and Shimizu, 2000). Measurements at the Schwelgern 1BF, Germany, with lower PCI rates of 130–190 kg/thm, detected no influence from the coal volatiles (VM 18–42%) on the overall extent of coal conversion (Bachhofen and others, 1998; British Steel and others, 2001). Utilising HV coals at high PCI rates may lead to soot formation (unburnt volatiles) in the raceway and consequent problems in the gas cleaning system (see Section 7.4).

VM release is influenced by the coal particle size. The granular coals tested by Hutny and others (1996) released lower amounts of VM than when pulverised. Char particles collected 65 cm from the injection point showed that the parent coal (27% VM) released 89% of its VM in PCI compared with 35% in GCI. Calculated pyrolysis yields indicated that nearly all the VM from the pulverised coals was released whereas it was incomplete from the granular coals. The coals were injected into a hot blast with an injection rate of 8.5 kg/h, and carried into a short residence reaction zone at 1700°C in a combustion rig (Atkinson and others, 2004). The presence of residual VM in the granular coals would have a significant influence on the subsequent CO₂ gasification reactivity of the chars (see Section 7.1). Mathieson and others (2005) found that combustion efficiency decreased with the coarser grind sizing. The decrease become more pronounced as coal VM content decreased (coals with 32.1, 26.9 and 20% VM db). The coals were injected into a test rig which tried to replicate the expanding coal plume development within the raceway. However, tests at the Burns Harbor plant in Indiana, USA, found that overall BF performance was basically unaffected by whether the HV (37% VM) bituminous coal was pulverised (74% <75 µm) or granular (25% <75 µm) (Bethlehem Steel, 1999; Hill and others, 2004).

The actual VM yield in a BF is higher than that determined in a standard proximate analysis test – typically 1.2 to 2 times higher (Badzioch and Hawsley, 1970; Bennett, 2000; Toxopeus and others, 2002). This is because the heating rate and final temperature are much higher in the BF than those used in the proximate analysis determination. The pressure in the BF, though, will decrease the volatile yield (Lee and others, 1991). The ratio between the actual and standard proximate volatile yield is usually termed the Q factor.

Investigating coal combustion in the tuyere and raceway of a BF is difficult because of the hostile conditions that prevail in these areas. Direct measurements in operating furnaces are costly and require sophisticated equipment. Plüm and others (2005) discuss various analytical techniques for monitoring the raceway. Some experimental techniques are possibly best considered as a means of comparing coals since they do not closely simulate BF conditions. Techniques, such as pilot-scale rigs, that simulate BF conditions more closely have a greater significance, but even these do not reproduce all the operating conditions. For example, due to costs, pilot-scale test rigs may not work at pressures close to the tuyere/bustle main pressures of operating blast furnaces (about 450 kPa). Devolatilisation of coal at elevated pressure generates less VM, especially tar (Niksa and others, 2003). Higher pressures in the raceway have been shown to increase the gasification rates of coals. All other factors remaining equal, a rise in raceway pressure from 50 kPa to 300 kPa increased the gasification rate of coal from 58% to 92% (Lüngen and Poos, 1996). Mathieson and others (2005) report that the test rig configuration has a significant effect on coal burnout. When the blast and combusting coal plume was expanded through the restriction of a tuyere into a combustion test section with a significantly larger diameter than the previous test rig, then higher coal burnouts and a reduced influence of coal VM were observed. The variety of test rigs and test procedures used may explain the sometimes contradictory results published in the literature.

6.4 Char reactivity and combustion

Char oxidation contributes the majority of the heat released during combustion. Unlike the combustion of volatiles, in which the volatiles diffuse towards the oxygen-rich atmosphere (resulting in a large reaction area), the oxygen for char oxidation must be transported to the relatively small particle surface. As a result, char oxidation is a slower process. As long as volatiles are being released, oxygen cannot contact the char surface due to the high stoichiometric requirements of the volatiles. In PC-fired power plants where heating rates are of the order 10⁴ to 10⁶ °C/s and temperatures are around 1500°C (but with no oxygen enrichment), char burnout times are typically 1 to 4 s.

The char particles pass through a series of gas zones reacting with oxygen in the combustion zone near the tuyere nose (high O₂ concentration) and with CO₂ in the gasification reaction zone (see Figure 13 on page 36). Char combustion (oxidation) can be divided into three different regimes depending on the steps limiting the reaction rate (see Figure 15). At temperatures below about 600°C, combustion of char is controlled by the rate of chemical reactions since there is time for the oxygen to diffuse into the pores of the char particle and react with the carbon there (Regime I). At temperatures between about 600–800°C, the
Coal combustion

Figure 15 Reaction zones of char oxidation
(Wu, 2005)

Char oxidation is controlled by both chemical reaction and the diffusion of oxygen into the pores of the char particle (Regime II). The char combustion rate is controlled by external diffusion of oxygen at temperatures above about 800°C (Regime III) because the chemical reactions are so fast that all the oxygen which is transported to the particle surface is consumed (Wu, 2005). At the high temperatures in the raceway, char combustion is mainly diffusion controlled, whereas reactions in the furnace stack will be more chemically controlled.

An investigation in a wire mesh reactor (WMR) under simulated raceway conditions showed that the extent of char combustion was limited by the amount of oxygen supplied, that is, was diffusion limited (Pipatmanomai and others, 2003). The chars were produced by heating the coal sample under nitrogen to 1500°C, and injecting short (5–220 ms) pulses of air (that are similar to the particle residence time in the raceway) through the sample holder. The extent of combustion was low for the two LV coals (13.2% and 17.4% VM db). The total pressure in the WMR was limited to 150 kPa, which is lower than the pressure in the raceway (typically around 450 kPa). To simulate the effect of total pressure, the oxygen concentration was raised to 75%, which has the effect of raising the mass flow of inlet oxygen to values that would be present at higher pressures. Again, the extent of char combustion was low and was limited by the oxygen supply rate. The extent of gasification that occurs under simulated raceway conditions was studied by switching to a CO2/N2 mixture after the air pulse. The rate of gasification was high at 1500°C, but a residence time of at least 10 s is needed to achieve a reasonable extent of char gasification. Consequently, a significant proportion of char will be carried out of the raceway.

The combustion efficiency (or burnout) of coal generally decreases with increasing injection rate. The reactivity of char can influence its burnout and subsequent gasification behaviour. Chars with a higher reactivity have a higher combustion efficiency. Selecting a coal that will produce a char with higher reactivity, and by optimising operating conditions, may improve combustion efficiency. However, at the high temperatures occurring in the raceway, chemical reactivity becomes less important since combustion rates are limited by the rate of oxygen diffusion to the particle, and burnout times depend more on particle size and oxygen concentration. Combined with the short residence time, the effect of char reactivity differences between coals may not be very significant in the raceway (Bennett, 2000). Lu and others (2002b) argue that in view of the small particle sizes used (more than 80% <75 µm) and the highly turbulent conditions that exist in the raceway, the overall rate of char combustion will be influenced by the intrinsic chemical reactivity of the char. Char reactivity is important outside the raceway. Under the conditions in the upper furnace, char gasification is likely to be controlled by the rate of chemical reaction (Regime I). Therefore, the overall char gasification reaction rate is likely to be influenced by the chemical reactivity of char to CO2 (see Section 7.1).

Char reactivity, and hence its burnout, is influenced by factors such as:

- its surface area/porosity;
- its mineral matter;
- its resultant structure;
- the operating conditions.

The chemical and physical properties of char are, of course, dependent on the parent coal properties.

The burning rate and reactivity of the char partly depends on the size of the particle and its pore structure. The pore structure controls the supply of reactive gases into the interior of the coal particle and provides a variable internal surface for reaction. The char surface area varies during combustion. Typically it increases rapidly during the initial stage of combustion due to the growth of pores in the char particles. It then decreases gradually due to coalescence of the pores (Lu and others, 2001; Wu, 2005). Fragmentation of char also increases its external surface area. Char fragmentation is influenced by its structure. A higher proportion of char particles with thin-walled cavities and higher macroporosity and macropore surface areas are produced at high heating rates. In general, these types of chars tend to fragment more than those with thicker walls and lower porosity (Wu, 2005), increasing the particle’s total external surface area, and hence the char reaction rate. The porous structure of chars is
Combustion efficiency generally increases with decreasing particle size since a higher surface area is available for reaction. Smaller particles have shorter devolatilisation times and therefore the longest times available for dispersion and mixing with the oxygen. Granular coals typically burn slower than the corresponding pulverised coals and consequently need a longer residence time for burnout (Hutny and others, 1996; MacPhee and others, 1997). Since complete combustion of coal in the raceway is not possible at high PCI rates, some operators are introducing practices which are counter-productive to good burnout, such as the use of coarser PC (Bennett, 2000; Poveromo, 2004). The unburnt char is consumed elsewhere in the furnace (see Chapter 7). Coarser coal can reduce milling costs (see Section 5.1.4) and improve handling behaviour (see Section 5.2.3).

In general, char reactivity increases with coal volatile content (Bennett, 2000; Du and others, 2001; Hutny and others, 1997; Zhang and Bi, 2003), although there are exceptions due to the morphology of the char produced. For example, Pipatmanomai and others (2003) found that the reactivity of the pyrolysis-derived char from the lower VM (13.2% db) coal was greater than that from the higher VM (17.4% db) coal. The two chars were produced in a WMR and their reactivities determined in a thermal gravimetric analyser (TGA) at 500ºC. This may reflect the higher extent of microporosity in the higher rank coal, together with differences in the chemical structure and composition. In addition, the lower rank coal was a blend of two low-mid volatile coals. The lower VM coal char also had the highest post-combustion reactivity (that is, after exposure to pulses of air in the WMR). The post-combustion reactivity of the chars were greater than those prepared under pyrolysis conditions alone, and their reactivity increased with increasing (20–220 ms) air pulse duration (longer residence time). This suggests that particles at the centre of the coal plume, experiencing only low O2-concentrations, are more likely to remain unchanged or become fragmented, thus contributing to the unburnt particles in the furnace.

Changes in a coal’s maceral composition may account for differences in combustion reactivity, particularly among coals of similar rank. The inertinite macerals have traditionally been considered to be ‘inert’ (unreactive) by the combustion industry. However it is not as simple as this. Not all the inertinite macerals are, in fact, unreactive, and not all the vitrinite ones are reactive. Vitrinite, inertinite, and even liptinite, can contribute to unburnt carbon in the carbonaceous residue (Carpenter, 1995). How important petrographic composition is in PCI is debatable since combustion occurs at very high temperatures (>2000ºC) and short residence times (under 50 ms). Kalkreuth and others (2005) found that although inertinite-rich subbituminous coal chars were intrinsically less reactive than the vitrinite-rich ones at 500ºC, this was no longer relevant at high temperatures (1300ºC). It is likely that differences in the combustibility of coals would be greatly reduced under the very intense combustion conditions in the raceway. This has been observed for coals fired in a pressurised entrained flow reactor (Stainlay, 2004).

The combustion performance of coals can be enhanced due to catalytic effects of coal minerals or retarded by the excessive mineral concentration in coal. Silica and alumina can slow down the reaction rate, whilst calcium, magnesium, iron and alkali species can enhance it, with the catalytic effects more pronounced in lower rank coals (Carpenter, 1995; Gupta and others, 2006; Sahajwalla and Gupta, 2005). However, the improved combustibility of mineral-rich particles has been attributed, not to catalytic effects, but to favourable diffusion of the reacting gas through the minerals and maceral-mineral interfaces (Méndez and others, 2003; Menéndez and others, 1994). The lack of a clear correlation between char reactivity and the individual inorganic phases may be related to differences in the influence of temperature on coal mineral transformation. Sahajwalla and Gupta (2005) found that the improvement of coal burnout with increasing temperature was influenced by the nature and extent of the mineral-mineral association which could lead to blockage of char pores by an increased proportion of slag phase in the char particles.

The chemical structure of char plays a role in determining char combustion reactivity. Hutny and co-workers (Hutny and others, 1996; MacPhee and others, 1997) report a linear relationship between char reactivity (wt% loss/min) and the atomic H/C ratio of the parent coal for 12 bituminous and subbituminous coals. The chars were produced in a pilot-scale tubular reactor fed with preheated air (900ºC), and their reactivity determined in a TGA at 1300ºC. Temperature also plays a role as char reactivity was higher at 1700ºC than that determined at 1300ºC. Coke competes with coal for oxygen in the raceway. While the reactivity of a PCI char was 20% higher than that of a tuyere coke at 1300ºC, this difference diminished to 10% at 1700ºC.

Lu and others (2001, 2002a,b) related the reactivity of char to its chemical (atomic) structure. A quantitative X-ray diffraction analysis (QXRDA) technique was employed to differentiate and quantify the different types of carbon structure present, namely carbon in the amorphous phase, carbon at aliphatic side chains and carbon within the aromatic structure (crystallite carbon, L002). They found that the char structure becomes more ordered during pyrolysis and combustion – the amorphous and aliphatic carbon are preferentially lost, whilst the average carbon crystallite size and aromaticity increase. This is shown in Figure 16 for a LV bituminous coal char. This structural ordering of the char was shown to be responsible for the loss of char intrinsic reactivity during combustion (char deactivation). A disorder index (DOI) was defined to quantitatively describe char structural evolution, based on the amorphous and crystallite carbon, and aromaticity. The intrinsic char reactivity for a LV (15% VM) bituminous coal linearly increased with DOI. It was also found that char structure is influenced by coal type and pyrolysis conditions. This QXRDA technique could be used to predict a coal’s char performance, and help optimise PCI process conditions. The evolution of char structure during combustion may also help in PCI combustion modelling.

The combustion efficiency of three industrial HV bituminous coals were tested in a drop tube furnace (DTF) at 1200ºC and
23% O₂, and dust/sludge samples were taken from operating BFs employing these coals. The combustion efficiency of the three coals were similar despite the differences in their VM contents and fuel ratios. This difference in combustion efficiency could be explained only on the basis of the char surface area. During combustion, the percentage of amorphous carbon (determined by XRD) decreases, that is, the amorphous carbon is selectively removed. The proportion of coal char in the BF dust/sludge samples was estimated from differences in the (XRD) crystalline order of carbon in char and coke. A direct correlation between combustion efficiency and the amount of coal char in the dust was not observed due to possible differences in char consumption behaviour within the BF (Sahajwalla and others, 2003). Nevertheless, by monitoring the carbon structure of the residual coal char in the emitted dust, the PCI process parameters, such as blast gas composition and temperature, could be optimised (Gupta and others, 2006; Sahajwalla and Gupta, 2005).

Certainly, a rapid technique for differentiating the various types of carbon present in the offgas dust could provide early warning of poor combustion in the raceway. A different approach was taken by Dong and others (2006). They used size exclusion chromatography to determine the mass distribution of NMP (1-methyl-2-pyrrolidinone) extracts from BF dusts. The high molecular weight NMP soluble materials were derived from the injected coal volatiles (soot and tar), and so could provide an indication of deteriorating combustion conditions in the raceway. Preliminary results suggest that Fourier transform-Raman spectroscopy, which responds to changes in the crystal structure, could distinguish between coal char and coke. However, fluorescence problems would need to be solved. This may mean some prior treatment of the dust to remove the iron-bearing materials.

The majority of bench-scale experiments investigating coal combustion have been carried out at atmospheric pressure. A literature review on PC combustion and gasification by Wall and others (2002) found that pressure influences volatile yield and coal swelling during devolatilisation (see also Section 6.4), and hence the structure and morphology of the char generated. More char particles of high porosity are formed at higher pressure. The effect of pressure on char reactivity is therefore mainly related to surface area development during devolatilisation. Differences in apparent char reactivities can be minimised by correcting for surface area (Kalkreuth and others, 2005). Atkinson and others (1997) found that the heating regime and maximum temperature attained had more influence than pressure on devolatilisation and gasification (oxidation) of the coal, especially at pressures typical of BF operation. The rapid devolatilisation and gasification of coal promoted the formation of highly anisotropic, network char cenospheres. Formed from highly plastic particles, these were found to have reduced reactivities at higher temperatures. This was thought to be due to a reduction in available surface area, by virtue of char morphology, and a reduction in active sites caused by structural ordering and removal by oxygen. The greatest influences on char yield were the blast temperature and oxygen content.

6.5 Operational factors

Measures to intensify coal combustion in the tuyere/raceway region, and hence increase PCI rates, include:
- increasing the amount of oxygen in the tuyeres;
- adjusting blast temperature and moisture;
- preheating the coal;
- use of coal blends;
- adding additives to improve coal combustion.

This section will discuss each of these factors, in turn.

6.5.1 Oxygen level

The addition of oxygen means more oxygen is available for participation in coal combustion in the raceway. Oxygen can be added to the tuyere by:
- enrichment of the hot air blast;
- oxy-coal lances;
- separate oxygen lances.

Oxygen enrichment of the hot air blast produces both a reduction in bosh gas flow and a rise in flame temperature. The former effect can help counteract the increase in burden...
resistance (lower permeability) and the pressure drop associated with high PCI rates. The latter effect can help compensate for the cooling effect of the decomposition of the coal volatiles. The CO and H2 contents also increase with oxygen enrichment, resulting in improved reduction in the central shaft (Stainlay, 2004). However, measurements at IJmuiden 6BF during the high PCI rate trial found that although the volume of H2 increased, the CO volume in the raceway remained constant (Sert and Godijn, 2002). The calorific value of the BF top gas usually improves with oxygen enrichment (Stainlay, 2004).

When Posco switched from a HV coal to a high fixed carbon (LV) coal at the Gwangyang furnaces in 2000, oxygen enrichment and the blast temperature were increased to compensate for the lower combustibility of the new coal (Choi and others, 2004). However, the influence of oxygen enrichment on combustion efficiency is limited. Zhang and Bi (2003) calculated that combustion efficiency would increase by only 6.71% for a HV coal and 3.31% for a LV coal when oxygen enrichment is raised from 0 to 6 vol%. With higher oxygen enrichment, combustion efficiency could actually decrease due to insufficient mixing (Pandey and Yadav, 1998). Increasing oxygen enrichment enhances the diffusion of oxygen, but diminishes the volume of combustion gas that transfers heat to the PC. Baosteel in China have achieved PCI rates of over 200 kg/thm with an oxygen enrichment of 1.5–2.5% compared with the more normal rates of over 3% in other countries. The flame temperature was about 2050°C. Smooth and stable BF operation at PCI rates of 165 kg/thm were obtained at 2BF without any oxygen enrichment (Zhu and Guo, 2000).

The lower limit of oxygen enrichment is usually determined by the amount needed to maintain the required RAFT, with more oxygen required as the volatile content of coal increases. The upper limit is dependent on maintaining a sufficient top gas temperature. As oxygen is increased, the gas mass flow within the furnace decreases, which decreases the heat flow to the upper region of the BF for drying the burden. The upper limit of the top gas temperature may also be governed by the need to protect the top gas equipment. Other limitations to oxygen enrichment include its cost and availability.

Oxygen enrichment and injection technology are inseparably linked together. Mixing of the coal and blast is critical in achieving a high degree of burnout. The position and design of the injection lance influence coal combustion efficiency and ash deposition in the tuyere. Rapid consumption of oxygen in the hot air blast by combustion of the volatile matter tends to form an oxygen-deficient atmosphere. If dispersion of the coal particles is relatively uniform, then the oxygen across the blowpipe is more efficiently utilised for combustion (Ariyama, 2000a,b). A more uniform flow has been achieved with the eccentric double lance arrangement (see Section 5.3). The high combustion efficiency at the Fukuyama 3 and 4BFs (PCI rate >200 kg/thm) was attributed to the better mixing of the coal and oxygen in the hot blast that was achieved with this arrangement (Ariyama, 2000b).

Preliminary mixing of PC with process oxygen before its introduction into the tuyere can intensify coal combustion in the raceway (Bennett and Fukushima, 2003). This can be achieved with oxy-coal lances, discussed in Section 5.3. Coaxial lances typically inject coal through an inner pipe and oxygen through the annulus surrounding it. This induces immediate ignition of the coal at the lance tip. The ignition temperature for coal in oxygen is 180–200°C, which is 400–600°C lower than at normal atmospheric conditions (Langner, 2003). However, Yeh and others (2002) report that double lances gave a higher combustion efficiency than a single coaxial lance (see Section 5.3). They suggest that although the higher oxygen content at the coaxial lance exit is helpful for volatile and char combustion, the oxygen’s lower temperature may retard devolutilisation.

Too high a concentration of volatiles in the coal plume can cause a local deficiency of oxygen, which retards the oxidation of the volatile matter. Oxy-coal lances have been designed that produce a swirl that breaks up the coal plume and reduces the volatile concentration which builds up in the axis of the coal jet. Such a swirl favours exposure of the carbon to oxygen and hence enhances the coal gasification rate (Lüngen and Poos, 1996).

Oxygen can be injected into the blowpipe/tuyere through a separate lance to provide good dispersion of coal in the blast at a high local oxygen concentration. The injection of hot oxygen was tested at the U.S. Gary Steel Works 6BF in 1999/2000. The ’thermal nozzle’ system produces a high temperature (1650°C), high momentum jet (which contains about 80 vol% O2) by combusting oxygen with a small quantity of natural gas in a combustion chamber at the end of the injection lance. Heat load on the blowpipe was essentially unchanged, but total heat load on the tuyere increased by about 10% and heat load on the tuyere tip by about 50%. Bosh temperatures remained within the usual operating range. Performance in these areas was considered to be acceptable. The hot oxygen increased coal combustion in the blowpipe and tuyere by about 30% (Riley, 2002).

Injection of hot reducing gases (HRG) into the tuyere, along with oxygen enrichment of the blast, has been proposed for increasing PCI rates and lowering coke consumption. The HRG can be produced, for instance, from BF top gas recycling (after CO2 removal) or coal gasification. It is claimed that using HRG allows a higher oxygen enrichment of the blast. Calculations using a mathematical model indicate that with 300 m3/thm HRG and an oxygen enrichment of 75%, the PCI rate rises to 250 kg/thm and coke consumption decreases to 208 kg/thm. With higher oxygen enrichment of 80–100%, PCI rates could be increased to 300–400 kg/thm (with a low ash coal) with a productivity increase of 140–150% (Babich and others, 2002). But oxygen is expensive and becoming more so. Injecting export gas (after CO2 removal) from a Corex® smelting reduction plant (if present) could reduce coke consumption by up to 20% (Böhm and Peer, 2002).

The use of oxygen enrichment and coal injection generally moves the point of the most intense temperatures and chemical reactions back closer to the tuyeres and therefore the bosh walls. Combined with increased bosh gas flow at the
walls, this means that enhanced bosh cooling and refractory quality are necessary at high PCI rates.

6.5.2 Blast temperature and moisture

Oxygen enrichment, increase in blast temperature and/or a decrease in the blast moisture can compensate for the cooling effect of PCI. At very high PCI rates, the key measure is a high blast temperature. Oxygen enrichment plays a more important role as a means of controlling gas flow in the furnace rather than controlling PC combustion (Kamijou and Shimizu, 2000; Zhang and Bi, 2003). Generally, a higher hot blast temperature compensates for RAFT at a lower cost than oxygen enrichment – a higher blast temperature allows a lower oxygen consumption. Increased blast temperatures also reduce coke consumption, typically 10 kg/thm for every increase of 40°C (Poveromo, 2004). Limitations in existing equipment may mean that blast temperatures cannot be improved. This may mean a costly rebuild of the hot blast stoves to ensure a maximum hot blast temperature consistent with the overall design of the hot blast system. Otherwise other means to raise the RAFT are required. Since the blast temperature is kept at a maximum and blast moisture at a minimum at China Steel’s 3BF in Taiwan, oxygen enrichment was the only effective method for raising the RAFT when PCI rates were increased. At a PCI rate of 160 kg/thm and oxygen enrichment of 4%, the RAFT was 2142°C (Yeh and others, 2002).

A higher blast temperature is generally required as the coal VM increases. Experiments have shown that raising the blast temperature increases the coal devolatilisation rate, but decreases coal gasification (Ariyama, 2000a; British Steel and others, 2001; Lüngen and Poos, 1996). The gasification decrease was more pronounced for the lower volatile coals, and was attributed to their lower char reactivities (see Section 6.4). Chars formed from higher rank coals at high temperatures are generally more ordered and hence less reactive (Lu and others, 2002b). The development of highly anisotropic char cenospheres with increasing temperature also decreases char reactivity. These coals will therefore benefit from a lower blast temperature in order to improve combustibility. The decrease in gasification could be retrieved by employing oxygen enrichment or increased excess air levels (greater plume dilution) (British Steel and others, 2001).

The temperature used is a compromise between efficiency and reliability. Operating temperatures can be reduced to increase efficiency, but the furnaces would require more sophisticated monitoring and control to avoid local cool areas (Sakurovs, 2004). The AFT of coal would become more important under low operating temperatures. The mineral matter in coal can cause a variation in the slag composition across the furnace hearth, with resultant variations in slagging properties. A high viscosity slag present around the tuyeres would lead to serious gas flow problems.

Lowering blast moisture can help to compensate for the cooling effects of PCI. If the RAFT becomes excessive, then blast moisture can be increased. Raising hot blast moisture means more hydrogen in the bosh gas for iron ore reduction. The optimum RAFT in furnaces operating with higher hydrogen contents can be lower than those operating with lower hydrogen contents (see Section 3.4).

In addition, the blast speed can be adjusted to not only improve coal combustion, but to maintain the required length of the raceway zone which is critical for obtaining good conditions in the hearth (Zhu and Guo, 2000).

6.5.3 Preheating coal

One strategy for obtaining better combustion, and hence higher PCI rates, is to preheat the coal before injection. Preheating (to below its ignition temperature) removes the surface moisture from the coal, generates more carbon monoxide and hydrogen, and accelerates coal oxidation in the tuyere (Langner, 2003).

Figure 17 shows the increase in the combustion rate achieved after preheating three coals to 250°C in a pilot-scale plant simulating a BF tuyere. The highest combustion rate increase (12.1%) was for Blend B. This blend also had the highest combustion rate, even though it did not have the highest VM content. This suggests that interactions between the component coals have enhanced its combustibility (see Section 6.5.4). The combustion rate of Blend A improved by only 8.8%, which was about the same as that for the single coal (9%). The PCI rate was maintained at 190 kg/thm, equivalent to an oxygen consumption of 245 m³/thm. Compania Siderurgia de Tubarao in Brazil has been injecting Blend A at a PCI rate of around 190 kg/thm at its 1BF. It has been estimated that with a three-coal mixture and preheating to 250°C, the PCI rate could be raised by about 20 kg/thm without causing problems (Assis and others, 2004).

The injection of preheated coal was tested at the Schwelgern 1BF in Germany as a way of decreasing the coke rate and...
increasing the PCI rate (Langner, 2003). PC, heated by pipe heat exchangers, was injected through oxy-coal (coaxial) lances in 20 of the 40 tuyeres. In a second stage, the preheated coal injected in 5 of these tuyeres underwent an intermediate degassing process and a second stage of preheating before injection. Preheating the coal changes the transport conditions because the carrier gas expands as it is heated and steam from vaporisation of the coal surface moisture is present. The higher volume of carrier gas and steam increases the transport velocity of the coal. The degassing system removes the excess carrier gas and steam. Overall, the results showed that the BF could be stably operated at coke rates of less than 280 kg/thm with preheated coal injection rates of 190 kg/thm. Even at low coke rates the productivity was high (3 thm/d m³). No plugging of the conveyance lines occurred, and the parameters of the pneumatic transport were similar to those for cold coal transport. The other 20 tuyeres have now been fitted with the preheated coal system (Langner, 2005).

With the degassing and superheating system installed at Schwelgern 1BF, the maximum achievable PC temperature was 262°C. Around 40% of the coal surface moisture was released, although the release of hydrocarbons was less than expected. Both the gas separator and conveying pipes would need to be enlarged for higher coal injection and throughput rates. A coke rate of 286 kg/thm and PCI rate of 197 kg/thm were achieved with the 5 tuyeres fitted with this system (Langner, 2003). Whether the extra cost of the degassing system, which is calculated to improve coal oxidation in the tuyere by an extra 16% over just coal preheating, is cost effective would need to be assessed.

### 6.5.4 Coal blends

The majority of companies inject coal blends. The higher VM coal component typically has a lower ignition temperature and produces more reactive chars than the lower volatile coal, and hence promotes combustibility. The higher carbon content of the lower volatile coal component provides the high calorific value and a higher coke replacement ratio. For instance, coke rates well below 300 kg/thm were achieved at the Corus IJmuiden 6BF with blends of (ultra) HV coals (42% VM) with low or mid volatile coals (den Exter and others, 2003).

The combustion performance of a coal blend, however, is more complex than that of a single coal. A blend of high and low volatile coals will:

- combust at different temperatures;
- combust at different times;
- burnout at varying rates.

In addition, interactions between the component coals can occur, complicating predictions of the blend’s combustion behaviour. The interaction first occurs in the milling plant where there is potential for large differences in the size distribution of the component coals, especially if there are significant differences in the hardness of each coal. The more easily ground coal (see Sections 3.11 and 5.1.4) becomes concentrated in the smaller size fraction, which could affect the blend’s combustion (and handling) behaviour. For example, the burnout performance of a blend containing low and high volatile coals would be closer to that of the softer LV coal which is concentrated in the finer fractions. Disproportionation also occurs during grinding, influencing the mineral and petrographic composition of the resultant particles, and the subsequent combustion behaviour.

The interactions between the component coals can enhance combustibility of the blend, as indicated in Figure 18. This Figure shows the combustion rates of three single coals and their blends obtained in a pilot-scale test rig simulating a

![Figure 18 Combustion rates of the single coals and their blends (after Assis and others, 2004)](image)
single tuyere. The combustion rates of the single coals (A, B, C) increased with increasing VM. The Figure demonstrates how by adjusting the blend ratio, the combustion rate, and hence burnout, could be improved. The two-coal blends (D and E) both gave higher combustion rates than the component coals. The combustion rate further improved with the three-coal mixtures F and G, where the LV coal from the two-coal blend D has been partially substituted by the higher volatile coals. Replacing the highest volatile coal with lower volatile coals lowered the combustion rate (see samples H and I compared to E). The highest combustion rate was achieved with a three-coal blend (sample G); this was superior to that for the single coal C and the 2-coal blend E, both of which had higher VM contents. One explanation for these results is that the higher volatile coal ignites and burns first, forming a high temperature field that promotes the combustion of the lower volatile coal (Kunitomo and others, 2004).

A review of bench- and pilot-scale tests by Carpenter (1995) showed that the ignition temperatures of blends may not be additive. This is because interactions between the component coals can occur, particularly for blends of petrographically heterogeneous coals or coals with different ash compositions. The addition of a coal that produces a more reactive char could, in some cases, improve burnout performance. The carbon burnout values for blends of high and low volatile coals tend to approach those for the lower volatile coal. One suggestion is that the ignition and combustion of the more reactive char (HV coal) consumes the oxygen. The lower oxygen concentration then inhibits the burnout of the less reactive char (LV coal). These tests were carried out without any oxygen enrichment, which can improve the combustion performance of coals/blends.

The majority of BF operators began PCI operations with HV coals. Chinese BFs, though, began by injecting anthracite, but are now blending it with HV coals. The steel plants in the southern coastal area of China currently use a blend of about 70% anthracite and 30% HV coal. All the coal has to be transported from elsewhere in China and so the cost difference between the two coals is not very significant. The percentage of HV coal in the blend is expected to increase, particularly in northern China which has local deposits of HV coals (Pei, 2003). Increasing the proportion of HV coals not only improves combustibility, but also accelerates indirect iron ore reduction due to the resultant higher hydrogen content of the bosh gas (see Section 3.4). Other countries are increasing the proportion of LV coals in their HV coal blends.

The importance of blending will increase as injection rates approach the theoretical maximum and will provide BF operators with the flexibility to select coals to meet their particular needs.

### 6.5.5 Additives

The addition of combustion improving agents to the coal is a further possibility for achieving higher PCI rates. The burning time of coal can be shortened by adding 2% CaCO₃ (Pandey and Yadav, 1998; Turan, 2000), KMnO₄ or other oxygen-rich materials. However, it is not clear whether the improvement is a result of the oxidising agent in the additives or their catalytic effects (Ariyama, 2000a).

Injection of coal with iron-containing wastes (such as basic oxygen furnace (BOF) slags and BF flue dust), plastics and other waste materials have been carried out, partly as a means of waste recycling. Any decrease in combustion efficiency when co-injecting BOF slag or BF flue dust can be counteracted by adjusting the combustion conditions, such as oxygen enrichment and blast temperature. BOF slag addition has a positive effect on the melting properties of the tuyere slag, resulting in a higher permeability in the raceway end and a decreased SiO(g) generation, and hence a lower silicon content in the hot metal. The addition of BF flue dust did not increase combustion efficiency in the blowpipe model tests, but did increase it in the fixed bed (muffle furnace) tests. The supply of oxygen from the haematite in the flue dust was enhanced due to the longer time available for reaction in the fixed bed, and the improved contact between coal and flue dust allowed direct reduction by carbon. Thus a decreased combustion efficiency of coal is counteracted by the consumption of char and coke fines by FeO in the raceway slag, giving a higher efficiency of the total use of coal (Ökvist and others, 2004). Waste plastics injection can improve combustion efficiency (Murai and others, 2004; Sahajwalla and others, 2004b; Stainlay, 2004), but may be limited by the chlorine input.

Co-injection with natural gas or gas fuels may enhance coal burnout, and also supplies more hydrogen for indirect reduction of the iron ores than coal alone (Hutny and others, 2001; Murai and others, 2004). The improved burnout with increasing natural gas flow was attributed to the formation of a higher concentration of volatiles which, upon burning, lead to higher temperatures and hence to the more rapid combustion of coal. Co-injection of coal and natural gas is favoured in the USA (Poveromo, 2004).
7 Unburnt char

The consumption of unburnt char within the BF is one of the factors that could influence the maximum PCI rates achievable. As the injection rate increases, coal combustibility tends to decrease resulting in unburnt coal fines, char and fly ash exiting the raceway. Some of the char and coke debris accumulate at the back of the raceway, in the bird’s nest, hindering the rising gas flow and entrained solids in this area. The majority are swept upwards where they can accumulate under the cohesive zone. Unburnt char tends to accumulate at positions where large changes in gas flow occur. Thus fines accumulate in the lowest parts of W-shaped cohesive zones. The V-shaped cohesive zones accumulate less fines than the W-shaped one, with the fines collecting near the walls (Akiyama and Kajiwara, 2000; Dong and others, 2003). The unburnt char is eventually entrained into the gas flow, passing through the cohesive zone coke slits, and up the stack, where it can affect burden permeability, and is finally emitted with the offgas.

The fine material circulating in the fluid and deadman zones includes not only coal char but coke fines, slag (some of which originates from the coal and coke) and metal droplets. Sampling of the deadman at the tuyere level has shown that the amount of smaller sized coke fines rises with increasing PCI rate (Akiyama and Kajiwara, 2000). Accumulation of the fine materials in the lower part of the furnace lowers permeability and hinders gas flow. Furthermore, the presence of unburnt char in the slag can interfere with tapping by increasing slag viscosity (Seo and Fruehan, 2000). Fines deposition is a complex phenomenon consisting of several generation mechanisms, reactions, multiphase flow, accumulation and re-entrainment (Nogami and others, 2003). Various gas flow models have been developed to understand and predict the behaviour of fine materials in blast furnaces (for instance, Dong and others, 2003; Feng and others, 2003; Nogami and others, 2003; Pintowantoro and others, 2004).

With appropriate burden charging patterns (such as central coke charging) and the use of stronger coke many of the problems relating to gas flow have been overcome. On well balanced furnaces, with good burden distribution and injection practice, unburnt coal char discharged in the offgas rose by only a small amount, or not at all, when PCI rates were increased to over 200 kg/thm (Akiyama and Kajiwara, 2000; England and others, 2001; Kimura and others, 1996; Lüngen and Poos, 1996; Okochi and others, 2000). In some cases the permeability even improved at high PCI rates (Zhu and Guo, 2000). This suggests that most of the unburnt char is consumed within the furnace. The three mechanisms for this are:

- gasification with CO2 and H2O;
- reaction with molten iron (carburisation);
- reaction with slag.

It would be advantageous if the unburnt char participated in ore reduction reactions, thereby replacing more of the coke and also reducing the amount of unburnt solids in the offgas. This chapter discusses each of these char consumption processes, and then the emission of coal char in the offgas.

7.1 Char gasification

The reaction of chars with CO2 and H2O begins in the raceway, but since the residence time is too short for appreciable reaction, gasification mainly occurs in the furnace shaft. The reaction of char carbon with CO2 (the solution loss or Boudouard reaction) is a slower process than char combustion. Coal chars compete with coke for CO2 (and H2O). They are more reactive than coke and consequently are preferentially gasified (Akiyama and Kajiwara, 2000; Kentaro, 2006). Thus coke degradation by the solution loss reaction decreases.

Measurements along the furnace radius above the stockline at the Schwelgern 1BF (PCI rates up to 190 kg/thm) found that the amount of unburnt coal char in the sampled dust was highest in the furnace centre (Bachhofen and others, 1998). This was expected since the highest gas flow is here and the charged burden approaches zero. The amount of unburnt carbon from the coke rose towards the furnace periphery, whereas that from unburnt coal char decreased.

Measurements at Fukuyama 4BF showed that the quantity of carbon (coal and coke) consumed by the solution loss reaction decreased with increasing PCI rate in the centre and middle regions of the BF, but remained almost constant in the peripheral regions. This was attributed to the promotion of hydrogen reduction, as well as the lower descending speed of the burden and the higher temperature of the thermal reserve zone. The extent of solution loss reaction decreased as bosh gas hydrogen rose. Figure 19 shows the variation in the amount of solution loss reaction and shaft efficiency with increasing PCI rate. The solution loss carbon decreased by

![Figure 19 Relation between PCI rate, shaft efficiency and amount of solution loss carbon (Kimura and others, 1996)](image-url)
about 10 kg/thm as PCI rate increased from 100 kg/thm to 200 kg/thm, whereas shaft efficiency remained stable at about 0.95. At PCI rates over 200 kg/thm, the shaft efficiency improved by about 0.02 and the amount of solution loss carbon suddenly dropped. This behaviour was attributed to the higher reducibility of the hybrid pelletised sinter used during this period and the small amount of slag (Ishii and Kashiwaya, 2000; Kimura and others, 1996). The amount of unburnt char (from coal and coke) also decreased in the deadman when the PCI rate was raised from 200 kg/thm to 230 kg/thm. This was attributed to the use of higher strength coke and the lowering of the solution loss reaction (Kimura and others, 1996).

The properties of char change as it moves up the furnace, and hence its reactivity to CO₂. In addition the reacting environment is not uniform. In particular, the relative concentrations of CO and CO₂ vary at different locations within the BF. In the lower part of the furnace, char gasification is partly diffusion controlled, whilst in the upper cooler part it is likely to be chemically controlled. Pipatmanomai and others (2003) investigated the extent of char gasification in a WMR using an 18% CO₂/N₂ mixture, which simulates the gaseous environment in the post-combustion region of the raceway and in the lower part of the furnace shaft. The chars were produced in the WMR at 1500°C using the pulsed air technique (see Section 6.4). The extent of gasification increased with temperature. The weight loss after 10 s was lower at 800°C than at 1500°C (about 10% daf of initial char loss compared with about 50%). This suggests that chars which are rapidly swept into the cooler regions of the furnace by the up-flow of gas are less likely to be completely consumed. Carbon escape in the offgas could then occur (Atkinson and others, 2004).

CO₂ is present in the upper part of the furnace due to the reduction of iron ore. Under the conditions here, char gasification is likely to be controlled by the rate of the chemical reactions. Therefore the overall reaction rate of char gasification is likely to be influenced by the chemical reactivity of char to CO₂ in this region (Lu and others, 2002b). Char reactivity towards CO₂ is influenced by its chemical structure, with less ordered structures being more reactive, as discussed in Section 6.4 for char combustion reactivity. The presence of certain minerals, such as iron and alkalis, can catalyse the gasification reaction. In the lower part of the furnace, condensed alkalis from the recirculating gases could have a catalytic effect, as has been found for coke gasification. The loss of carbon by gasification will increase the char ash content. Chars from lower rank coals are generally more reactive to CO₂ than those from higher rank coals.

There is, as yet, no standard test for determining the reactivity of coals and their chars to CO₂ in regard to PCI performance.

### 7.2 Interactions with liquid metal

Unburnt char (and coal fines) exiting the raceway can contact the dripping molten metal in the bosh and hearth zones. Carbon and other elements, such as silicon and sulphur, dissolve from the char into the liquid iron influencing the composition of the hot metal (pig iron). The dissolution of carbon contributes to the carburisation of liquid iron, and dictates the level of char consumption by the hot metal. It will be critical where combustion efficiency is low. At higher rates of PCI, carbon dissolution may help reduce the consumption of coke by hot metal carburisation. However, the dissolution rate of carbon from coal char is a slower process than that from coke (Cham and others, 2004; McCarthy and others, 2002), implying that coke carbon may be preferentially consumed. This section discusses carbon dissolution in hot metal. The transfer of silicon and sulphur is covered in Chapter 8.

Carburisation of the metal begins in the solid phase. Experiments carried out by Danloy and others (2002) under conditions of high PCI rates found that the pellet samples were completely reduced before melting and that carburisation of the metal had taken place. The carburisation probably proceeded via the gas phase, rather than by direct reaction with the char, by the equation:

\[ 2CO \rightarrow C(\text{metal}) + CO_2 \]

A study at the Port Kembla works in Australia, with no coal injection, showed that the state of the coke bed in the deadman and hearth can be related to the carburising ability of the coke (Nightingale and others, 2003). Unsaturated liquid hot metal can consume any fines that have accumulated in the deadman and hearth. If the hot metal is close to saturation when it reaches the deadman and hearth, the fines cannot be consumed, thus diminishing permeability in these regions.

The carbon subsaturation (ΔC, wt%) of hot metal is employed as the routine deadman cleanliness assessment tool at these works. Essentially, as the hearth becomes less permeable, carbon saturation in metal increases due to increased contact time (and probably contact area) between the metal and carbonaceous material. As expected, ΔC decreased with the introduction of PCI. Satisfactory operation was achieved with the injection of a 33% VM coal, despite an increase in the silicon hot metal content. However, when this coal was blended with a 20% VM coal (50 wt%), it was difficult to maintain ΔC above the nominated 0.28% set point (under the existing combustion conditions) and so the PCI rate was reduced to 130 kg/thm. It was also found that silicon transfer to the metal was related to the ΔC of the metal and the PCI rate.

Carbon dissolution from coal char (and coal fines) into liquid metal is influenced by the operating conditions and factors such as the:
- char particle size;
- char structure;
- char mineral matter;
- liquid metal composition.

#### 7.2.1 Char particle size

Work discussed by Lüngen and Poos (1996) investigated the
reaction of coal char with liquid metal and slag samples. Tests showed that the char and coal fines react very little with the liquid iron and slag as long as they maintain their pulsed form which cannot penetrate into the liquids. If, however, they are agglomerated into larger particles or captured by the larger pieces of coke, then they behave like bosh coke and carburise the metal up to saturation. However, a tuyere probe sample taken at the Port Kembla 6BF, Australia, indicated that ultrafine coal char particles can react with the dripping hot metal, and that they are more readily dissolved than ultrafine coke particles (Nightingale and others, 2003). Experiments discussed in the following section, though, found that the dissolution rate of carbon from coal char, albeit at larger particle sizes, is a slower process than that from coke.

7.2.2 Char structure

It has been reported that char structure can influence the dissolution of carbonaceous material (graphite, coke and coal chars) in iron and Fe-C-S melts. In general, graphite has the faster dissolution rate and coal char the lowest, that is, the rate of dissolution improves as the carbon structure becomes more ordered. For example, McCarthy and others (1999) and McDonald and others (1998) investigated the dissolution of graphite and coal chars using a carburiser cover technique in an induction furnace at 1550°C and 1500°C, respectively. The graphites dissolved markedly faster than the chars. The dissolution behaviour of the chars did not show any significant dependence on their fixed carbon, sulphur or ash contents, but was dependent on the crystallite size (Lc value determined by X-ray diffraction). The higher the degree of ordering for the chars, the greater their dissolution rate into hot metal. It has been postulated that the removal of small aromatic carbon regions in coals and chars by liquid Fe-C is more difficult than the removal of large sheet-like graphite. This changes the rate limiting step to the removal of the carbon atoms at the phase boundary by interfacial reactions (unlike graphite dissolution where the rate controlling step is mass transfer of carbon in the liquid boundary layer). This implies that the type of coal char could have a significant influence on carbon dissolution into hot metal. If a coal char’s dissolution rate is known, then this may help in the selection of PCI coal.

An investigation of coke dissolution into molten iron, again using the carburiser cover technique in an induction furnace at 1550°C, showed no obvious correlation of dissolution rate with the atomic structure of coke. Ash yield and composition played the dominant role (Cham and others, 2004), the subject of the next section.

7.2.3 Char mineral matter

Studies on coke and coal char carbon dissolution into molten iron and Fe-C-S melts carried out by various researchers and summarised by Cham and others (2004) and McCarthy and others (2002) suggest that:

- the ash fusion temperature (AFT) is one of the controlling mechanisms that limits carbon dissolution. The formation of an ash layer on the carbonaceous material reduces the surface area available for dissolution, thus retarding carbon dissolution rates. Low AFTs allow easy removal of the ash, in the form of liquid slag. This results in constant exposure of fresh carbon surface to the hot metal, permitting the mass transfer of carbon to the liquid iron;
- additions of oxides to the carbonaceous materials affect the dissolution rate. Additions of SiO₂, MgO and Al₂O₃ slow the carbon dissolution kinetics, whilst additions of CaF₂ and Fe₃O₄ enhance the rate. The effect of CaO was less clear.

McCarthy and others (2002, 2005) investigated the iron/char interactions over 3 h using the sessile drop technique in a horizontal furnace at 1550°C (see Figure 20). The two coal chars were produced in a DTF at 1200°C. Reactions between the char ash oxides and the liquid iron were found to influence the level of carbon in the metal. Carbon is initially transferred from the char into the liquid iron until reduction of silica by the dissolved carbon begins. This reduction of silica at the interface (and of other reducible oxides, such as iron oxides, in the char ash) retards the accumulation of carbon in the liquid iron. Since silica reduction consumes carbon, higher coke degradation rates could occur in the BF as more carbon is required to carburise the hot metal. Silicon transfer is discussed further in Sections 7.3.2 and 8.1.

The formation of a calcium sulphide layer from the reaction of char calcium with sulphur in the metal (see Section 8.2) may also inhibit carbon transfer. Alumina present in the ash is deposited at the interface, but due to its non-wetting nature, it can inhibit the dissolution of carbon into liquid iron (McCarthy and others, 2005).

Carbon dissolution from nine coke samples in molten iron at 1550°C, using the carburiser cover method, showed that the rate of carbon dissolution decreased with increasing ash yield with the exception of one coke (Cham and others, 2004). The dissolution rate of this coke was surprisingly similar to that of graphite. It had an unusually high level of Fe₃O₄ and low level of Al₂O₃, and had the lowest AFT of the coke samples. It has been suggested that iron oxide increases the carburisation rate since the ash layer formed at the interface is liquid and is therefore easily removed from the coke surface. Thus a fresh surface for carbon dissolution is continually exposed. However, the chemical composition of the ash analysis is reported in terms of oxides, which can be misleading. Under the experimental conditions employed any iron oxide present in the coke is readily reduced to the metal. Hence it would be difficult under these conditions for iron oxide to be a fluxing agent for the mineral matter because the iron is not present as iron oxide. Consequently, if iron in the mineral matter is responsible for increasing the carburisation rates, it does not do so by fluxing the mineral matter. These results suggest that the ash composition of coal char is likely to have a similar effect.

Thus knowledge of the ash reactions affecting carbon dissolution will allow better coal selection for PCI, with a view to maximising char consumption by BF hot metal.
The carbon dissolution rate is influenced by the composition of the liquid iron, which changes over time. Using the carburiser technique, McDonald and others (1998) found that increasing the initial carbon content of the molten iron lowered the carbon dissolution rate constant. This was a result of the retarding effects of the interfacial reactions. Adhesion between the iron melt and the solid char decreased, thereby resulting in a decrease in the rate of carbon transfer across the carbon/melt interface.

Combustion of coal (and coke) releases sulphur oxides which can react with the descending metal and slag. Experiments have shown that increasing the sulphur content of the Fe-C-S melt retards carbon dissolution. McDonald and others (1998) found that the carbon dissolution rate constant was linearly proportional to the sulphur concentration, whilst McCarthy and others (1999) report a non-linear relationship. The latter authors found that the effect of sulphur became less pronounced at the higher sulphur levels (above approximately 0.1 wt% sulphur; the sulphur content of melt varied between 0.02 and 0.35 wt%). The wettability of char by the melt may be one of the mechanisms limiting carbon transfer. Increasing the sulphur content of the melt increases the contact angle between the liquid metal and the char surface. This results in a smaller contact area (see Figure 20b). Consequently, the area of the char available to interact with the liquid metal is reduced. Sulphur may also be causing a decrease in the carbon diffusion coefficient or blocking surface sites, impeding carbon transfer.

7.3 Interactions with slag

Unburnt coal char, ash and fines, as well as coke, can interact with the slag. Sampling at the Muroran 2BF in Japan with PCI rates of 157 to 190 kg/thm indicated that about 15–20% of the dripping (bosh) slag reacted with and assimilated the coal ash. One of the causes of reduced permeability in the deadman zone was attributed to the formation of high viscosity <1 mm fines originating from the coal ash (Ichida and others, 2001). Experiments performed in a horizontal rotary furnace quoted by Akiyama and Kajiwara (2000) showed that, when combustion efficiency in the raceway is 70 or 90%, about 4% of unburnt char is assimilated in the slag, and less than 1.5% contributes to the carburisation of the molten iron. From these amounts, it is presumed that the total amount of unburnt char consumed in the bosh region would be about 5%.

Calculations by Mehta and others (1998) suggest that char consumption in the slag would be about 49.6 kg/thm, based on a PCI rate of 180 kg/thm and 50% combustion. Similarly, about 40 kg/thm would dissolve into the hot metal, giving a total char consumption of about 89.6 kg/thm. These figures would be lower in practice since they do not take into account parameters such as the competition with coke consumption.

Factors influencing coal char interactions with the slag include the slag composition, char carbon content, and char ash content and composition, as well as the operating conditions. Basically, char consumption by slags occurs via:
• reduction of the iron oxides in slags by carbon in the char;
• reduction of silica in slag by char carbon;
• interactions between components in the slag and char, leading to the assimilation of char ash components such as sulphur.

In addition, the reduction of MgO in slag by char carbon could lead to further consumption. Self-reduction of the oxides in the char ash by carbon can also contribute to char consumption (Mehta and others, 1998, 1999).

7.3.1 Iron oxide reduction

The slag composition changes as it moves down the furnace, with the iron oxide concentration being continuously lowered as it is reduced. The reactions at the interface between the solid char and molten slag play a major role in char consumption since they influence the kinetics of the reduction reactions and the contact area between the slag and char available for reaction.

The reduction of iron oxides in slag by solid carbon occurs via a gas ferrying mechanism (Sarma and others, 1996; Seo and Fruehan, 2000; Teasdale and Hayes, 2005a,b), as illustrated in Figure 21. Following initial reaction between the solid carbon and slag, CO gas is produced, forming a gas film between the char and slag surface. This CO is transported through the gas film (reaction step c) and reacts with FeO in the slag (reaction step b) to produce CO2 and metallic iron. This CO2 is transferred or ferried back through the gas film to the carbon, where reduction of CO2 to CO (Boudouard reaction) occurs (reaction step d). The cycle of reactions is then repeated. However, there are significant differences in the reaction paths of coke and char.

The wetting characteristics have a significant effect on the dominant reduction mechanism taking place. Studies have shown that the wetting characteristics of slags vary with slag composition, temperature, time, and carbonaceous material (Mehta and Sahajwalla, 2000, 2001; Mehta and others, 1998, 1999). Wetting varies as a function of time since the reduction of iron oxide in the slag by char, and the dissolution of the char ash components into the slag, results in continuous variations in the slag and char compositions. An increase in temperature generally results in improved wettability at the slag/carbon interface.

Using the sessile drop technique (see Figure 20 on page 48), it was shown that, in general, coal chars are poorly wetted by slags containing more than 10 wt% iron oxide at 1400ºC and 1500ºC (Mehta and Sahajwalla, 2000, 2003; Mehta and others, 1998, 1999; Teasdale and Hayes, 2005a,b). Mehta and co-workers used a slag containing 31.5 wt% Fe2O3, representative of slag that is present in the BF soon after melting, whereas Teasdale and Hayes used a slag containing 10.8 wt% FeO. The metallic iron that is formed initially in the slag at the slag/carbon interface is carried away from this surface to the external free surface of the slag. Since the iron is no longer in contact with solid carbon, the reduction of the slag takes place predominantly through the gasification and gas ferrying mechanisms occurring at the char/slag interface. Thus the rates of reduction of coal chars are determined principally by the chemical reaction at the carbon/gas interface and slag phase mass transfer (Teasdale and Hayes, 2005a,b). It is only in the later stages of reduction that significant quantities of metallic iron accumulate at the char/slag interface and contribute to reduction through the liquid Fe-C alloy (the principal mechanism for coke consumption). The slight improvement in the wetting of chars by slags that occurred after some time (>80 mins) was attributed by Mehta and Sahajwalla (2003) to the presence of significant amounts of metallic iron in the interfacial region. Reduction reactions lower the interfacial free energy, decreasing the surface tension of slag.

The reduction rates of FeO in slags with coke (and graphite) at 1400 and 1450ºC were found to be faster than those with coal chars (Sarma and others, 1996; Teasdale and Hayes, 2005a,b). The exception was an anthracite char (the rest were bituminous coal chars) where the reduction rate approached that of coke. This was unexpected since the coke and anthracite char have a lower CO2 reactivity. The higher rates were attributed to the formation of liquid Fe-C alloy droplets at the slag/carbon interface and the associated gasification of carbon from the alloy (Teasdale and Hayes, 2005a,b). The dissolution rate of carbon from coke and graphite into molten iron is higher than from coal chars (see Section 7.2). However, Mehta and Sahajwalla (2003) found that the reduction rate constants for the reduction of iron oxide at 1500ºC for the two coal chars were similar to those for graphite, and were comparable to the rates quoted in the literature for smelting slags. They suggest that the slightly higher reaction rates for chars could be due to faster rates for the Boudouard reaction. They were using a slag with a higher iron oxide content (31.5 wt%) than Teasdale and Hayes (10.8 wt%). They also found that all of the iron oxide was reduced. Reduction rates generally increase with increasing slag FeO (2–10 wt%) contents (Sarma and others, 1996) and with increasing reaction temperature (1300–1600ºC) (Teasdale and Hayes, 2005b). A faster reaction rate for coke suggests that coke fines would be preferentially consumed before coal char.

Use of PCI in blast furnaces
Seo and Fruehan (2000) found that the reduction rate of FeO was independent of the parent coal used. The reaction rate at 1 and 3 wt% FeO in the slag was about the same for the two chars prepared from a high (36.7%) and low (16.6%) volatile coal, with ash contents of 7.4 and 5.5%, respectively. However, more carbon is likely to be consumed by the high FeO slag compared to the low FeO slag (Mehta and others, 1998).

Solid metal droplets have been reported in BF slags (Gustavsson, 2004; Nightingale and others, 2003). These droplets were very small, with the majority <2–3 µm. The improved drainage at the Port Kembla 6BF that resulted when PCI was introduced was attributed to the presence of the ultrafine (1–3 µm) metallic iron prill. These prills may modify the dynamic bulk slag viscosity by deforming under high shear stress conditions such as those experienced during passage through the taphole. Nightingale and others (2003) suggest they could be generated by reaction between a single coal char particle and FeO contained in the dripping slag.

Only the smallest char particles could generate prills that are retained in the slag. The larger prills must have separated from the slag. Two casts from the pre-PCI period also had a high prill content. These were associated with the use of unusually low strength coke. This suggests that coke ultrafines can also generate prill in a similar fashion to coal char.

### 7.3.2 Silica reduction

Silica reduction is a function of temperature. At temperatures below 1500°C, only reduction of iron oxide occurs. At temperatures above this value, both silica and iron oxides in the slag are reduced, resulting in increased consumption of the char. Silica is reduced by carbon, via gaseous SiO, to silicon carbide (SiC) or silicon. Self-reduction of silica in the char ash by carbon can also occur, resulting in further consumption of the char.

The reduction kinetics of silica are influenced by the wettability of chars by the slags. Investigations have shown that the wettability of chars by a silica-rich (36.3 wt%) slag with negligible iron oxide (0.26% Fe₂O₃) content was dictated by the extent of silica reduction at the slag/char interface (Mehta and Sahajwalla, 2000, 2001, 2003; Mehta and others, 1998, 1999). The authors used the sessile drop technique at a temperature of 1500°C, and the slag composition was typical of a BF hearth slag. Wetting behaviour of high iron oxide slags (see Section 7.3.1) was dictated by the deposition of reduced iron at the interface, and all of the iron oxide was reduced. Not all of the silica was reduced in the silica-rich slags – considerable amounts of unreduced silica remained even after 30 mins of contact. Wetting behaviour improved with an increase in slag silica content, and with an increase in temperature (1500–1700°C). The char ash content and composition also play a role. Higher amounts of silica and iron oxides in the char ash facilitated the slag/carbon interactions, leading to improved consumption of these oxides through reduction reactions.

Mehta and Sahajwalla (2003) suggest that the reduction and depletion of silica at the interface sets up concentration gradients leading to increased rates of mass transfer from the bulk to the interfacial region. With the silica present in the char also taking part in the reactions, the chemical composition of the char becomes quite important. As the reduction reactions at the interface slow down due to the depletion of carbon and deposition of SiC, supply of silica begins to exceed consumption, thereby decreasing the interfacial tension. A small decrease in interfacial tension leads to the onset of rapid wetting. The deposition of SiC at the interface can also improve wetting. It took longer for rapid wetting to begin for the char with the lower silica content (about 115 mins compared to around 80 mins for the second char). The overall silica reduction rates in the initial stages of contact (before the onset of rapid wetting) was faster for the chars than for graphite. This was attributed to the higher Boudouard reaction rates of the chars. The gasification of carbon therefore plays an important role in silica reduction.

These investigations have shown that char consumption by low iron oxide containing slags are influenced by the ash content and composition of the char. This could influence the choice of coal. For example, given that some chars may have a similar combustibility, their interactions with the slag, and therefore the consumption of unburnt char, could be a criterion for the selection of PCI coals (Mehta and others, 1998).

### 7.3.3 Slag viscosity

Unburnt char remaining in the slag can interfere with tapping by increasing slag viscosity (Seo and Fruehan, 2000), whereas assimilation of char generally increases the fluidity of the bosh slag. Changes in slag mobility can affect the position and shape of the fluid and cohesive zones. Laboratory-scale tests under simulated BF conditions on mixtures of pre-reduced iron oxide sinter (70% reduction degree) and coal char using the SMEDRA (Softening MElting DRipping Apparatus) test showed that the mobility of the ferrous material improves with char addition (Atkinson and others, 2004). In particular, the extent of initial dripping increased and the dripping starting temperature was lower with char. This was dependent on the amount of char added and its characteristics, or better, to the characteristics of the parent coal (whether pulverised or granular, and VM content), as indicated in Table 8. The char from the pulverised coal sample (BS5pf) gave one of the highest amounts of melt material (67%) and the start of the dripping temperature was one of the lowest. Only a small amount of char from the other PC sample (BS6pf) was added to the sinter; in this case the amount of material dripped was less than the reference test. The different behaviour of the two CSM chars was difficult to explain; the parent coals have similar characteristics, and the char production conditions and char characteristics were fairly similar. The three TKS chars were obtained from two single coals (TKSN and TKSP) and from a blend of these two coals (TKSN/P). The blend sample gave results in between those obtained from the single coals, although the start dripping temperature was slightly higher than the two single coals.
Slag viscosity is a complex function of slag composition, temperature and oxygen partial pressure. As well as unburnt coal char and coke, unburnt ash from the coal can interact with the slag (Ichida and others, 2001). All of these carbonaceous materials contribute oxides to the slag. In general, higher amounts of SiO$_2$ or Al$_2$O$_3$ (acidic components) increase slag viscosity, whereas a higher basicity (higher CaO or MgO) lowers slag viscosity because of depolymerisation of the silicate network (Kim and others, 2003, 2004; Lee and others, 2004). The silicate structure changes from a three dimensional network to discrete anionic groups containing simple chains and/or rings. Slag viscosity decreases with increasing FeO (0–20 wt%) content at a fixed basicity (Lee and others, 2004). Basicity is typically determined by the CaO/SiO$_2$ ratio. Since the slags do not fully assimilate the char and ash in the bosh region, bosh slag normally has a higher basicity than tapped slag.

Slag formation problems that occurred during the testing of self-fluxing iron ore pellets were solved by co-injecting pulverised fluxes (BOF slag) through the tuyeres with the coal (Ökvist and others, 2004; Wikström and others, 2002). Mixing of the fluxes with ash from the coal and coke reduced the melting point of the tuyere slag by more than 200ºC, at the same time improving slag viscosity. Formation of acidic slag in the raceway from coal and coke combustion was avoided, as well as the formation of slag with excessive basicity in the lower shaft, which can lead to permeability problems in the cohesive and bosh regions. A reduction in slag volume was also achieved in the pilot plant trials (PCI rates of 100 kg/thm). Decreased combustion efficiency resulting from BOF slag injection can be counteracted by adjusting combustion conditions. Thus flux injection could be used to adjust slag chemistry, and hence char consumption, as well as slag viscosity.

Higher ash coals can increase the volume of slag to be tapped. A lower slag volume helps secure good gas/liquid permeability in the lower part of the BF. To allow Posco (Korea) to operate at a high PCI injection rate with a low slag volume (about 270 kg/thm instead of 300 kg/thm), it was proposed that the amount of MgO in the sinter should be reduced to 0.8 wt% so that the MgO content in the bosh slag is around 5 wt% (Kim and others, 2004). The Al$_2$O$_3$ content in the bosh slag would be around 10 wt%. The viscosity of the bosh slag is higher than in conventional operations, whilst the viscosity of the tapped slag would be about the same because of the assimilation of silica from the injected coal and the addition of CaO and SiO$_2$ to the sinter.

### 7.4 Char in offgas

Unburnt char, soot and coke fines can be carried up the stack before eventually exiting with the offgas. Tests in 1998 with an ultrahigh volatile Indonesian coal (VM 42%) at the IJmuiden 6BF, Netherlands, increased the amount of fine dust in the gas cleaning system, resulting in the efficiency of the water cleaning system decreasing. The amount of carbon in the sludge doubled from 3–4 kg/thm with the normal coal injection rate of 200 kg/thm to 7–8 kg/thm with the Indonesian coal at an injection rate of more than 240 kg/thm. This caused the end of the trial after 2 weeks of operation (Sert and Godijn, 2002; Toxopeus and others, 2000). The increased carbonaceous material in the fine dust was identified as soot coming from the coal.
Soot originates from the incomplete combustion of coal volatiles. Tar released as gases during coal pyrolysis can crack to form soot (heating in the absence of combustion). It has been estimated that in the temperature range 1600–2000ºC, about one third of the mass of volatiles is transformed into soot (Bennett, 2000; Chatterjee, 2002), although others suggest a lower figure of 20% (Wu, 2005). Studies in a WMR found that about 8% (by weight) of a 13% VM (db) coal was released as primary tar (Pipatmanomai and others, 2004). Some of the soot is trapped within the coke bed, lowering coke bed porosity, and the remainder is emitted, either as discrete particles (soot) or trapped within the fine coke and char dust. Soot has poor combustibility and is less reactive than the residual coal char. Its complete consumption once it leaves the raceway would require higher air/fuel ratios, a longer residence time and more reactive environments than are commonly practised in the operation of BFs. Good control of the initial stages of coal combustion are thus required to minimise soot formation.

Table 9 gives the coal char proportion in flue dust and sludge samples taken from three American BFs burning different HV bituminous coals (VM 30–36 wt%, db). The char proportions were estimated on the basis of differences in the crystalline order of carbon in the char and coke using XRD (Sahajwalla and Gupta, 2005). The char proportion in all the dust samples was lower than that in the sludge. The lower char proportion in the second set of flue gas samples from BF A was attributed to the higher blast temperature (>25ºC), which enhanced combustion and thus reduced the amount of unburnt char. For BF B, the char proportion in the offgas emissions was lower in the second set of samples, even though the PCI rate was higher. This was again ascribed to the higher blast temperature. The higher residual char in the offgas from BF C occurred during operation with the lower blast temperature and oxygen level, at similar PCI rates. A different coal, which might have a different combustion behaviour, was used in the second set of operations. Blast oxygen and blast temperature, through their impact on combustion performance of coals, could therefore influence char carryover and hence influence PCI rates and furnace efficiency. The determination of char carryover could be used as one of the indicators to monitor PCI performance in a BF.

The determination of char carryover could be used as one of the indicators to monitor PCI performance in a BF.
The objective of a BF is to produce the desired hot metal quality in the required amounts at the lowest possible cost. Low levels of impurities in the hot metal are preferred in order to reduce the refining costs in the steel shop. The two major impurities of concern that can originate in the coal are silicon and sulphur. This section discusses silicon and sulphur transfer to the hot metal.

### 8.1 Silicon transfer

Experience in BFs has shown that hot metal silicon content can either decrease (Jin and others, 2003; Stainlay, 2004) or increase (Gustavsson, 2004; Matsui and others, 2003a) with PCI. Low metal silicon levels are needed to reduce refining costs and to lower BF energy consumption. For every 0.1% increase in hot metal silicon, an extra 0.105 GJ/thm is consumed, equivalent to a 3–4 kg/thm increase in the reductant rate (Kumar and Mukherjee, 2004).

Silicon in the hot metal originates from silica in the:
- iron ore, pellets and sinter (gangue);
- coke mineral matter;
- coal mineral matter.

Table 10 gives a typical material balance for some of the impurity elements in the Sollac Fos BF in France. From this it can be seen that the iron-bearing materials (sinter) contribute the highest amounts of silicon, followed by coke and then coal.

The transfer of silicon into the hot metal takes place in the lower part of the BF. Figure 22 shows the main transfer route

<table>
<thead>
<tr>
<th>Table 10 Typical example of material balance of elements in Sollac Fos BF (Steiler and others, 1998)</th>
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<td>Input</td>
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Figure 22 Silicon transfer in lower part of BF (Matsui and others, 2003a)
(via gaseous SiO) and the amounts of silicon contributed by
the raw materials under a PCI rate of 200 kg/thm. The silica
is partially reduced by carbon present in the raw materials
to either gaseous silicon monoxide (SiO) or solid silicon carbide
(SiC). The SiC can be further oxidised to SiO by reaction
with CO. The gaseous SiO is either re-oxidised on cooling or
is further reduced on contact with the molten metal. The
reduction of SiO and the dissolution of silicon into the hot
metal occurs via the following reactions:

\[
\begin{align*}
\text{SiO} + \text{C} &= \text{Si} + \text{CO} \\
\text{SiO} + \text{CO} &= \text{Si} + \text{CO}_2
\end{align*}
\]

Gaseous SiS can also play a role in silicon transfer (Basu and
others, 2001; Gustavsson, 2004). As the metal droplets trickle
through the slag layer in the hearth, part of the silicon already
picked up by the iron reacts with oxides in the slag resulting
in silicon removal from the metal. Therefore the highest
molten metal silicon contents are found typically at the
tuyere level. But if the silicon content of the metal at this
level is too high, then there may not be enough time for silicon re-oxidation to occur in the hearth.

The hot metal chemistry basically depends on the extent of
the slag-metal-gas reactions taking place and the partition
of silicon between these three phases. By adjusting the partition
ratio, the silicon hot metal content could be controlled.
However, this is complicated due to the number of factors
involved, some of which are discussed below, and process
constraints.

Factors influencing the gasification rate of SiO from coke
and coal/char (Gustavsson, 2004) include:

- activity of SiO2 and ash composition;
- temperature;
- carbon activity;
- wettability between coke/coal char and slag
  (see Section 7.3.2). A decrease in wettability decreases
  the rate of silica reduction by the carbon;
- total gas pressure and local oxygen potential;
- blast volume. A higher blast volume decreases SiO gas
  formation rate.

The SiO gas reduction rate and dissolution in the hot metal
and slag are mainly influenced by:

- slag composition;
- height of the cohesive zone;
- carbon activity in the metal.

Finally, reactions in the hearth between the hot metal and
slag will determine the final amount of silicon in the tapped
metal.

Since silica activity is much higher in coke mineral matter
than in the iron ore slag, most of the gaseous SiO is formed
from reductions in the coke mineral matter in the high
temperature zone around the raceway (Steiler and others,
1998). The SiO generation rate from coke SiO2 is about ten
times greater than that from slag silica, although a
two-dimensional simulation of silicon transfer in a BF puts
the figure even higher at about 40 times (Matsui and others,
2003a). These authors also derived the SiO generation rate
from pulverised coal char by heating the char under flowing
CO in an electric furnace at 1500 or 1600°C. The reaction
rate constant was three times higher than that for coke. This
was attributed to the melting ash permeating the char pores,
thus increasing the interfacial area available for reaction
between carbon and silica in the ash. Consequently, the
composition of the coal ash influences SiO generation.

An analysis of coke taken from around the tuyeres in two
different BF s indicated that vapourisation of SiO2 from the
coke decreased as the PCI rate increased (Jin and others,
2003). They suggest that higher oxygen content in the
raceway from enrichment of the blast restricts the production
of SiO. As discussed in Section 6.3, higher PCI rates shorten
the length of the high temperature zone since the peak point
of CO2 production moves closer to the tuyere. This hinders
silica reduction.

Bench-scale combustion tests carried out with a blast
temperature of 1200°C indicated that, for methane-cooled
coaxial lance injection, only around 2–5% of the original coal
ash silica content is vapourised in the raceway; this figure is
about double for air-cooling lances near stoichiometric
combustion conditions. Silica vapourisation rates of 10% or
less were recorded for almost all the coals tested on the
combustion facility. Related studies suggest that coal ash
silica vapourisation is not simply related to coal ash silica
content or the quartz content of the coal mineral matter
(Nightingale and others, 2003); other factors play a role, such
as the silica mineral form.

The different silica forms that occur in the coke mineral
matter contribute different amounts to hot metal silicon. A
model for predicting hot metal silicon content indicated that,
based on the assumption that all of the coke silica reaching
the tuyeres as quartz is reduced and gasified, the SiO
generated has a 51% yield to hot metal silicon. The yield for
clay derived tuyere ash silica was 20%. This difference was
considered reasonable when the relative thermodynamic
activities of the two silica forms are taken into account
(Nightingale and others, 2003). Utilising coals and coke with
low silica contents will help lower hot metal silicon content.

Temperature is a major factor affecting the amount of
gaseous SiO in and around the raceway, and hence the hot
metal silicon content. Bench-scale experiments by Jin and
others (2003) found that the higher the temperature, the
higher the silicon content, with most of the increase
occurring above 1500°C; this is the temperature where
reduction of silica begins. In addition, the silicon amount
decreased with increasing coal ratio (PCI rate) at the same
temperature. The apparatus discharged pig iron from the
bottom of one crucible into another one containing coke
placed on top of coal ash in a preheated furnace (1450, 1500
or 1550°C) for 40 mins. The coal ratio was equivalent to 0,
100, 150 and 200 kg/thm.

Thermodynamic calculations using the Thermo-Calc software
showed that a higher temperature gives a higher equilibrium
ratio between silicon in the hot metal and silicon in the slag
around the raceway area in a pilot plant (Gustavsson, 2004;
Gustavsson and others, 2005). At temperatures below 1600°C, the total gas pressure (or rather increased CO partial gas pressure) additionally influenced the amount of gaseous silicon. Increased gas pressure lowers the equilibrium ratio between silicon in the hot metal and slag. The main reason for this is that below 1600°C, the amount of liquid slag at equilibrium increases with the total gas pressure. Liquid slag contains large amounts of silica that then cannot be found in the gas phase. In the cases where total gas pressure rises with increasing temperature (due to larger gas volumes), the hot metal silicon content will increase due to the higher temperature.

Since a higher RAFT produces more gaseous SiO, lowering it can decrease hot metal silicon content. This can be achieved, for example, by employing a lower blast temperature or a higher blast humidity. However, lower RAFTs can give lower hot metal temperatures. To avoid this, heat losses from the shaft must be decreased (Gustavsson, 2004). Parameters that affect RAFT may also affect the position of the cohesive zone. This may be why there are occasions where increased RAFTs lead to lower silicon content in the hot metal.

Controlling the height of the cohesive zone can help to control silicon hot metal content. In the Sollac Fos 2BF, France, the silicon content of the metal was generally lower at the tuyere level than at cast. This was attributed to the lower temperatures at the tuyere level, a result of the low cohesive zone. In addition, owing to the low temperature conditions, the centre of the deadman was somewhat impervious for liquids. This concentrated the flow of liquids into a narrow region, located between 1 and 2.5 m from the tuyere tip. A lower cohesive zone also limits the contact time between gaseous SiO and the carburised metal droplets (Steiler and others, 1998).

The consumption of carbon fines (including unburnt char) by the hot metal can affect its silicon content. Laboratory reduction studies on olivine and acid pellets found that the carbon activity in the cohesive zone increases with longer reduction times, which provides more time for carburisation of the pellets. Reduction of SiO and dissolution of silicon into the metal is enhanced if the metal carbon content is high (Steiler and others, 1998). Furthermore, equilibrium calculations for coal and coke ash showed that increased carbon activity raises the amount of gaseous silicon at temperatures up to about 1600°C. This is because the reaction of silica with carbon to form gaseous SiO and CO takes precedence. At higher temperatures more solid SiC is formed in the coke/coal, lowering the amount of gaseous silicon (Gustavsson, 2004; Gustavsson and others, 2005). Controlling the local oxygen potential (local ore/coke ratio) to oxidise SiO will help limit silicon transfer.

The composition of the slag in the high temperature zone is another factor influencing the behaviour of gaseous SiO. Acidic slags generate SiO, whereas slags with a high basicity (low SiO2 activity) and high FeO absorb SiO, oxidising it to silica (Ito and Tokuda, 1998; Steiler and others, 1998). However, if the basicity is too high, slag viscosity increases and the SiO absorption rate will decrease (Gustavsson, 2004).

Lower temperatures also promote the silicate capacity of the slags. Operating with a low cohesive zone produces slags with a higher FeO content. FeO increases the partial pressure for oxygen which decreases the partial pressure for SiO gas with consequently lower hot metal silicon. Silicon in the metal is also consumed by the FeO. Injecting iron oxides or fluxes, such as BOF slag, into the tuyeres increases tuyere slag basicity and hence lowers silicon hot metal content (Ökvist and others, 2004; Wikström and others, 2002). There are also indications that the high oxygen activity just inside the tuyere may oxidise the iron (usually termed re-oxidation), thus also increasing tuyere slag FeO content (Gustavsson, 2004).

Transfer of silicon (and other elements) between the metal and slag occurs as the metal droplets pass through the slag in the coke packed bed and the molten slag layer in the hearth. For example, silica in the slag is reduced by carbon in the metal transferring silicon to the metal. On the other hand, silicon at the droplet interface is oxidised by FeO and/or MnO in the slag, transferring the silica product back to the slag. Thus desiliconisation can be enhanced by a suitable slag chemistry and by increasing the availability of oxygen at the metal-slag interface. At the Sollac Fos 2BF, slag-metal equilibrium for silicon was approximately achieved at a CO partial pressure of 300 to 400 kPa (equivalent to an oxygen activity between 1.5 x 10^-6 and 2.5 x 10^-6). The temperature and metal composition varies between the different zones within the hearth, and therefore also equilibrium conditions. Thus the hot metal silicon content will vary horizontally across the molten metal layer and consequently, its silicon content as it is tapped. In addition, silicon can become oxidised when flowing from the tap hole to the skimmer (Steiler and others, 1998).

From the above discussion it can be seen that there are many mechanisms affecting the silicon content of hot metal, some of which will tend to lower the silicon content when coal in injected, and others will increase it. The interplay of these mechanisms and different BF operating conditions may explain why some operators report lower silicon metal contents with PCI, whilst others found higher silicon levels.

8.2 Sulphur transfer

Hot metal with a low sulphur content is preferred to avoid the cost of desulphurisation in the refining plant. Additionally, sulphur in the hot metal retards carbon dissolution from coal char (and coke) and hence char consumption. This is partly due to its influence on the interfacial reactions taking place in the char/iron interfacial region (see Section 7.2.4). In the sessile drop technique, most of the sulphur from the coal char is transferred in the first minute of contact. The transfer then slows due to the formation of a calcium sulphide layer. This is formed from the reaction of calcium oxide in the char ash with sulphur in the liquid iron, that is, some iron desulphurisation is occurring (McCarthy and others, 2002, 2005). Higher levels of carbon in the liquid iron would provide a higher resistance to sulphur transfer into the iron.

Unlike silicon, most of the hot metal sulphur originates in the
coal and coke (see Table 10 on page 53). Consequently, low sulphur coals and coke are favoured. Coal contains both organic and mineral sulphur. During pyrolysis, the volatile organic sulphur is driven off primarily as H₂S which exits with the offgas. Most of the sulphur is in the mineral matter and it is the SO₂ from the mineral matter that is the principal mechanism for transferring sulphur to the metal:

\[ \text{SO}_2 + 2\text{C} \text{(metal)} = \text{S} \text{(metal)} + 2\text{CO} \]

Gaseous SiS is also responsible for transferring sulphur (and silicon) to the hot metal. SiS is formed by the reaction of CaS in the coal and coke mineral matter with gaseous SiO (Basu and others, 2001).

The partition of sulphur between the gas, metal and slag phases, and hence hot metal sulphur content, can be controlled by adjusting furnace conditions. Of course, control of the sulphur content can only be considered in connection with other requirements of the BF process.

Desulphurisation of the hot metal through the gas phase (around the raceway) becomes important when sulphur concentration is higher than 0.1% for high carbon metal. The possible reactions are:

\[ \text{H}_2 + \text{S} \text{(metal)} = \text{H}_2\text{S} \]

\[ \text{C} \text{(metal)} + \text{S} \text{(metal)} = \text{CS}_2 \]

\[ \text{CO} + \text{S} \text{(metal)} = \text{COS} \]

Since the reaction rate of the first reaction, which produces gaseous H₂S, is larger than those of the other two reactions, an increase in the partial pressure of hydrogen will enhance gas desulphurisation (Ito and Tokuda, 1998). The amount of hydrogen in the raceway increases with increasing PCI.

Sampling in a pilot scale BF found that the liquid metal in the bosh region contains the largest amounts of sulphur, lowering the melting point of pure iron (Steiler and others, 1998). As the iron droplets flow down through the coke bed, sulphur is transferred to the slag. Oxides in the slag react with sulphur in the metal to form sulphides. Therefore the basicity of the slag directly influences metal desulphurisation. Sulphur transfer to slag is promoted by a high slag basicity, high temperatures, a high slag reduction degree and a low oxygen potential (Basu and others, 2001; Ito and Tokuda, 1998; Steiler and others, 1998). Unfortunately, it is difficult to remove sulphur and unwanted alkalies simultaneously as alkali removal requires an acidic slag. The lower the FeO in the slag, the higher the amounts of sulphur retained, since FeO in slag promotes sulphur transfer to the metal. An increase in the partial pressure of CO decreases the distribution ratio of sulphur between slag and metal (Ito and Tokuda, 1998). BF operating practices that promote these conditions, such as injecting fluxes with the coal to increase slag basicity, will enhance metal desulphurisation. Most of the desulphurisation occurs as the metal droplets pass through the liquid slag layer. Hence the thicker the slag layer the more effective will be the desulphurisation (Basu and others, 2001).
Use of PCI in blast furnaces

9 Conclusions

In the present climate of high steel demand, blast furnace operators are under increasing pressure to lower operating costs and maximise productivity. Replacing coke with cheaper reductants can reduce operating costs. PCI is the most widespread measure used to substitute coke. Coal is typically cheaper than natural gas and oil. A tonne of coke, which takes some 1.4 t of coking coal to make, can be replaced by about 1 t of injected low volatile coal. Increasing PCI rates by only a small amount would represent significant financial savings.

Stable furnace operation with PCI rates of around 200 kg/thm and with coke rates below 300 kg/thm have been successfully maintained. PCI rates of over 260 kg/thm have been reached, but it can be difficult to maintain them over long periods of time. Without PCI, coke consumption is around 500 kg/thm. On well balanced furnaces, and with good operating practices, total reductant rate (coal and coke) has been reduced to below this level. Nowadays, new blast furnaces, and when upgrading existing injection systems, are commonly designed for PCI rates of 200 kg/thm or more. These high injection rates, though, have been achieved by using high quality, and hence more expensive, coke and iron ore materials. The challenge now is to achieve these high PCI rates with cheaper, lower quality raw materials, without losing hot metal quality, productivity or BF availability.

However, it can be difficult to maximise both productivity and the PCI rate at the same time. As PCI rates are increased, factors such as higher ore-to-coke ratios, the presence of unburnt char and increased furnace gas production lead to a reduction in furnace permeability. Various operational changes such as centre coke charging and higher oxygen enrichment can help improve permeability, but oxygen is expensive. The cost of the more sophisticated control systems required at higher PCI rates may also limit the economic attractiveness of very high coal injection rates. This has led some BF operators to lower the PCI rate. Kobe Steel in Japan, for example, has lowered the PCI rate to around 160 kg/thm at the Kakogawa 3BF because of a preference for more stable operation and higher productivity over the reductant cost.

The chemical and physical phenomena taking place in the furnace are complex. Understanding the effect of PCI and other factors on these phenomena is still far from complete. These include the influence of coal properties, and hence coal selection, on:
- pulverising, pneumatic transport and injection of coal into the blast furnace;
- coal combustion in the raceway;
- char gasification and reactivity;
- assimilation and dissolution of unburnt char in the slag and hot metal, and consequently, its affect on the hot metal quality.

Coal pulverising

Higher coal injection rates are putting increasing demand on the pulverisers in existing plants. If the design capacity of the pulveriser is limiting the PCI rate, then it may be possible to increase throughput by switching to a softer coal. With the recognition that unburnt char can be consumed outside the raceway, many BF operators have relaxed the PCI size requirements in order to maximise coal throughput. A larger particle size can lower pulveriser energy consumption and hence reduce grinding costs. The validity of the empirical tests for assessing the grindability (HGI test) and abrasion/erosion behaviour (YGP test) of a coal, and for predicting the capacity and power consumption of pulverisers have been questioned. Mill capacity for lower rank coals and coal blends are particularly difficult to evaluate using the existing grindability correlations. Despite the technical limitations of the HGI and YGP tests, no alternative procedures have yet gained widespread acceptance.

Pneumatic transport and injection

The required handling characteristics of the coal are dependent on the design of the system that transports the coal from the pulveriser to the injection lances and the injection system itself. Along with unique blast furnace operating conditions, this makes the choice of coal plant specific. With high coal injection rates, the reliability of the transport and injection system is crucial. Any interruption in reductant supply can quickly lead to serious problems. An equal distribution of coal through the tuyeres is also important. Blockages in the transfer pipelines have been attributed to coal moisture content, clay minerals and/or the presence of ultrafine particles. Lances still frequently become blocked, possibly because of the swelling and partial coking of the coal within the hot lances. This has led to set procedures for detecting and clearing blockages before they can cause any damage. Various tests have been proposed for assessing the flowability and handleability of a pulverised coal, but these tests generally only provide a relative ranking of coals. A standard test is required that is capable of identifying problematic coals.

Coal combustion

The combustion efficiency of the coal is important because of its affect on furnace permeability. Unfortunately, the combustion efficiency tends to decrease with increasing coal injection rate. Selecting a coal with a high burnout and optimising operating conditions, such as blast temperature and oxygen enrichment, can improve combustion efficiency. Typically high volatile coals produce more reactive chars than low volatile coals and hence a better burnout. However, these coals give a lower coke replacement ratio, produce more furnace gas, and may lead to soot formation (from unburnt volatiles) and consequent problems in the gas cleaning systems. Low volatile coals usually require a higher oxygen enrichment, adding to the cost. But char reactivity differences between coals may not be very significant at high injection rates because of the very short residence time (10–50 ms) in the raceway. In addition, at the high temperatures occurring in the raceway, the chemical reactivity of chars becomes less important since combustion
Conclusions

rates are limited by the rate of oxygen diffusion to the particle, and burnout times depend on particle size and oxygen concentration. There is a lack of a clear understanding of the effect of coal minerals on its combustion performance.

Determining the amount of soot (from unburnt volatiles), and unburnt coal char in the dusts emitted in the offgas could provide an early warning of poor coal combustion and allow PCI process parameters, such as blast gas composition and temperature, to be optimised. The amount of coke fines in the dust could be used to assess coke behaviour. A quick, simple and inexpensive analytical technique that can determine the different carbon types in the emitted dusts would prove useful. For example, differences in the carbon structure determined by X-ray diffraction can distinguish coal char from coke fines. Fourier transform-Raman spectroscopy appears capable of differentiating between the different carbonaceous materials in the dusts, in the absence of iron-bearing impurities. But the fluorescence problems have not yet been solved.

Char gasification and reactivity
The consumption of unburnt char outside the raceway is a major factor influencing the coal injection rate. Research is still needed to identify the fundamental factors contributing to char gasification and its assimilation in the slag and hot metal. The reaction of char with CO$_2$ (the solution loss or Boudouard reaction) is influenced by the char’s reactivity, which, in turn, is influenced by its chemical structure and mineral composition. The literature on char reactivity in relation to its behaviour in power station boilers is likely to provide a substantial framework/methods to investigate char reactivity in the BF context. This is already being undertaken. There is, as yet, no standard test for determining the reactivity of coals and their chars to CO$_2$ with regard to PCI performance.

Unburnt coal char
Factors influencing coal char interactions with slag, and hence the rate at which it is consumed, include the char carbon content, char ash content and composition, and slag composition, as well as the operating conditions. The principal mechanism is the reduction of iron oxides and silica in the molten slag by char carbon, and this is influenced by the wettability of chars by the slag. Char assimilation tends to lower slag viscosity whereas trapped unburnt char increases viscosity. Changes in slag mobility can influence the position and shape of the fluid and cohesive zones, and tapping of the slag. Higher PCI rates lead to increased amounts of coal ash and, consequently, higher slag volumes which can affect permeability in the lower part of the furnace. This may entail manipulating the slag chemistry to consume more unburnt char and/or processing lower ash iron ore materials.

The dissolution of carbon from char can make significant contributions to the carburisation of liquid iron, and can assist in reducing the consumption of coke and the accumulation of unburnt char at high PCI rates. Carbon dissolution is influenced by the fusion point of the ash, but probably more so by reactions between the ash oxides and liquid iron. These reactions are influenced by both the reactivity and wettability of the chars. Knowledge of the ash reactions affecting carbon dissolution could allow better coal selection for PCI applications, with a view to maximising char consumption by the hot metal.

Hot metal quality
An undesirable consequence of PCI is the transfer of silicon and sulphur from coal to the hot metal since it adversely affects hot metal quality, adding to the refining costs in the steel shop. The main source of silicon, though, is the iron ore. Higher coal injection rates generally mean higher amounts of silicon and sulphur transfer from the coal. There are many mechanisms affecting the silicon content of hot metal, some of which tend to lower the silicon content when coal in injected, whilst others increase it. The interplay of these mechanisms and different operating conditions may explain why some operators report lower silicon metal contents with PCI, whilst others found higher silicon levels. The main transfer mechanism is via gaseous silicon monoxide. However, vaporisation of coal ash silica is not simply related to its silica content. The different silica forms (quartz and clay minerals) in the coal ash could contribute different amounts of silicon to the hot metal. Understanding the silicon transfer route will help in modelling and predicting the hot metal silicon content.

Unlike silicon, most of the sulphur originates from the coal. Consequently, low sulphur coals (and coke) are preferred. Desulphurisation of the metal occurs as it passes through the molten slag layer. Sulphur transfer to slag is promoted by a high slag basicity, high temperatures, a high slag reduction degree and a low oxygen potential. BF operating practices that promote these conditions, such as injecting fluxes with the coal to increase slag basicity, will enhance metal desulphurisation. Unfortunately, it is difficult to remove sulphur and unwanted alkalis simultaneously as alkali removal requires an acidic slag.

Coke
Coke quality issues are more important at high PCI rates as less coke is available to supply reducing gases and to provide sufficient physical support without significant fines generation and accumulation. The current understanding of coke fines behaviour is still far from complete. A standardised coke test at temperatures over 1100°C is also required to cover coke properties in the high temperature region.

Emissions
Greenhouse gas emissions are of increasing concern. Raising PCI rates does not of itself reduce the greenhouse gas emissions because it only changes the carbon source and therefore has only a small affect on total carbon consumption. However, some indirect advantages accrue because of the smaller-sized coke plants that are required to support such as furnace; reduced plant construction means reduced total greenhouse gas emissions.

Coal properties
A considerably wider range of coals can be injected than those suitable for coking. These range in rank from subbituminous to anthracite. At high PCI rates, the preference
is for coals with both the ash and moisture contents below about 10%, sulphur content below 0.8%, and low phosphorus and alkali contents. These are good quality, and hence more expensive, coals. These properties put them into competition with the power generating industry. Blending coals will extend the range of acceptable coals and increase the number of supply options. With the recognition that unburnt coal char is consumed outside the raceway, the proportion of low volatile coals in the blend has risen. China, though, is an exception as it injected low volatile coals from the beginning.

There are ample supplies of PCI coals, although competition with electric utilities will affect availability and price. Since coal sources change over time, it is crucial to know the effect of these changes on BF performance. Although generalisations can be made about the expected behaviour of a coal (or blend), each unique combination of coal and BF design has to be individually assessed to confirm the acceptability of the coal blend. The number of variables involved makes each situation unique.

Coal evaluation
The coal properties given in a PCI specification are determined using standard tests. These tests are empirical and hence depend on the specified conditions. These conditions typically do not reflect those occurring in a BF and so the relevancy of some of the tests are questionable. Tests need to be developed that simulate, for example, the high temperatures and the pressure that occur in the raceway. The standard tests primarily provide a ranking of unfamiliar coals in comparison to a known coal, rather than providing absolute performance parameters. Most BF operators have their own in-house tests for assessing coals in more depth. This may include testing the coals in pilot plants that better reflect the conditions in full-scale plants than bench-scale tests. There is still the uncertainty of how far data obtained from bench- and pilot-scale tests can be extrapolated to industrial BFs. In addition, there is the question of whether the milligrams or grams samples used in bench-scale tests can provide a truly representative sample of the tonnes of coal consumed in the furnace.

Computer models offer a way of assessing the impact of a coal change and different operating conditions on BF performance and the quality of the hot metal product. But their validity has been questioned because the mechanisms they are portraying are complex and not fully understood. Their accuracy is dependent on the validity of the relationships and coal (and coke) quality indices built into the model. As the models become more widely validated in BFs, using a large number of different coals/blends, they will become more useful. However, it may never be possible to forecast behaviour with absolute certainty.

Blending offers advantages in improving the performance of coals. Its importance is likely to increase as injection rates approach the theoretical maximum and will provide furnace operators with the flexibility in coal selection to meet their particular needs. With better prediction and improved understanding of the effect of coal properties and how operating conditions can be optimised, there is the potential to identify suitable, as well as cheaper, coals. This could provide significant cost savings whilst maintaining a high productivity.


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